New facet of solar activities revealed by high-resolution imaging at he i 10830 Å

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Major solar activities such as major flares and associated coronal mass ejections (CMEs), have a great impact on space weather, which requires us to develop the ability to predict them. Despite the extensive studies already made, however, many basic processes, such as energy accumulation processes in solar active regions and the triggering mechanism of solar activities, are still not well understood.

One reason why the basic processes are hard to be understood is that the large-scale activities are complicated, involving many small-scale energy releases, making it hard to understand the basic picture of the events. Small-scale solar activities, such as chromospheric jets, small filaments, and surges, are generally accepted as the epitome of major solar activities, coupled with less physical processes. Studying these small-scale events will help us understand the basic physical process in large-scale solar activities, and further benefit space weather predictions. With the advent of large aperture solar telescopes, numerous well-sampled high resolution observational data enable us to study the small-scale solar activities, which are distributed at the lower end of the power-law spectrum. The New solar telescope (NST), among the new generation of large aperture, high resolution ground-based solar telescopes, is now the largest optical solar telescope in the world, which provides the major data source for this dissertation.

Another major reason why the basic processes are hard to be understood is that most of previous observations did not provide information of the solar interface region, which is essential for understanding how the convective motions and flows in the photosphere activate and drive solar activity in the corona. He I 10830 Å imaging
has proven to be an excellent choice for observing the interface region. First, the formation of 10830 Å triplet requires extreme conditions which are mainly present in the upper solar chromosphere or lower corona, providing the information in the interface layer. Second, the triplet is optically thinner than other chromospheric lines, such as Hα 6563 Å or Ca II 8542 Å, making the photosphere visible as a background. In this way, the solar activity could be traced from the photosphere, the chromosphere to the transition region. The purpose of the present work has been to investigate the small-scale activity using observations with NST in He I 10830 Å, based on which the goal of this dissertation is to further the understanding of the driving mechanism and energy release process of solar activities. Meanwhile, we believe that this kind of research will also be very helpful for learning the formation mechanism of the He I 10830 Å triplet.

Besides 10830 Å observations with NST, the research presented in this dissertation benefits significantly from multiwavelength observations, including photospheric images in TiO and chromospheric images in Hα from NST, (extreme) ultraviolet data and full-disk magnetograms from Solar Dynamic Observatory (SDO), X-ray data from RHESSI, and X-ray images from Hinode. In addition, several advanced data analysis tools are utilized such as Kiepenheuer-Institute Speckle Interferometry Package speckle reconstruction code, Fourier Local Correlation Tracking, Regularised Inversion to Infer Differential Emission Measure from SDO and Zero-dimensional Enthalpy-based Thermal Evolution of Loops Model. Studies are carried out for one surge on July 22 2011. The associated photospheric motions are also investigated. A small filament eruption on June 17 2012 is analyzed quantitatively. The fan-spine structure of a limb jet on July 8 2012 is also investigated.

The main findings in this dissertation are as follows: (1) the study of the surge on July 22 2011 shows that it is produced by magnetic flux cancellation which is triggered
by the advection in a rapidly developing large granule at the base of the surge; (2) both clear fan-spine topology and bi-directional flows of chromospheric jet are observed, which are signatures of the magnetic reconnection; (3) footpoint emission of the filament eruption is analyzed and the results indicate that photoionization of chromospheric plasma followed by radiative recombination is essential for populating the triplet states of the 10830 Å during the decay phase of a flare.
NEW FACET OF SOLAR ACTIVITIES REVEALED BY HIGH-RESOLUTION IMAGING AT HE I 10830 Å

by
Zhicheng Zeng

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NEW FACET OF SOLAR ACTIVITIES REVEALED BY HIGH-RESOLUTION IMAGING AT HE I 10830 Å

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Genius is one percent inspiration and ninety nine percent perspiration

Edison

I have to try harder! Do not be a lazybones!

To my parents, my grandparents and grandfather-in-law, for their endless love!

献给我的爸爸妈妈，爷爷奶奶，外公，感谢他们无尽的爱。
First, I would like to faithfully thank my advisor, Dr. Wenda Cao, who advanced my knowledge in solar instrumentation and sharpened my skills in data processing. He provided me the learning conditions so that I could easily get access to the most advanced data and gave me chances to learn from other professors. Without his patient and careful help I could not have successfully finished my dissertation. To me, he is more a mentor than an academic advisor, because the most important thing I learned from him is that details are the key to success. With his valuable help about everything I needed during the past years, I become a person who knows how to listen, speak, read, write and more importantly, solve problems and present solutions.

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CHAPTER 1

INTRODUCTION

1.1 Solar Physics — a Science for Modern Technological Society

The Sun, being the nearest star to human being, is the ultimate energy source of all living things on Earth. With the development of human civilization, people realize that the Sun is more than just for sustaining habitability on Earth. First, as the nearest star to us in the universe, the Sun is a unique and readily discernible sample for the research of other stars, helping us to analyze similar phenomena that occur in those distant stars and, thus, to understand basic underlying physical processes in remote area of Universe. Furthermore, it is an enormous natural plasma laboratory with extreme physical conditions (high temperature and high pressure), strong magnetic field and large length scale that are still difficult to realize on Earth. This natural laboratory is of very practical reference value from which a lot have been learned. For instance, flux rope eruption on the Sun might bear the same physical mechanism as the frequent disruption of controlled nuclear fusion. This has been identified by experiments on ground laboratory that a curved current channel will produce instability. This is also believed to be the underlying physical mechanism for driving filament eruptions. The observed magnetic configuration for so-called “failed (confined) filament eruption” is quite referential to the aim of controlling nuclear fusion. Experiments by a research group in Caltech have shown that disruption of current systems can be inhibited by the imposition of an additional “strapping” potential magnetic field oriented perpendicular to the plane of the current channel (Figure 1.1). The “strapping” potential magnetic field is quite similar to the overlying coronal magnetic field above an erupting filament. More detailed observations of solar
eruptions and related extensive research will surely be much beneficial to plasma physics, especially, experimental plasma physics.

Figure 1.1 Configuration showing basic prominence simulation geometry and “strapping” magnetic field (green lines) designed for constrain eruption.

[33]

The Sun is an active star with roughly 11 years’ cycle. The cycle varies much from one to another, for which the intrinsic mechanisms remain a mystery. The long-term changes of solar cycles could have intimate influence on the climate changes on the Earth. The relationship of Maunder minimum and little ice age is still a hot research topic. More importantly, major solar activities, e.g., solar flares and the coronal mass ejections (CMEs) often have a great impact on the Earth’s environment.
and human life. Figure 1.2 demonstrates the influences that solar activity could have on the modern society. Solar flares/CMEs are resulted from abrupt release of free magnetic energy in solar active regions, during which a mass of magnetized plasma as well as high-energy particles are ejected into interplanetary space. It is often referred to or nicknamed as solar storms. These storms can hit the Earth and bring us disastrous space weather. Physical conditions of the ionosphere around the Earth can be greatly changed, bringing a severe interference to radio communication and navigation. Highly energetic particles can not only damage the electronics on the space crafts and satellite but also be lethal to astronauts outside the space crafts, causing destructions to crucial high-technology systems in orbit. They can change the geomagnetic structure aggressively and generate destructive electrical current, causing large-scale blackout, e.g., Quebec blackout in 1989. It is one of the natural disasters which bring enormous economic and commercial losses to modern human beings.

As the development of modern technology, lack of knowledge about the solar activity will definitely cause unpredictable disasters. Thus, it is urgent to develop the ability of forecasting solar activity for the world to take precautions against the solar storms, safeguarding ground-based as well as space-based high-technology property. Therefore, the top priority goal across the solar research community is to understand the physical process for the explosive energy release processes of the Sun. Due to the great importance of the space weather to the modern human activities, solar physics and the space science have become a joint, practical science for the safety of technological society.

1.2 General Description of the Sun

The Sun is an typical G-type star in the main-sequence of the Hertzsprung-Russell diagram. The Earth travels around the Sun in an elliptical orbit with perihelion
around January 3 and aphelion around July 4. The length of semi-major axis, half of the distance from perihelion to aphelion, is 149,597,870.691 km, which is defined as the value of the astronomical unit (AU) by the International Astronomical Union (IAU). Using the Earth’s orbital period of 365.2568983 days, the mass of the Sun
could be estimated as $1.989 \times 10^{30}$ kg from Newton’s formulation of Kepler’s third law. The mass of the Sun accounts for $\sim 99.86\%$ of the total mass of the Solar System, thus, the Sun dominates the solar system. The Sun’s radius is $6.955 \times 10^5$ km, measured from its center to the edge of the photosphere. Its diameter is about 109 times and mass is about 330,000 times that of the Earth, respectively.

The Sun is stratified and can be divided into two basic parts: the interior and atmosphere. Figure 1.3 illustrates the current knowledge about the general structure of the Sun.

1.2.1 Interior of the Sun

The interior of the Sun is a spherical region which is opaque to visible light and has relatively higher density. Deep inside the solar interior is a nuclear core, which converts hydrogen to helium through fusion, providing the power source of the Sun. After the collapse of a hydrogen molecular cloud $\sim 4.58$ billion years ago, the core has been consuming the hydrogen fuel and by estimation, the fuel could still last for 5 billion years. The temperature in the core could reach as high as 15 million K. The diameter of the core is about 0.2 of the Sun’s radius. Right above the core is a thermal convection free zone, i.e., radiative zone, transferring the nuclear energy from the core by thermal radiation.

In the radiation zone, the density is so high that photons can travel only a short distance before they absorbed or scattered. As the photons travels outward, they shift to longer wavelength while the temperature drops.

As the temperature drops to $\sim 2$ million K (much cooler than 5 million K in radiation zone) around 0.71 solar radius, the energy transfer through radiation is not sufficient since atoms will absorb photons and not release them efficiently in cooler and denser plasma. Then the temperature gradient becomes larger and when it gets steep enough, the convection starts according to the Schwarzschild criterion. This
Figure 1.3 A cutaway view of the Sun with labels identifying various parts of the Sun. Moving outward from the center, the regions of the Sun's interior are the core, radiation zone, and convection zone. The atmosphere of the Sun includes the photosphere, the thin chromosphere and the extended corona. The photosphere is the visible surface of the Sun. Its base is the boundary between the solar interior and atmosphere (courtesy of NASA).

Convection region is known as the convection zone. The hotter plasma at the bottom of this region will rise up and remain warmer and less dense than its new surroundings even after expanding and cooling. The buoyancy will then force the hotter plasma to continue rising and when they reach the top of the convection zone (photosphere), they begin to cool and sink. After sinking to the bottom, the plasma are heated, rising to the surface again. This circular convection takes only about a week for carrying
the hot plasma to the solar surface, transferring energy much faster than radiation in this region.

It is worth mentioning that some fraction of convective energy is then converted into magnetic energy through the MHD dynamo mechanism, generating the solar magnetic field, without which there would be no solar activities such as flares and CMEs.

1.2.2 Atmosphere of the Sun

Being transparent to visible light, the atmosphere of the Sun surrounds the interior, with relatively lower density. The atmosphere could be separated into several layers. The layer at the bottom of the atmosphere is the photosphere, which is on the top of convection zone. When humans look at the Sun with naked eyes, they are looking at the photosphere, the visible surface of the Sun, which has the thickness of a little more than one hundred kilometers and a temperature of $\sim 6000$ K. In the photosphere, the smallest convective cells are granules, with typical size of 1,500 km and lifetime 8-10 minutes. Sunspots, which are the sites of strong magnetic fields, are the most common features besides granules in the Sun’s photosphere. Due to the pressure balance between magnetic field and gas, plasma density is lower inside the sunspots, resulting in a relatively cooler and darker region comparing to their surroundings.

The primary chemical compositions of the solar atmosphere are hydrogen and helium, which account for 92.1% and 7.9% of the number of atoms in the photosphere, respectively. Table 1.1 lists the 20 most abundant elements in the photosphere.

Above the photosphere, the solar atmosphere comprises three zones: the chromosphere, the transition region and the corona. The chromosphere was first discovered during total solar eclipses. The density of the chromosphere is only $10^{-4}$ times that of the photosphere, making the chromosphere invisible without special equipment owing to the overwhelming brightness of the photosphere. The thickness
of the chromosphere and transition region varies a lot and are about 2000 km and 200 km, respectively in quiet regions. The temperature increases gradually with altitude from about 4000 K up to around 20,000 K in the chromosphere. Then the temperature rises abruptly from 20,000 K to nearly 1,000,000 K in the transition region. Above the transition region is the corona, in which the average temperature ranges from 1,000,000 to 2,000,000 K. These extremely high temperature in the corona is abnormal because the second law of thermodynamics prevents heat from flowing directly from lower atmosphere of lower temperatures. This has been puzzling solar physicists for a long time. In such extremely high temperature corona, there are dense, cool chromospheric matter (10^4 K) supported by magnetic fields, which is called filaments. They appear as dark, long and narrow structures when seen against the disk in Hα. Viewed above the limb, filaments appear brighter against dark sky, which are called prominences. The size of the filaments on the Sun varies much, ranging from several arc-seconds to half of the disk.

From upper corona to outside, plasma is flowing out to inter-planetary space, making bubble-like region against the outside pressure of the interstellar medium. This whole region is called heliosphere. The physics of heliosphere is a joint discipline of solar physics and space physics.
Table 1.1  Twenty Most Abundant Elements in the Photosphere from Lang (2001) [51].

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Atomic Number</th>
<th>Abundance$^a$</th>
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<tr>
<td>Hydrogen</td>
<td>H</td>
<td>1</td>
<td>$2.79 \times 10^{10}$</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
<td>2</td>
<td>$2.72 \times 10^9$</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>$1.01 \times 10^7$</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
<td>7</td>
<td>$3.13 \times 10^6$</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>$2.38 \times 10^7$</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>10</td>
<td>$3.44 \times 10^6$</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>11</td>
<td>$5.74 \times 10^4$</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>12</td>
<td>$1.07 \times 10^6$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>13</td>
<td>$8.49 \times 10^4$</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>14</td>
<td>$1.00 \times 10^6$</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>p</td>
<td>15</td>
<td>$1.04 \times 10^4$</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
<td>16</td>
<td>$5.15 \times 10^5$</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Cl</td>
<td>17</td>
<td>$5.24 \times 10^3$</td>
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<tr>
<td>Argon</td>
<td>Ar</td>
<td>18</td>
<td>$1.01 \times 10^5$</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>19</td>
<td>$3.77 \times 10^3$</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>20</td>
<td>$6.11 \times 10^4$</td>
</tr>
<tr>
<td>Chromium</td>
<td>Cr</td>
<td>24</td>
<td>$1.35 \times 10^4$</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn</td>
<td>25</td>
<td>$9.55 \times 10^3$</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>26</td>
<td>$9.00 \times 10^5$</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>28</td>
<td>$4.93 \times 10^4$</td>
</tr>
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$^a$Normalized to an abundance of Silicon = $1.00 \times 10^6$.

1.3 Solar Activities

1.3.1 Brief Introduction

Although the Sun is in stratified equilibrium, it is very dynamic and exhibits activities at various spatial (from about $10^{-2}$ to $10^3$ Mm) and temporal scales (from about $10^1$ to $10^3$ seconds). Thus, there are many types of solar activities occurring in the solar atmosphere. The most notable activity is solar flares. Solar flares are sudden, rapid and intense brightness enhancements in the chromosphere, corona and even photosphere. These energetic explosions involve sudden particle acceleration, plasma heating, and bulk mass ejection, releasing up to $10^{32} - 10^{33}$ ergs in $10^2 - 10^3$ seconds.
for major solar flares. Flares, and often associated CMEs, are the most important solar explosive events as far as space weather effects are concerned [29].

Smaller flares (e.g., microflares) which could have as small as $\sim 10^{27}$ ergs, reaching down to the limits of detectability of modern instruments. Besides microflares, there are other small-scale activity including small-scale surges, jets, mini-filament eruptions, Ellerman bombs, and type II spicules, as well. A surge or a jet is the phenomenon of straight or slightly curved mass ejections shooting out from a brightened chromospheric patch up to coronal heights with speeds of 20-200 km $s^{-1}$ [75] and lifetime of 10-20 minutes [88]. Surges can be visible in Hα, Ultraviolet (EUV) or Ultraviolet (UV), and even soft X-ray (SXR), i.e., cool and hot ejected components co-exist in the same ejection event [79]. Historically, the term “surge” and “jet” refer to the cool and hot ejected plasma, respectively. Examples of surges are shown in Figure 1.4 observed with Hinode Ca II H broad band filter. The surges appear as anemones, with one bright base at the bottom and one spine of ejections.

Solar activities result from sudden release of free magnetic energy stored in solar atmosphere. Without magnetic fields, the Sun would be a rather boring star. Generally, magnetic fields are generated in the interior of the Sun through magnetic induction, and transported into the surface, initiating all kinds of solar activities. Figure 1.5 is an overview of the highly magnetized, and very complex solar atmosphere, which consists of the four layers mentioned in §1.2: the photosphere, the chromosphere, the transition region and the corona.

From the point of view of energy build-up and release, small-scale activity and large solar activity (major flares and CMEs) are believed to have the same physical mechanism. Small-scale activity, which is relatively simpler, provides us with much more comprehensive physical pictures since major events contain many coupled smaller spatial scale energy release processes, thus, overlapping the basic physics processes in time and space. Small-scale activity is thought to be the epitome
of the large solar activity. Taking the filament eruption as an example. The size of chromospheric filaments on the Sun ranges from several arc-seconds to around half of the disk. Small filaments with the size of several arc-seconds are called mini-filaments. The average lifetime of mini-filaments is about 50 minutes and their eruptions are always accompanied by microflares, with morphology similar to a large two-ribbon flare.
Furthermore, small-scale solar activity may be the trigger of large-scale activities. The small-scale solar activity usually occur in the lower atmosphere and at the edge of active regions, being associated with magnetic field cancellation. The small-scale activities, e.g., moving magnetic features and magnetic cancellations of the parasite polarities, often occur at feet of large filaments, driving upward flows in filaments. Since major flares are preceded with many small activity, which are thought to be the signature of energy bulid-up, observation and studying of small-scale solar activity with telescopes of meter-aperture will advance the understanding of flare energy build-up mechanisms.

Therefore, although small-scale activities are far from solar storms, observing and investigating these small-scale activities have great significance for the research of solar storms.

1.3.2 Multiwavelength Observations

In the 19th century, the development of spectroscopy provides a powerful tool of studying the chemical composition of and physical processes in stars and planetary
atmospheres, as well as the motion of objects in the Universe. In 1814, Joseph von Fraunhofer discovered 570 dark lines in the visible spectrum of the Sun, which were explained by Gustav Robert Kirchhoff in 1859 as the absorption of light passing cooler gases in the solar photosphere. In the photosphere, the emission has an overall distribution similar to emission of a blackbody at $\sim 5770$ K. As light passes through the surrounding atmosphere, part of the photons with specific wavelength is absorbed by cooler and denser gas through a quantum process in certain atoms. The absorbed photons by the gas are re-emitted in other directions and wavelengths while the emission generated by the gas could not compensate the discrepancy. As a result, an absorption line is created in that specific frequency range in the blackbody spectrum. An sample of the solar spectrum in the visible-light is shown in Figure 1.6. Each dark absorption line corresponds to specific chemical elements and the intensity of the absorption provides clues of the relative abundance of the elements.

Not only absorptions but also emission lines could be observed in the solar spectrum. When the plasma gets hot and tenuous in the upper solar atmosphere, the emission produced by the gas at some specific frequency surpasses the its weak absorption, generating emission lines over continuum spectrum. The emission lines have proven to be very useful for diagnosing temperatures of solar upper atmosphere and thus, enabling us to observe different solar layers with different temperatures. Hot corona was actually discovered in this way. The observed green line at 5303 Å from the corona had puzzled astrophysicists for half a century. Because this emission line could not match any spectral lines of known elements on Earth, it was once believed that a new element called coronium was discovered. Later, the green line at 5303 Å was identified as a line produced by highly ionized iron with temperatures of million degrees, bringing up the famous corona heating problem. Due to the discovery of the super hot corona, solar physicists began to observe the solar corona and transition
region with wavelengths from (E)UV, SXR and HXR to even gamma rays. Figure 1.7 shows the different facets of the Sun observed in different wavelengths.

All solar activities involve plasma heating by high-energy electron beams, producing plasma at various temperatures. These plasma have different observational signatures distributed at different wavelengths. Therefore, observations in different wavelengths provide totally different scenario. Synthesizing various signatures is essential for understanding the physical processes of these energetic events. For example, standard flare model (Figure 1.8) is established in this way according to observations at different wavelengths. Flare’s energy generated from magnetic reconnection heats the plasma at the loop top while the accelerated charged particles precipitate downward to the lower atmosphere with higher density, producing HXR emissions at footpoints via bremsstrahlung. The heated plasma at the footpoints
evaporate along the magnetic loops, enhancing EUV and/or SXR emissions as observed. As the hot flaring loop cools down, it becomes visible at chromospheric lines like H$_\alpha$.

Through the example shown above, multiwavelength observations, which provide information for different layers and regions with different temperatures, are essential for revealing the physical process of the solar activity.

1.3.3 Importance of Interface Region

Despite extensive multiwavelength observations have been conducted during past decades, many physical processes, e.g., energy accumulation processes in solar active regions and the triggering mechanism of the solar activities, have not been well
understood yet. This makes the forecasting ability of solar activities much lower compared with weather forecasting on Earth.

One major reason is that most of previous observations are lack of good observations for solar interface region, which lies between the photosphere and the lower corona. This interface region represents physical links, without which a comprehensive physical picture for all levels solar atmosphere would not be obtained. For the physics of solar activity, one big question is how the convective motions and flows in the photosphere activate and drive solar activity in the corona. It is believed that solar activities comes from sudden release of free magnetic energy stored in the corona. The photosphere (surface layer immediately above the convective zone), which exhibits a constantly evolving/moving, multipolar magnetic flux distribution, plays a key role in the magnetic energy storage and even triggering magnetic energy
release. The photosphere and the corona are two quite different layers. The corona hosts a tenuous multi-million degree plasma, which is nearly three orders of magnitude hotter than the underlying photosphere. It is very much desirable to have a simultaneous well-sampled observation for the interface-layer between the photosphere and corona. An easy and conventional observation of the interface region is using H$_\alpha$ 6563 Å or Ca II 8542 Å to image and/or get spectra of the chromosphere. However, the data thus obtained reveal only the chromosphere, bearing totally different morphologies with the photosphere and corona. Thus, simultaneous and cospatial observations of other layers are required for comprehensive analysis. Furthermore, these data lack the information of the transition region, an important layer for energy transportation. These drawbacks make it notoriously hard to clarify the physical link between the photosphere and corona. Achieving the spectral and spatial information of the interface region is the key science of IRIS (Interface Region Imaging Spectrograph), a recent satellite launched by NASA, aiming to tease apart what is happening in the interface region and find the physical links between cause and effect. To do this, IRIS will have a spectral imaging from the chromosphere, an expanse of ionized plasma lying right above solar surface, and the transition region, where the chromosphere transfers into the hotter corona above (Figure 1.9). IRIS will advance studies about how the solar atmosphere is energized by tracing the flows of energy and plasma from chromosphere to corona.

1.3.4 Narrow-band Imaging at 10830 Å — a Newly Developed Means for Observing Interface Region

The research frontier for the interface region observation has been pushed forward with the arrival of the 1.6 m aperture New Solar Telescope (NST) at Big Bear Solar Observatory (BBSO) [28]. With NST, Ji, Cao and Goode [38], for the first time, obtained new facet of the Sun’s upper chromosphere using high resolution narrow-band imaging at Helium near infrared line 10830 Å: especially narrow loops (∼ 0.3″)
of solar material scattered on the Sun’s surface, which are connected to higher lying, wider loops. The novel observations have proven to be very useful for resolving the coronal heating problem, e.g., they reported first direct observations of dynamical events originating in the Sun’s photosphere and subsequently lighting up the corona. Moreover, these ultrafine loops, and their overlying hotter counterparts, may also help with the quest to determine how the magnetic energy is accumulated in photosphere and released into corona.

The He II 10830 Å triplet is a very special spectrum line. There are two electrons in one helium atom. The helium atom having states with a symmetric spin function is called orthohelium. Electron transitions between the two lowest energy levels, i.e., $2^3S_1$ and $2^3P_{0,1,2}$, of the orthohelium produce three sub spectrum lines at 10829.911 Å,
10830.250 Å and 10830.339 Å, respectively, which are refereed to as the 10830 Å triplet. The bottom panel\(^1\) in Figure 1.10 shows the general spectrum of the 10830 Å triplet, which are pointed by the red arrows, in the quiet Sun.

As shown in Figure 1.10, there are mainly two ways to populate the metastable \(2^3S_1\) state in order to have 10830 Å triplet, either by ionizing the neutral helium atoms followed by recombination with free electrons (indicated by a green path), or by direct collisional excitation from the ground level of parahelium (depicted by a yellow path). The corresponding formation mechanisms have been proposed, namely photoionization-recombination mechanism (PRM) and collisional mechanism (CM), respectively. In active regions, neutral helium atoms could also be ionized through collisions by non-thermal electrons and then recombine with free electrons to populate the \(2^3S_1\) state \([17]\), which is called CRM.

In quiet regions of the Sun, both excitation (PRM and CM) methods require extreme conditions which are mainly present in the upper solar chromosphere or lower corona. Therefore, the 10830 Å lines are formed in an interface layer that connects the high temperature atmosphere and low temperature atmosphere, which makes the observations with 10830 Å imaging part of the transition region (Figure 1.11).

He I 10830 Å lines have another predominant advantage for solar observations. The triplet is optically thinner than other chromospheric lines, such as H\(\alpha\) 6563 Å or Ca II 8542 Å, making the photosphere visible as background, thus capturing some photospheric features. In this way, the solar activity could be traced from photosphere, chromosphere to transition region. Furthermore, the granulation in the background of He I 10830 Å filtergrams give us irreplaceable aid for pinning exactly down the small-scale activity in the photosphere. Observing the Sun in 10830 Å has proven to be an excellent choice for high resolution observations \([38, 95]\). Snapshot of the observations in both H\(\alpha\) and 10830 Å from NST is shown in Figure 1.12. The larger

\(^1\)This figure is from http://bass2000.obspm.fr/solar_spect.php?WL=10826&DW=8&sel_resol=0.001&Find.x=16&Find.y=11&Find=Find
Figure 1.10 The top picture shows the energy structure of the parahelium and orthohelium. The coloured paths indicate the formation mechanisms of 10830 Å. The green path represents the photon-ionization followed by recombination while the yellow dashed path represents the direct collisional excitation from the ground state of parahelium to the $2^3S_1$ state of orthohelium. The bottom picture shows the general spectrum of the 10830 Å triplet in the quiet Sun. The red arrows point to the positions of the 10830 Å triplet.

dark feature on the left top of both panels is a sunspot while smaller dark feature in the center of both panels is a small pole. In 10830 Å filtergram, not only the
Figure 1.11 Right: A 171 Å image of coronal magnetic loop complex observed by AIA (Atmospheric Imager Assembly) onboard SDO (Solar Dynamic Observatory) on July 22, 2011 for the active region NOAA 11259. Left: Simultaneous NST He I 10830 Å narrow band filtergram (band width of 0.5 Å) at line center. Under these hot coronal loops, cooler and much thinner loops with similar configuration are observed. These cooler loops are scattered on a background teeming with features of the photosphere: granules, inter-granular lanes and a sunspot.

dark loops above the photosphere, but also the granules in the photosphere could be observed, while in the Hα image, it is opaque for observing the underlying background except sunspots and poles.

It is extremely hard to make a precise alignment between chromospheric images and photospheric images, since there are hardly any common features. Traditional observations, e.g., Hα, usually use far-wing to achieve optically thin observations. Far-wing observations at Hα could present a picture similar to the photosphere, however, a lot information in the chromosphere are lost. In addition, Hα line center features usually bear no resemblance with transition region. The He I 10830 Å imaging serves as much better intermediate for linking photospheric observations and chromospheric observations in other spectrum lines. With these advantages and high resolving power of NST, Ji, Cao and Goode [38] were able to trace small activities from the surface
layers to the lower corona. They pinned down the root of some activities to inter-
granular lane areas.

As demonstrated in Figure 1.13, the top row shows the images with hot loops (a brightening process) in corona observed by SDO/AIA at 171 Å. The bottom row shows the photosphere observed NST in broadband TiO at 7057 Å. Nothing is identical in the TiO and AIA images for us to establish connections between these two observations. Nonetheless, the 10830 Å images shown in the middle row have features in both the photosphere and corona, enabling us to trace the activity through the atmosphere. This could not be done using Hα line-center or even off band observations which have only chromospheric features of low temperatures. The He I 10830 Å observations will no doubt advance the understanding of the photosphere’s role in powering the solar activity and supplying energy for the solar upper atmosphere.
1.4 Scientific Goal and Dissertation Outline

In the era of low-resolution observations, solar physicists mainly concentrate on major flares and/or CMEs. In a major activity, many observational phenomena are coupled or mixed, making it very difficult to clarify. With unprecedented resolving and photon-collecting ability of NST, it is an era to study small-scale solar activities. First, most of solar activities are distributed at the lower end of the power-law spectrum and there will be numerous well-sampled observations of small solar activities with high spatial, temporal and spectral resolution by NST. Second, small-scale solar activity is thought to be the epitome of major solar activity. Therefore, investigating the
small-scale solar activities will surely help us to understand major solar activities, and further benefit the space weather prediction.

As stated above, observations with He I 10830 Å could help us trace the small-scale activity from photosphere to lower corona. Utilizing NST data in 10830 Å provides us with valuable means to understand the driving mechanism with less ambiguous information. In addition, combining X-ray, EUV, and UV data of flares, analyzing emission at He I 10830 Å could help us to build models of energy transport from corona to chromosphere during the process of a flare. Meanwhile, it is believed that this kind of research will also be very helpful for learning formation mechanism of He I 10830 Å triplet.

Thus, observing and studying the small-scale activity in He I 10830 Å are timely topics in the era of large aperture solar telescopes, especially NST, which is also the main objective of this dissertation.

The relevant background and previous studies are introduced in Chapter 1, followed by the descriptions of data sets and analysing tools in Chapter 2. The studies and results of this dissertation will be shown in Chapters 3-6.
CHAPTER 2

SOURCES OF DATA, ANALYZING TOOLS, AND MODELS FOR THIS DISSERTATION

Like other disciplines in astronomy, solar physics is a science relying solely on observations. There are more advanced research topics, i.e., subject of modelling and making predictions, however, which must be based on results from observations. Thus, carrying out observations and collecting observational data are quite essential for the study of solar physics. Nonetheless, solid physical models that explain the observations are needed to understand the mechanisms that are related to the observed phenomena. In following sections, the data sources are introduced and an elaboration about the tools and models for data analyzing in this dissertation is given.

2.1 Data Sources for Current Study

2.1.1 Ground Based Observation with New Solar Telescope

Solar observations started with ground based observation. During current space age, ground based observation is still an indispensable means for obtaining high-quality data. It is easier and much more inexpensive to build a large aperture telescopes on the ground comparing to space missions of similar class. Ground-based large aperture telescopes, equipped with flexible combination of various instruments, give us not only high-resolution images but also high-cadence data. The main data source for this dissertation is from ground based observations with NST of BBSO. The 1.6 m aperture NST, which began its scientific observations in 2010, is the first of a new generation of large aperture, high-resolution ground-based solar telescopes and it is now the largest optical solar telescope in the world [27, 9]. Its off-axis design eliminates any obscuration in the path of the sunlight, giving an essential advantage in high resolution observations for distinguishing low contrast features on the Sun.
Excellent seeing conditions, augmented with an Adaptive Optics (AO) system and speckle-reconstruction processing, help deliver diffraction limited images frequently in a continuous data stream. For high resolution imaging, it is functioning with several wavelength bands observed simultaneously. Following wavelengths are used in this dissertation. First, broad-band (10 Å) of TiO 7057 Å. This molecular band has stronger absorption in the cooler intergranular lanes, thus enhancing the contrast of intensity in the photosphere. The second is narrow-band (0.25 Å) imaging at Hα 6563 Å. As stated in above section, this is the traditional way for studying features in the chromosphere. Last but most importantly, narrow-band (0.5 Å) filtergrams of He I 10830 Å triplet. Simultaneous multi-wavelength observations made in these bands provide us with an opportunity to investigate the solar activity from the photosphere through the chromosphere in unprecedented details.

2.1.2 Space Observation

The solar corona exhibits extraordinary high temperature exceeding 1,000,000 K, which is dominated by high energy emissions in (E)UV and X-ray. Observations in (E)UV and X-ray could provide information in the corona for studying solar activity. Furthermore, solar activity, especially large solar activity, are accompanied with processes of high-energy releasing, which generate photon emissions in (E)UV and even x-ray. For a comprehensive understanding the solar activity, observations in (E)UV and X-ray are indispensable. However, due to the absorption by the Earth’s atmosphere, only visible light, some infrared bands, and radio waves can reach the ground. Measurements have to be taken at a height at least 30 km to observe HXR and γ-ray emissions effectively, and height greater than 100 km to detect soft X-ray and UV radiation. Therefore, in order to study the solar activity in the corona, space observations are necessary. All the researches in this dissertation used supplementary data from space observations, e.g., Chapter 4.
Solar Dynamic Observatory, SDO, was launched on February 11, 2010, which is designed to advance the knowledge of solar activity and its influence on Earth and Near-Earth space, through studying the solar atmosphere on small spacial scales and cadence in multiple wavelengths simultaneously. Three instruments on board the SDO are delivering a huge number of images in a continuous data stream for 24 hours each day. The instruments are: (1) Atmospheric Imaging Assembly (AIA), (2) Helioseismic and Magnetic Imager (HMI) and (3) Extreme Ultraviolet Variability Experiment (EVE).

AIA uses multiple (E)UV wavelengths as well as white light to image the Sun’s photosphere, chromosphere, transition region, corona and flaring region. The (E)UV images of AIA provides unprecedented views of the evolving sun, with 12-second cadence of image stream and 4096 by 4096 pixel images at approximately 0.6 arcsec per pixel. All the AIA wavelength channels are listed in table 2.1, with corresponding sources from the Sun and characteristic temperatures. The AIA data are also useful for diagnosing differential emission measures (DEM) in the corona, which will be discussed in the following sections.

HMI is an instrument designed to study not only the solar oscillations, characterizing the Sun’s interior, but also the various components of magnetic fields in the solar surface, i.e., photosphere. The HMI extends the capabilities of the SOHO/MDI instrument with continuous full-disk coverage at 6173 Å with higher spatial resolution of 1 arcsec. The temporal cadences are 45 s for line-of-sight magnetograms and 720 s for both vector magnetograms and dopplergrams, respectively. In this dissertation, the evolution of line-of-sight magnetograms in the photosphere serves as a solid evidence for the triggering mechanism of the solar activity.

EVE measures the Sun’s extreme ultraviolet irradiation with unprecedented spectral resolution, temporal cadence, and precision for a scientific understanding the variation of Sun’s EUV influence on Earth’s climate and near-Earth space.
Table 2.1  All the AIA Wavelength Channels, with the Corresponding Source from the Sun and Characteristic Temperatures

<table>
<thead>
<tr>
<th>Wavelength channel</th>
<th>Source</th>
<th>Region of solar atmosphere</th>
<th>Characteristic temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>White light</td>
<td>continuum</td>
<td>Photosphere</td>
<td>5000 K</td>
</tr>
<tr>
<td>1600 Å</td>
<td>C IV + continuum</td>
<td>Transition region &amp; upper photosphere</td>
<td>$10^5$ &amp; 5000 K</td>
</tr>
<tr>
<td>1700 Å</td>
<td>continuum</td>
<td>Temperature minimum, photosphere</td>
<td>5000 K</td>
</tr>
<tr>
<td>304 Å</td>
<td>He II</td>
<td>Chromosphere &amp; transition region</td>
<td>50,000 K</td>
</tr>
<tr>
<td>94 Å</td>
<td>Fe XVIII</td>
<td>Flaring regions</td>
<td>$6.3 \times 10^6$ K</td>
</tr>
<tr>
<td>131 Å</td>
<td>Fe VIII, XX, XXIII</td>
<td>Flaring regions</td>
<td>$4 \times 10^5$, $10^7$ &amp; $1.6 \times 10^7$ K</td>
</tr>
<tr>
<td>171 Å</td>
<td>Fe IX</td>
<td>Quiet corona, upper transition region</td>
<td>$6.3 \times 10^5$ K</td>
</tr>
<tr>
<td>193 Å</td>
<td>Fe XII, XXIV</td>
<td>Corona &amp; flaring regions</td>
<td>$1.2 \times 10^6$ &amp; $2 \times 10^7$ K</td>
</tr>
<tr>
<td>211 Å</td>
<td>Fe XIV</td>
<td>Active region corona</td>
<td>$2 \times 10^6$ K</td>
</tr>
<tr>
<td>335 Å</td>
<td>Fe XVI</td>
<td>Active region corona</td>
<td>$2.5 \times 10^6$ K</td>
</tr>
</tbody>
</table>

Reuven Ramaty High Energy Solar Spectroscopic Imager, RHESSI, was launched on 5 February 2002, making a unique contribution to the study of solar flares [56]. RHESSI is the sixth mission in the line of NASA SMall EXplorer (SMEX) and it has unprecedented spatial, temporal and energy resolution, as well as continuous coverage over a wide energy range in SXR, HXR and γ-rays. The primary scientific objective of RHESSI is to understand particle acceleration and
transportation during the impulsive energy release process of solar flares. Taking advantages of high purity germanium detectors as well as temporal modulation Fourier-transform imaging technique, RHESSI is providing the first HXR imaging spectroscopy, the first high-resolution spectroscopy of solar γ-ray, the first imaging above 100 keV, and the first imaging of solar γ-ray. Thus, both the original source and evolution of the accelerated high energy particles could be investigated, advancing understanding of the fundamental high-energy processes at the core of the solar explosive events. RHESSI’s imaging spectroscopy covers the energy from 3 keV to 17 MeV with energy resolution of ~1 keV. The spatial resolution could be as high as 2.3″, while the temporal resolution could be as short as tens of milliseconds.

2.2 Data Processing Tools

2.2.1 Kiepenheuer-Institute Speckle Interferometry Package (KISIP) Speckle Reconstruction Code

AO systems have been used for several meter-class ground based solar telescopes to improve spatial resolution of the recorded data. However, the residual aberration still remain in AO corrected images, e.g., only wave front of the on-axis isoplanatic patch is corrected. Therefore, post-facto image reconstruction techniques such as speckle interferometry are required to achieve consistent, near-diffraction limited resolution. The principle of speckle imaging is to estimate the undisturbed source from a set of images, each of which is taken by freezing the atmospheric turbulence. Freezing the movement of the atmosphere requires short exposure times on the order of 100 ms for infrared images and as little as 10 ms for the visible-light images.

For data reduction in this dissertation, the KISIP v.6 program [101] is used to perform the speckle reconstruction. The core has been written in the C programming language and enhanced for parallel processing. It separates the image’s Fourier Phases from its amplitudes. The KISIP program incorporates two different algorithms to reconstruct the object’s Fourier phases. One is an extension of the Knox-Thompson
(KT) algorithm and the other is a speckle masking (or triple correlation) algorithm. Although the KT algorithm is computationally less expensive, it is sensitive to alignment errors of the speckled images, whereas triple correlation algorithms do not suffer from this kind of error. Thus in bad seeing conditions, this leads to a better performance of the speckle masking algorithm. Figure 2.1 shows the comparison between raw data (left) and the corresponding speckle reconstructed image (right).

![Figure 2.1](image)

**Figure 2.1** Comparison between a raw image and the corresponding speckle-reconstructed image. Left panel: filtergram before the speckle reconstruction processing. Right panel: a snapshot of reconstructed He I 10830 Å image using the KISIP speckle reconstruction code.

### 2.2.2 Fourier Local Correlation Tracking (FLCT) Method

In order to track the flows in the photosphere, data processing tools have been developed and implemented, including local correlation tracking (LCT) and fourier local correlation tracking (FLCT) methods. The basic idea is to have two images separated in time. Then, the two images are divided into sub-images in the same way. Each sub-image in one image has a correspondent sub-image in the other image. The shifts that maximize a “localized” cross-correlation function is determined between one sub-image and its correspondent sub-image. The estimations of all the shifts for
the sub-images constitute a 2-d velocity field. FLCT uses fast fourier Transforms (FFTs) to compute the cross-correlation function, and uses a 2nd-order accurate Taylor expansion of the 2-d images to locate the peak of the cross-correlation function to achieve accuracy down to sub-pixel.

The FLCT code [21] is written in C, using the FFTW3 library (“Fastest Fourier Transform in the West”). It is designed for easy usage within an IDL or GDL session. Latest version (1.01) runs very fast (4096 by 4096 images in about 6 minutes). The technique only allows to detect the feature’s shifts without taking any physical laws into account. Consequently, the result could not resolve the effects of compression and stretch. However, the flow tracking code turns out to be useful and powerful in most cases for studying the flow field of solar activity. Figure 2.2 gives an example of the result showing the flow field in the photosphere obtained by FLCT. It is noticeable that, inside granules, the velocity field is weaker in the middle and stronger toward the intergranular lanes, which is consistent with the visual convection movements inside granules.

2.2.3 Zero-dimensional Enthalpy-based Thermal Evolution of Loops (EBTEL) Model

For understanding heating processes in the corona during a flare, Klimchuck [46, 12, 13] developed an highly efficient model to compute mean coronal plasma properties, i.e., temperature and density, inside a magnetic flux strand, with an assumption that the distribution of plasma is approximately uniform inside one magnetic strand. The model is called “enthalpy-based thermal evolution of loops (EBTEL)”, which has proven to be an efficient and accurate description for the evolution of the average temperature and density along one magnetic strand.
Figure 2.2  The result obtained by FLCT, which shows granular flows in the vicinity of a sunspot. The background image is observed in TiO. The Dark feature is the sunspot, which is located at the lower left corner of the image. The lengths of the arrows indicate the speed of the flows.

There are three basic equations for the hydrodynamic loop models, which are shown below. The first one is the continuity equation, based on the mass conservation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial s} = 0
\]

(2.1)

where \( \rho \) is the total mass density, \( v \) is the fluid velocity, and \( s \) is the coordinate along the loop. The second one is the momentum equation:

\[
\rho \frac{dv}{dt} = -\frac{\partial P}{\partial s} + \rho g + \frac{\partial}{\partial s} (\mu \frac{\partial v}{\partial s})
\]

(2.2)
where $P$ is the total gas pressure from electrons and ions, $g$ is the component of gravitational acceleration along the loop, $\mu$ is the viscosity coefficient of the plasma.

The third one is energy equation, obeying the law of energy conservation:

$$\frac{de}{dt} + \omega \frac{\partial v}{\partial s} = \frac{\partial}{\partial s} \left( \kappa \frac{\partial T}{\partial s} \right) - R + \mu \left( \frac{\partial v}{\partial s} \right)^2 + Q_q(s) + H(t, s) \quad (2.3)$$

where $e$ is the internal energy per unit volume, $\omega$ is the enthalpy per unit volume, $\kappa$ is the thermal conductivity coefficient, $R$ is the radiative loss, $Q_q(s)$ is the quiet sun heating term to maintain pre-flare equilibrium, $H(t, s)$ is the input flare heating rate. The third term on the right is viscous dissipation.

In the optically thin corona with a high temperature and low density, the radiative cooling is dominated by collisional excitation. Then the radiative term $R$ could be written as: $n^2 \Lambda(T)$, with $\Lambda(T)$ being the empirically-determined radiative loss function for optically-thin plasmas.

$$\frac{\partial e}{\partial t} + v \frac{\partial e}{\partial s} + (e + P) \frac{\partial v}{\partial s} = -\frac{\partial F}{\partial s} - n^2 \Lambda(T) + \mu \left( \frac{\partial v}{\partial s} \right)^2 + Q_q(s) + H(t, s) \quad (2.4)$$

where the relation $\omega = e + P$ and $F = -\kappa \frac{\partial T}{\partial s}$ is used. $F$ is the heat flux. The viscosity term could be neglected under the ideal gas assumption. In active region, quiet sun heating term is small. Thus, the $Q_q(s) + H(t, s)$ could be combined into one volumetric heating rate $Q$. Moreover, the net force along the loop is balanced in momentum equation: $\frac{\partial P}{\partial s} = \rho g$. Following equation is deduced:

$$\frac{\partial e}{\partial t} = -\frac{\partial (ev)}{\partial s} - \frac{\partial (Pv)}{\partial s} - \frac{\partial F}{\partial s} - n^2 \Lambda(T) + Q(t, s) + \rho gv \quad (2.5)$$

where $e$ is combined with thermal and kinetic energy density: $e = \frac{3}{2}P + \frac{1}{2}\rho v^2$.

If the flow is subsonic and the loop is shorter than a gravitational scale height, the kinetic energy and gravity terms in equation 2.5 could be neglected:

$$\frac{3}{2} \frac{\partial P}{\partial t} \approx -\frac{5}{2} \frac{\partial (Pv)}{\partial s} - \frac{\partial F}{\partial s} - n^2 \Lambda(T) + Q(t, s) \quad (2.6)$$
By averaging the above equations along the length of a magnetic loop, this model becomes a 0-dimensional model. The loop is divided into two sections. One is from the top of chromosphere to the base of corona (transition section). The other is from the base to apex of corona (corona section). The base of the corona is defined as the transition region (close to footpoint), designated by the subscript 0. First, the integration of equation 2.6 is done through the corona section, with the assumption that both velocity and heat flux vanish at the apex of corona due to symmetry. The result could be written as:

\[ \frac{3}{2}L \frac{\partial \overline{P}}{\partial t} \approx \frac{5}{2} P_0 V_0 + F_0 - R_c + LQ \]  

(2.7)

The overbars indicate spatial averages along the corona section, which has length L. \( R_c \) is the radiative cooling rate per unit cross-sectional area in the corona (ergs \( cm^{-2}s^{-1} \)).

If equation (2.6) is integrated over the transition section with thickness l. Using the fact that the heat flux and enthalpy flux are both ignorable at the top of the chromosphere since they are dissipated throughout the transition region, a similar result is obtained:

\[ \frac{3}{2}l \frac{\partial \overline{P}_{tr}}{\partial t} \approx -\frac{5}{2} P_0 V_0 - F_0 - R_{tr} + l\overline{Q}_{tr} \]  

(2.8)

\( R_{tr} \) is also a radiative cooling term as \( R_c \). l is actually very small because the transition section is much thinner compared to the thickness of corona. Then the above equation could be written as:

\[ \frac{5}{2} P_0 V_0 \approx -F_0 - R_{tr} \]  

(2.9)

Combined equation (2.9) with (2.7), following equation is obtained:

\[ \frac{d\overline{P}_i}{dt} \approx \frac{2}{3} [Q_i - \frac{1}{E_i} (R_c + R_{tr})] \]  

(2.10)
where \( i \) denotes each evolving loop. The time derivative of the electron column density \( \pi L \) (total electrons in the corona section) is equal to the flux of electrons through the coronal base: \( \frac{\partial}{\partial t}(\pi L) = J_0 = n_0 v_0 \). Together with the ideal gas law in a fully ionized hydrogen plasma: \( P_0 = 2kn_0T_0 \), where \( k \) is Boltzmann’s constant, equation (2.9) could be written as:

\[
\frac{\partial}{\partial t}(\pi L) = J_0 = -\frac{1}{5kT_0}(F_0 + R_{tr})
\]

(2.11)

which yields:

\[
\frac{dn_i}{dt} = -\frac{c_2}{5c_3kL_iT_i}((F_0) - R_{tr}),
\]

(2.12)

where \( c_2 = \frac{T_i}{T_a} \), \( c_3 = \frac{T_0}{T_a} \) and \( T_a \) is the apex temperature.

\( F_0 \) is the conductive flux from the base to corona, with the classical form of

\[
F_0 = -\kappa_0 T_0^{5/2} \frac{\partial T}{\partial s} \approx -\frac{2}{7} \kappa_0 \frac{(T/c_2)^{7/2}}{L}
\]

(2.13)

where \( \kappa_0 \) is the thermal conductivity coefficient[87].

Thus, after setting the initial conditions and inputting the heating rate \( Q \), the evolution of the mean pressure and density in the corona could be computed. In this way, the evaluation of average temperature, density, and pressure of each loop in response to a heating event are achieved very efficiently.

Although the EBTEL model is highly simplified as described above, it has physical significance, e.g., the chromospheric evaporation and condensation. From equation 2.2, at the beginning of the heating, the heat flux \(-F_0\) is larger than the radiation loss from the base, generating excess heat that drives the increment of the mean density in the corona, which is consistent with the observed chromospheric evaporation. At the late phase, when there is deficient heat flux, the mean density decreases, resembling the process of draining plasma from coronal loop through cooling, i.e., coronal condensation.
2.2.4 Regularised Inversion to Infer Differential Emission Measure from SDO

Since the solar corona is optically thin, the emissions are approximately proportional to the square of electron density integrated over the volume of emission, which is called emission measure (EM). $EM = \int n_e^2 dV$. It is used to characterize the amount of material available to produce the measured flux and it is a tool of fundamental importance to deduce the physical parameters like pressure, temperature and density.

Another term derived from EM, i.e., differential emission measure or DEM, provides a more refined temperature structure, which is defined as

$$\xi(T) = \frac{n_e^2 dV}{dT} [cm^{-3} K^{-1}]$$  \hspace{1cm} (2.14)

where $\xi$ represents DEM. The observational signals are produced through DEM convolved by the instrumental response, i.e.,

$$g_i = \int_T K_i(T) \xi(T) dT + \delta g_i$$  \hspace{1cm} (2.15)

where $i$ represents the $i$th filter, $g_i$ is the observed signal, which has a temperature dependent response function $K_i(T)$ with $\delta g_i$ being the error. The response functions for AIA are shown in Figure 2.3.

Thus determining the DEM from inversion of observational data is difficult due to the uncertainties associated.

Hannah et al. [32] developed an inversion code, which is fast, robust, with error estimations. Taking advantage of the observed data from AIA 6 band EUV filters (94 Å, 131 Å, 171 Å, 193 Å, 211 Å, 335 Å), the regularized inversion approach can robustly recover a variety of DEMs.

Examples are shown in Figure 2.3. Using synthesis of DEMs, the correspondent data of AIA 6 EUV channels are used as input for the code. Then the output are calculated and plotted in the figure as red error bars in Figure 2.4. From the figure,
both single component DEMs and multi-component DEMS are successfully recovered. In this dissertation, this code provides reliable inversed DEMs for characterising the temperature and plasma distribution of the corona.
Figure 2.4 The computed DEM compared with synthesis. Black dashed lines are simulated DEMs of Gaussian models, from which the synthetic SDO/AIA data are produced to recover DEMs using regularized inversion (red error bars). Blue histograms are recovered using \textit{xrt\_dem\_iterative2.pro} (a former developed program). The top and middle rows differ standard deviation $\sigma$ (increasing left to right) and normalisation magnitude ($10^{23}$ top row, $10^{22}$ middle row). The DEMs in bottom row have different number of Gaussian components (left to right). Courtesy of Hannah (2012).
CHAPTER 3

SURGE TRIGGERED BY ADECTIVE OF A LARGE GRANULE

The solar activity are believed to be triggered from the photosphere. The property that the observation in 10830 Å is optically thin provides irreplaceable aids for investigating the relation between the photospheric motions and the above small-scale activity. In this chapter¹, the first evidence of magnetic reconnection driven by advection in a rapidly developing large granule is reported, using high spatial resolution observations of a small surge event (base size \(~4'' \times 4''\)) with the 1.6 m aperture NST at BBSO. The observations were carried out in narrow-band (0.5 Å) Helium I 10830 Å and broad-band (10 Å) TiO 7057 Å. Since He I 10830 Å triplet has very high excitation level and is optically thin, its filtergrams enable us to investigate the surge from the photosphere through the chromosphere into the lower corona. Simultaneous space data from AIA and HMI on board the SDO were used in the analysis. It is shown that the surge is spatio-temporally associated with magnetic flux emergence in the rapidly developing large granule. During the development of the granule, its transverse flow \((\sim 2 \text{ km s}^{-1})\) squeezed the magnetic flux into an intergranular lane area, where a magnetic flux concentration was formed and the neighbouring flux with opposite magnetic polarity was cancelled. During the cancellation, the surge was produced as absorption in He I 10830 Å filtergrams while simultaneous EUV brightening occurred at its base. The observations clearly indicate evidence of finest-scale reconnection process driven by the granule’s motion, thanks to the unique property of 10830 Å.

3.1 Introduction

The solar chromosphere has been known to be very dynamic and is a sea of small-scale activity like microflares, Ellerman bombs and surges [18]. Recent observations made by Hinode and large ground-based solar telescopes have discovered that the chromosphere is even more dynamic than previously thought [82, 67, 28]. It is believed that such activity is actually activated and driven from the photosphere which exhibits a constantly evolving, multipolar magnetic flux distribution. However, how convective motion and flows in the photosphere activate and drive solar activity is still an open question. Using observations to answer this kind of question has proven to be challenging. With the advent of large ground-based solar telescopes with AO and state-of-the-art instruments, observing and studying small-scale activity will provide us less ambiguous information about the physical mechanism, since major events contain many couplings of smaller spatial scale energy release processes.

Surges, which can be precisely pinned down to the photosphere with their small spatial scales, are the most suitable observational targets to reveal the physical links between activities in the photosphere and upper atmosphere. A surge is the phenomenon of straight or slightly curved mass ejections shooting out from a brightened chromosphere patch up to coronal heights with speeds of 20-200 km $s^{-1}$ [75] and lifetime of 10-20 minutes [88]. H$_\alpha$ surges can be visible in EUV/UV and even soft X-ray, i.e., cool and hot ejected components co-exist in the same ejection event [76, 79]. Historically, the term “surge” and “jet” refer to the cool and hot ejected plasma, respectively. Surges show a strong trend for recurrence, being associated with magnetic flux emergence and cancellation around their bases in the photosphere [48, 62]. Previous observations support the idea that magnetic reconnection between emerging flux and overlying magnetic field plays a key role in powering a surge model [81, 8, 86, 15].
H$_\alpha$ and Ca II 8542 Å spectral lines are mostly used to probe the chromospheric activity. However, due to their opaque nature, it is not easy to obtain exactly co-spatial photospheric information simultaneously. He I 10830 Å imaging has a predominant advantage in this aspect and has proven a unique choice for high resolution observations [95, 38]. The line has a high excitation level reflecting the solar upper chromosphere, and the most important feature is that the line is optically thin, thus allowing the photosphere to be shining through. The granulation in the background of 10830 Å filtergrams give us irreplaceable aid for pinning exactly down the small-scale activity in the photosphere.

Observing small-scale activity with 10830 Å triplet is a timely topic with the advent of the 1.6 m aperture NST/BBSO [27, 10]. Its off-axis design can vastly reduce stray light since there is no central obscuration. The site’s good seeing conditions combined with the high order AO system enable observations with a spatial resolution close to the diffraction limit.

### 3.2 Observation and Data Reduction

The observations were carried out on July 22 2011, targeting coronal loops in solar active region NOAA 11259, with narrow band (bandpass: 0.5 Å) in He I 10830 Å, narrow band (bandpass: 0.25 Å) in H$_\alpha$ 6563 Å in the blue wing (-0.65 Å), and broad band (bandpass: 10 Å) of TiO 7057 Å lines. The 10830 Å narrow band filter was tuned to -0.25 Å, making the filtergram more sensitive to upward moving features. With the aid of high order AO [10] and KISIP speckle reconstruction code [101], diffraction limited resolution images at the three bands were achieved. The cadences at TiO, H$_\alpha$ and He I were all 15 seconds. A high sensitivity HgCdTe CMOS infrared focal plane array camera [9] was employed to acquire the 10830 Å data. TiO molecular bands are sensitive to temperature, thus enhancing contrast of intensity in the photosphere, due to the stronger absorption of these bands in dark cool intergranular lanes.
For investigating the million degree coronal plasma and the evolution of magnetic field, simultaneous data from SDO [53] were downloaded. In this chapter the SDO data include EUV data from AIA, full disk continuum images and line-of-sight magnetogram from the HMI [80]. Spatial co-alignment among these data were done by co-aligning the HMI continuum images with the NST TiO data, and then co-aligning the TiO data with the 10830 Å filtergrams. Sunspots and especially groups of bright granules are used for co-alignment. Owing to a multiplicity of common features (bright granulation), it was straightforward to precisely align the HMI/SDO continuum images with the NST He I and TiO images. The accuracy of the co-alignment is better than 0\".5. Since SDO images are already co-aligned before being available for downloading, HMI continuum images can serve as the intermediary for co-alignment between the AIA images and the NST images.

3.3 Results
An overview of the surge event is shown in Figure 3.1. The surge spurted out in the vicinity of the leading sunspot in the active region NOAA 11259, lasting from 17:33 to 17:55 UT. A full disk AIA 171 Å image (Figure 3.1a) shows the location and corona loop system of the targeted active region, which is encompassed by a white box. Each box in the panels depicts the FOV of subsequent frame(s) indicated by white arrow(s). Figure 3.1b is a subregion of a full-disk H\textsubscript{\alpha} filtergram observed with the BBSO 10 cm aperture telescope. Two ribbon-like plage regions are the footpoint regions of the EUV loop system. In low resolution H\textsubscript{\alpha} images, the surge is faint and ephemeral. It only appears at 17:48:03 UT as faint dark feature indicated by a blue arrow in panel b. A snapshot of the NST He I 10830 Å filtergram with FOV of 52 × 52 Mm is given in Figure 3.1c, which clearly shows the ultrafine loop structure. The loops connect two heavily absorbed regions, which correspond to H\textsubscript{\alpha} plages. A striking feature is that the cross section of the loops remains almost constant (\sim100
km) over long distances [38]. Also, photospheric background is shining through in the 10830 Å filtergrams and the granules and intergranular lanes could be observed roughly.

The surge appeared as a darkened area erupting along the direction denoted by the white arrow. The surge is of small-scale, with base size $\sim 4'' \times 4''$. The spine of the surge looks threaded, with thickness of each thread about 0.1''. The apparent width and maximum length of the threaded spine are 1-2 Mm and 18-20 Mm, respectively. The ejecta travel along surges threaded spine with maximum apparent velocity about 42 km s$^{-1}$ and finally fade away. The boxed area in panel c is enlarged, shown in the left three panels (x-z). Panel x shows simultaneous EUV 171 Å brightening. The brightening’s contours are overlaid on the enlarged 10830 Å filtergram (panel y) and a corresponding TiO image (panel z). An apparent corona loop, which is running across the surge, was seen to slightly light up during the surge. Strong EUV emission and 10830 Å absorption are co-spatial at base of the surge as shown in Figure 3.1y. Taking advantage of six filter wavelengths EUV data from AIA/SDO, a method developed by Aschwanden et al. [6] is used to calculate the emission measure at the footpoint of the surge during the second peak of the surge eruption. Then, according to the relation: $E_{th} = 3kT\sqrt{EM\cdot V}$, the estimated thermal energy is about $4.3 \times 10^{26}$ erg. A large developing granule (indicated by a blue arrow in panel y and z) expands and squeezes the material toward the intergranular lane area where the surge spurted out. A series of bright points were formed during the squeezing.

As reported by Shimojo et al., 1999 [85], most of the jets are produced in the satellite polarity (polarity opposite to nearby sunspot) type region. The surge in this chapter also was associated with the emergence of satellite polarity magnetic flux. The images at TiO and 10830 Å, as well as a simultaneous HMI line-of-sight magnetogram are co-aligned and combined them together to create Figure 3.2. The TiO image is plotted as the gray background while the pink stands for the absorbing features
Figure 3.1  (a) A full disk image of the Sun observed at 171 Å by AIA/SDO. White box depicts the active region NOAA 11259. (b) A subregion of BBSO full-disk Hα filtergram at 17:48:03 UT. The blue arrow points to the surge. (c) A sample of He I 10830 Å filtergram at 17:45:35 UT observed with the NST/BBSO. The surge, appeared as an elongated dark feature along the direction indicated by the white arrow. The boxed area in panel c is enlarged and shown in three different wavelengths on panels (x-z) with contours representing the 171 Å emission. (x) 171 Å emission (17:45:36 UT). (y) He I 10830 Å filtergram. (z) TiO image (17:45:40 UT). Blue arrows in panel x and y point to the large granule associated with the surge. Each box in the panels depicts the FOV of the next frames(s) indicated by corresponding white arrow(s).

extracted from 10830 Å filtergram. These pink features are distributed co-spatially with the intergranular lanes. The red and blue contours represent the positive and
negative magnetic field, respectively. In this figure, the excellent co-alignment of HMI observed magnetograms and NST observed photosphere image can be clearly seen from the nice correspondence between magnetic concentration and bright points. In Figure 3.2, the surge is the pink feature in the dotted box. The root of the surge is just sitting on the intergranular lane area, beside the aforementioned large granule. Positive magnetic flux concentration is formed in the intergranular lane area and pushed into the nearby negative magnetic field area due to the advecting motion of the developing granule. The strongest magnetic field strength is about 300 Gauss. Considering filling factor, the field there may reach or exceed one thousand Gauss.

By further looking into the time sequence images observed at different wavelengths, it is found that there is clearer evidence of the surge’s association with granular motion, magnetic field concentration and cancellation. Figure 3.3(a1) to (c1) are a series of He I 10830 Å images, from which the underlying developing granule can be clearly seen. Also, it can be seen that the surge anchors to the intergranular lane area throughout. Simultaneous TiO images overlaid with the surge (pink) extracted from Figure 3.3(a1) to (c1) are plotted in Figure 3.3(a2) to (c2). The large granule is found to be pushing material toward the intergranular lane area, where the surge footpoint anchors. In Figure 3.3(b2), FLCT [21] is applied to the time sequence to derive horizontal proper motions. The developing granule is squeezing the lane area at the surge footpoint with outstanding advection speed of 2 km s$^{-1}$ at its front, which is higher than the typical speed of granules ($\sim 0.5$ km s$^{-1}$).

From Figure 3.3(1) to (6), a time series of contours of line-of-sight magnetic field are shown. Red and blue contours represent positive and negative magnetic field, respectively. Simultaneous TiO images are presented from Figure 3.3(4) to (6) when they are available. The granular flow advected the magnetic flux and, meanwhile, the positive magnetic concentration seems to suppress the development of the granule. The picture is consistent with the findings using HINODE data [106]. According
Figure 3.2 A composite image overlaid with simultaneous line-of-sight magnetogram obtained by HMI on board SDO. The composite image is made of a TiO image (gray) and absorbing features (pink) extracted from a He I 10830 Å filtergram. Red and blue contours represent positive and negative magnetic field, respectively. The contour levels are ±5, ±10, ±30, ±50 (thick contours), and ±100 (thick contours) Gauss, respectively. White dotted box depicts the area for magnetic flux calculation in Figure 3.4.

to the change of the contours’ morphology, there is an obvious increment in both positive magnetic flux beside the surge base and “U” shaped negative magnetic flux below (blue contours), indicating emergence of a bipole. The positive magnetic flux emerged before the surge. The large granule pushed the emerged positive flux towards
the intergranular lane area, turning the contours of maximum magnetic concentration into lane. From Figure 3.3(4) to 3.3(6), the blue contour for negative magnetic field near the surge footpoint decays obviously, as shown by the upward shifting of the red contours on the granule. The phenomenon suggests that the pre-existing field is cancelled by the newly emerging positive flux of opposite polarity during the surge.

Figure 3.3 A series of He I 10830 Å filtergrams showing the evolution of the surge and underlying granules. (a2-c2): Simultaneous TiO images (gray) overlaid with the surge (pink) extracted from (a1-c1). Black circles encompass the surge’s roots, which anchor in the intergranular area. In panel b2, the transverse proper motion obtained through FLCT method on the large granule beside the surge is plotted, with maximum speed about 2 km s\(^{-1}\). (1)-(6): Time series of contours of line-of-sight magnetic field. The contours are overlaid on simultaneous TiO images when they are available. Red and blue contour represent positive and negative magnetic field, respectively, with contour levels at ±10, ±30, ±50 (thick contours), and ±100 Gauss (thick contours).
Figure 3.4 shows the time profiles of the surge. Panel a is the light curve of the surge footpoint in 10830 Å, while panels b and c represent positive and negative magnetic flux, respectively. These magnetic flux are calculated within the boxed area in Figure 3.2. Bottom panel d gives two samples of EUV emission time profile at 171 Å (dotted line) and 94 Å (solid line) as observed by AIA/SDO. The curves in panel a and d are both normalized with respect to their own maximum values. There are three depressions in the 10830 Å time profile (separated by vertical dashed lines), representing three main stages in the surge process. Before the surge, there is a steep increment of the positive flux starting at 17:31 UT. Then 3 minutes later, the surge spurts out immediately after the obvious cancellation of the negative flux. The negative flux varies significantly, although the signal is much weaker than the positive flux. After the positive magnetic flux stops increasing around 17:40 UT, it decreases slightly during the violent second stage of the surge. Several sizes of area are selected for calculating the magnetic flux at the base of the surge and the results are more or less the same. Basically, all three stages in the 10830 Å time profile have corresponding bumps in each of the EUV curves. However, there are some differences for the EUV response. During the first stage, the EUV 171 Å signal can hardly be seen and the emission of 94 Å is barely above noise level compared with the subsequent obvious emission enhancement in the second stage. The 171 Å spectrum line has a characteristic temperature of about 0.7 MK (log T ~ 5.85), while 94 Å has a higher characteristic temperature of about 7 MK (log T ~ 6.8), which implies the corresponding temperature of the surge is much higher in the beginning even though EUV emissions are weaker.

3.4 Discussion and Conclusions

With the NST’s high spatial resolution imaging observations as well as simultaneous space data from AIA and HMI on board SDO, a detailed analysis of a small surge
event is presented and the first evidence of magnetic reconnection driven by advection is observed in a rapidly developing large granule. Such a small event would have been neglected in low resolution observations, however, it proves to be valuable for exploring physical mechanism of small-scale activity. Furthermore, granulation in the background of He I 10830 Å filtergrams offer great help in precisely pinning the
granular scale surge down to the photosphere. High resolution H$_\alpha$ data are not shown in this Chapter since they give no new results.

A very clear picture is presented that there is an emergence of a magnetic bipole associated with the surge, while the positive emerging flux is accompanied by the development of a large granule. The granule’s advection pushed the positive magnetic flux into an intergranular lane area, causing magnetic concentration there and cancelling of nearby negative flux. The negative magnetic flux cancelled during the surge is about $6.2 \times 10^{17}$ Mx. Assuming the reconnection happens in a cubic box $\sim 2.1 \text{ Mm}^3$, within which the magnetic field is uniformly distributed, the released magnetic energy could be estimated to be $1.2 \times 10^{26}$ erg, which is comparable to the thermal energy estimated in previous section. These facts support the picture that the surge is a result of the magnetic reconnection directly driven by the granule’s advection.

These observations are consistent with the observations made by Shimojo et al. [86]. The surge resulted from the emergence of satellite polarity. As a matter of fact, the total positive magnetic flux was increasing because the positive magnetic field was dramatically emerging. When the emergence reached its peak, the positive magnetic flux decrement became visible, which was caused by cancellation with the opposite negative magnetic flux. And this corresponds to the second eruption of the surge.

Chae et al. [15] proposed a two-step reconnection model based on the fact that they found magnetic cancellation before the EUV brightening. For the surge event in this chapter, this two-step assumption could be supported if there were no 10830 Å and 94 Å observations. However, both excitation of Helium and brightening of 94 Å could be seen as soon as the negative magnetic was cancelled, which means the magnetic cancellation and reconnection occurred simultaneously.
In order to have 10830 Å absorption, electrons must be excited to the lowest triplet state of Helium atoms. Three distinct mechanisms have been proposed, namely PRM, CM and CRM [17]. For the surge analyzed here, the formation of 10830 Å absorption is complicated. As shown in Figure 3.4, during the second depression, where variations of 10830 Å absorption and EUV emissions are co-temporal, the PRM is favored as the primary mechanism of the 10830 Å absorption. But for the first depression, there are no apparent EUV signals in most AIA channels except weak emissions from 94 Å and 131 Å. Comparing to the third stage, which has stronger EUV emission but weaker 10830 Å absorption, there are not enough EUV photons to raise the strong He I 10830 Å absorption in the first stage. Thus, CM and CRM should be taken into account. Furthermore, considering AIA’s EUV response functions, the temperature during the first depression can be deduced as high as ~7 MK. These super hot electrons may play an important role in producing the stronger He I absorption during the first stage.

This granule advection triggering surge implies that magnetic reconnection is occurring on quite small spatial scales throughout the solar atmosphere and these ubiquitous small-scale reconnections may play an important role in heating the upper atmosphere. Nonetheless, it is not clear whether granular advection are indispensable in all small-scale activity in the upper atmosphere. A more detailed statistics is needed and it will be presented in a subsequent paper. With the high-resolution observations, the examination of interrelation between photospheric motions and overlying small-scale activity no doubt will shed new light on uncovering the nature of small-scale activity in the dynamic chromosphere.
CHAPTER 4

RESOLVING THE FAN-SPINE RECONNECTION GEOMETRY OF A SMALL-SCALE CHROMOSPHERIC JET EVENT WITH THE NEW SOLAR TELESCOPE

A fan-spine structure has been frequently reported in some coronal jets and flares, and has been regarded as a signature of ongoing magnetic reconnection in a topology consisting of a magnetic null connected by a fan-like separatrix surface and a spine. However, for small-scale chromospheric jets, clear evidence of such a structure is rather rare, although they are implied in earlier works that show an inverted-Y-shaped feature. In previous chapter, the event studied could not provide a clear picture of morphology of the jet since it is almost along the line of sight. Thus the magnetic reconnection site could not be distinguished. In this chapter\(^1\), high-resolution (0\(^{\prime\prime}\).16) observations of a small-scale chromospheric jet event is presented, which is obtained by the NST using 10830 Å filtergrams. The jet event is observed close to the limb of the Sun. Taking advantage of the special formation mechanism of He I 10830 Å, as well as the high resolution observation with NST, structures of intermediate temperature could be revealed, providing more clear physical picture of the jet from its to its spine. Bi-directional flows were observed across the separatrix regions in the 10830 Å images, suggesting that the jet event was produced due to magnetic reconnection. The origin of the bi-directional flows is inferred as the site of magnetic reconnection. At the base of the jet, a fan-spine structure was clearly resolved by the NST, including the spine and the fan-like surface, as well as the loops before and after the reconnection. A major part of this fan-spine structure, with the exception of its bright footpoints and part of the base arc, was invisible in the extreme ultraviolet and soft X-ray images.

\(^{1}\)This chapter is based on the following paper: Z. Zeng, B. Chen, H. Ji, P. R. Goode, and W. Cao 2016, ApJ, 819, L3 [104].
(observed by the AIA and the X-Ray Telescope, respectively), indicating that the reconnection occurred in the upper chromosphere. Our observations suggest that the evolution of this chromospheric jet is consistent with a two-step reconnection scenario proposed by Török et al. (2009) [92].

4.1 Introduction

Jets are a phenomenon of collimated plasma ejecta shooting out from a localized region in the low solar atmosphere. They have been observed in optical, (extreme) ultraviolet (UV/EUV), and X-ray with various sizes, speeds, and durations [77, 66, 91]. Jets usually show a strong tendency to recur, suggesting their association with a prolonged process of magnetic flux emergence and cancellation at their bases [48, 62]. Observations [81, 8, 58] and MHD simulations [4, 67, 68] support a scenario in which a jet is driven by magnetic reconnection between newly emerging magnetic fluxes and overlying ambient magnetic fields of opposite polarity. This process could result in a configuration for reconnection at a three-dimensional (3D) magnetic null point, connected by a fan-like separatrix surface and a spine along which the reconnected field lines approach or recede from the null [52, 3, ] (see, e.g., Figure 1 of Liu et al. 2011 [59] and Figure 4.5d of this paper). Signatures of such a “fan-spine” topology have been reported in various contexts that involve magnetic reconnection, including X-ray jets [83, 84], anemone-like active regions [5], and “circular-ribbon” flares [64, 97, 57].

For small-scale chromospheric jets, however, direct observations of fan-spine structures are rather rare, although the existence of a fan-spine structure is strongly implied by the frequently observed inverted-Y-shaped feature of the jet’s base [82, 67] and in one case, a dome-shaped jet’s base outlined by coronal-rain-like flows [59].

He I imaging at 10830 Å has proven to be an excellent method for observing plasma with temperatures characteristic of the upper chromosphere and transition region (>20,000 K), since the formation of 10830 Å requires the intermediary of
collisional excitation to a high energy level and/or a sufficiently high EUV radiation field serving the same purpose. One mechanism is photo-ionization followed by recombination (the “PR” mechanism) [107], in which neutral helium can be ionized by high-energy photons (shortward of 504 Å) and then recombine to the excited \( n = 2, 3 \) levels of orthohelium. Another mechanism appeals to the rapid collisional mechanism (CM) in which atoms are excited, before having a chance to be ionized, by electrons with temperatures higher than those expected in ionization equilibrium [39, 1, 71].

Here, high-resolution (0′′.16) 10830 Å imaging is exploited utilizing the New Solar Telescope (NST) to resolve the fan-spine structure in a small-scale chromospheric jet event. The instruments and data reduction are discussed in Section 2. Section 3 presents observational results using the NST and other instruments in EUV and X-rays. In Section 4, implications and interpretation of these data is considered.

4.2 Observation and data reduction

On 2012 July 8, the 1.6 meter aperture NST at the Big Bear Solar Observatory (NST/BBSO) [26, 10] was used to observe NOAA active region (AR) 11515, which was located close to the west solar limb. NST’s off-axis design eliminates any central obscuration, vastly reducing stray light. High spatial resolution images were obtained by using a broad band filter (bandpass: 10 Å) containing the well-known TiO lines, as well as a narrow band filter (bandpass: 0.5 Å) placed in the blue wing of the He I 10830 Å multiplet. Images in Hα line center and blue wing (−0.8 Å) were also acquired for comparison.

The 10830 Å Lyot filter was made by the Nanjing Institute for Astronomical and Optical Technology. This narrow-band filter was tuned to −0.25 Å relative to the two blended, strongest components of the multiplet (at 10830.3 Å), making the filtergram capable of imaging fine details of the chromospheric material and meanwhile, capturing the underlying photospheric features. This is also very helpful
for co-aligning with other instruments. A high sensitivity HgCdTe CMOS IR focal plane array camera [9] was employed to acquire the 10830 Å data at a cadence of 10 s. With the aid of high order AO and KISIP [101, 11], images with diffraction limited angular resolution ($\frac{\lambda}{D}$) in the three bands were achieved (~0.16" for 10830 Å).

This event was observed by the Atmosphere Imaging Assembly (AIA) [53] on board the Solar Dynamic Observatory (SDO) [70] and the X-Ray Telescope (XRT) [25] on board Hinode [47], which covered a broad temperature range of the jet material (~1 MK to > 10 MK). The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [56] and the Gamma-ray Burst Monitor (GBM) [65] aboard the Fermi Gamma-ray Space Telescope also observed this event in hard X-rays (HXRs). RHESSI images are reconstructed using the PIXON algorithm [37] based measurements from detectors 3, 5, 6, 7, and 8 with 40-s integration. White-light continuum images from the Helioseismic and Magnetic Imager (HMI) [78] on board SDO were used as the intermediary for co-aligning the AIA and NST images. The accuracy of the co-alignment is expected to be better than 0.6".

4.3 Results

The repetitive jet event under study occurred around the east edge of the leading sunspot in AR 11515 between 18:19-18:50 UT. Figure 4.1 shows images of the jet in 10830 Å (panels a and x), TiO (panel y), Hα (panel z), EUV (panel b), and soft X-ray (SXR; panel c). The jet was located near the footpoint of a closed coronal loop system as shown in the XRT Al-thick image (Figure 4.1c). The second row of Figure 4.1 shows a closer view of the jet’s base (green box in Figure 4.1a), rotated by 110° counterclockwise to an upright orientation. The jet’s base (~10" wide) appears as a fan-like structure in the 10830 Å filtergram (Figure 4.1x), spanning over the penumbral regions of a spot with positive magnetic polarity (Figure 4.1y). This structure can also be distinguished in the Hα blue wing images, which are, however,
badly saturated thus not shown here. Significantly, this structure is totally absent from all AIA EUV images, indicating that its temperature is well below coronal values. The footpoints of the fan-like loops in 10830 Å coincides very well with footpoint brightenings in AIA 171 Å images (yellow contours in Figure 4.1x), suggesting strong heating in the footpoint area.

The evolution of the jet event can be generally divided into two major steps separated by ∼20 minutes as delineated in the space-time plot of the AIA 304 Å intensity (Figure 4.1d; obtained at a slice shown as the dashed line in Figure 4.1a). The onset of each step was characterized by a strong footpoint emission in 304 Å, which correlated well with impulsive peaks in the 1–8 Å soft X-ray (SXR) derivative (from GOES, the Geostationary Operational Environmental Satellite) and the 12–25 keV HXR count rate from Fermi/GBM. This correlation suggests that the jet’s evolution was closely associated with electron acceleration and/or strong plasma heating processes [44, 23].

Figure 4.2 shows the evolution of the jet in the first step observed in 10830 Å, AIA 304 Å, and Hα line center (an animation is available online: stepI.mpg). The jet is visible in 10830 Å as a dark outgoing ejecta, which appears bright in 304 Å and Hα. With NST’s unprecedentedly high resolution, a fan-like structure is clearly seen at the jet’s base in the 10830 Å images, consisting of multiple individual loops. The loop system on the left side of the jet is brighter than that on the right, appearing as an unresolved brightening in the 304 Å images (blue arrows in Figure 4.2). The evolution of the fan-like loops suggests that magnetic reconnection is likely occurring between the loop systems on the left- and right-side of the jet. To visualize this, a curved slice is selected along the fan structure (dashed line in Figure 4.2b) and obtain a space-time plot of the 10830 Å intensity (Figure 4.4a). At ∼18:21:10 UT, two tracks with opposite slopes (directed by red arrows) appear at the slice location of 8” in the space-time plot (white arrow in Figure 4.4a). These two tracks correspond to bi-directional plasma
Figure 4.1 The jet event on 2012 July 8: (a) Sample of NST 10830 Å image. The blue box encompasses the FOV of the images in Figures 5.2-5.3. (b-c) EUV and X-ray images by AIA/SDO 171 and XRT/Hinode Al-thick, respectively. (a)-(c) have the same FOV of 60”×60”. (x-z) Closer views of the jet in 10830 Å, TiO, and Hα line center, showing the region enclosed in the green box in (a) (rotated counterclockwise by 110°). The contours show the AIA 171 emission (90%, 70%, and 50% of the peak intensity). Red arrows point to the footpoint of a dark strand in 10830 Å (i.e., the inner spine). (d) Space-time plot made from AIA 304 Å time-series images along a slice in (a) (dashed line). (e) Normalized GOES SXR derivative (black) and Fermi HXR count rate (red). Vertical dashed lines in (d) and (e) denote the start time of each step at 18:18:50 and 18:38:40 UT, respectively.

outflows (≈30 km s⁻¹) emanating from a common region. In the 10830 Å image, this region is located near the apex of the fan-like structure between the left and right loop systems (marked by an “x” symbol in Figure 4.2b), presumably the site of magnetic
Figure 4.2  Evolution of the jet event during the first step (an animation (stepI.mpg) is available on-line).  (a-c) 10830 Å filtergrams.  (d-f) AIA 304 Å images.  (g-i) Composite of NST Hα line center (grey) and AIA 304 images (red).  Short blue arrows in the center column depict the “footpoint” brightening in AIA 304 (appearing as small-scale loops in 10830 Å at the jet’s base).  Long white arrows indicate material flowing along the outer spine of the jet.  Red arrow in (i) indicates the transverse motion of the Hα surge.  Slice 1 (dotted line in (b)) is used to obtain the space-time plot in Figure 4.4a, with an “x” symbol denoting the inferred reconnection site.

reconnection. The time when the bi-directional outflows occurred coincides very well with the footpoint brightening seen in AIA 304 Å (c.f., Figure 4.1d).

The second step starts from 18:39 UT, ∼20 minutes after the first step (an animation is available online: stepII.mpg). In contrast to the first step, the 304 Å
Figure 4.3  Evolution of the jet event in its second stage (an animation (stepII.mpg) is available on-line). (a-c) 10830 Å filtergrams. (d-f) AIA 304 Å images. Green contours (85% and 50% of the peak intensity) in (d) and (e) are RHESSI 6–12 keV X-ray images at 18:39:12 and 18:41:48 UT, respectively. (g-i) Composite of Hα line center (gray scale) and AIA 304 images (red). White arrows depict the position of the dark spine while blue arrows point to the footpoint of the inner spine. Slice 2 in (c) is used to obtain space-time plots (Figure 4.4b), with an “x” symbol denoting the inferred reconnection site.

intensity at the jet’s base is dominated by the emission at the right side of the jet (Figure 4.3d-f). In 10830 Å images, again, the AIA brightening near the footpoint is resolved as a bundle of small-scale loops. The fan-like surface is clearly visible at the jet’s base, composed of alternating black and white fibrils with thickness of ∼0.3′′ (Figure 4.3a). A dark spine could be observed near the center of the jet, which
becomes more evident in 10830 Å, Hα, and AIA EUV after 18:41 UT (indicated by white arrows in Figure 4.3). This dark spine extends further downward across the fan structure and rooted at the photosphere, representing as the “inner spine” in the fan-spine reconnection geometry (c.f., Fig 5d). The foot of the inner spine is co-spatial with a Hα brightening (indicated by a blue arrow in Figure 4.3g) and a footpoint X-ray source (observed by RHESSI at 6–12 keV, green contours in Figure 4.3d). During the late phase of step 2, bright loops form at the right side of the jet spine in 10830 Å (Figure 4.3c), whereas a curtain-like surge (5″ across) extends to the left side, which appears dark in 10830 Å and bright in EUV 304 and Hα. Similar to the first step of the jet event, space-time plots obtained across the jet (Figure 4.4b, slice 2 in Figure 4.3c) show bi-directional flows (∼20 km s⁻¹) emanating from a common site near the apex of the fan structure (“x” symbol in Figure 4.3c), which is likely the location of the magnetic null point.

### 4.4 Discussions and conclusions

This chapter presents high-resolution NST observations of a small-scale recurrent jet event using the He I 10830 Å filter, which is sensitive to upper chromospheric temperatures. The NST observations were complemented by EUV and X-ray data from SDO/AIA, Hinode/XRT, and RHESSI, covering a broad temperature range from ∼1 MK to >10 MK.

The NST He I images reveal detailed structures of the recurrent jet event. In particular, the jet at each step consists of an elongated spine along the direction of ejection and a fan-shaped arc at the base, closely matching the fan-spine reconnection geometry for jet production. The fan-shaped arc at the base is only 10″ wide, spanning over the penumbral region of a spot of dominating positive magnetic polarity. According to the reconnection picture, the inner spine of the jet (seen in He I in absorption) that connects to the magnetic null point should be rooted in a
Figure 4.4  Space-time plots showing bi-directional outflows from a common region near the apex of the fan-like structure at the jet’s base. (a) and (b) are space-time plots of the 10830 Å intensity obtained along Slice 1 (dashed curve in Figure 4.2b) and Slice 2 (dashed line in Figure 4.3c) during the first and second step, respectively. Red arrows indicate the bi-directional outflows emerging from a common region (white arrow), which is located near the apex of the fan-like structure (denoted by the “x” symbols in Figures 5.2b and 5.3c).

newly emerged magnetic flux with negative polarity. It is difficult, though, to confirm this using HMI line-of-sight magnetogram directly, because the negative polarity region was presumably very small and the event occurred near the limb. However, there is multiple evidence supporting the fan-spine reconnection scenario: First, the root of the inner spine coincides with localized Hα, EUV, and X-ray emissions at the same location (c.f., Figure 4.3, indicated by the blue arrow), suggesting intense heating at the root, by either precipitated particles or thermal conduction, which is associated with magnetic reconnection at the null point. Second, bi-directional plasma flows are observed at the onset of each step. They originate from a common
region located near the apex of the fan structure, which is probably the site of the magnetic null point where reconnection occurs. This region is located at \( \sim 1800 \) km above the jet footpoints (the projection effect is minimal as the jet event occurred near the limb), probably embedded in the upper chromosphere. Depending on the local Alfvén speed, these bi-directional plasma flows, with an observed speed of \( \sim 20-30 \) km \( s^{-1} \), could be either direct reconnection outflows or secondary pressure-driven flows expelled from the reconnection site.

It is concluded that the observed features in the two major steps of the jet evolution are consistent with the two-step magnetic reconnection scenario of jets proposed by Török et al. [92], as depicted in the two schematic cartoons in Figure 4.5: The first step starts when reconnection occurs between the emerged negative magnetic flux and the ambient, unipolar field (Figure 4.5c). Reconnected loops shrink downward to the left side of the null point and are heated by the released energy (pink patch). The energy released from reconnection also drives heated plasma from the null point upward along the spine field lines, seen as the jet material in EUV, \( 10830 \) Å, and H\( \alpha \) (Figure 4.2 left column; shaded pink in Figure 4.5c). Simultaneously, cool plasma is also ejected from the right side of the jet spine due to magnetic tension force induced by the newly reconnected field lines, also known as the “slingshot effect” (shaded gray in Figure 4.5c) [83, 8, 89].

The second step corresponds to a fully-developed state of the fan-spine reconnection geometry, when the magnetic loops at the left side of the null point also reconnect with the ambient fields on the right (Figure 4.5d). During this step, the reconnected loops are visible on both sides and form a complete fan-shaped structure, separated by an inner spine near the center (Figure 4.5b). The dark and bright fibril-like loops consisting of the fan structure (in \( 10830 \) Å) represent a mixture of heated and cooled loops formed by the repeated reconnection process at the magnetic null point (Figure 4.5b). The reconnection also produces accelerated particles and/or
Step I  Step II

Figure 4.5  (a-b) Representative still images in the first and second step of the jet event. (c-d) Schematic depictions of the event in the two steps. Here red and green lines represent reconnected field lines in the first and second step, respectively. + and − signs denote the magnetic polarity. The pink area near the footpoint represents the footpoint brightening seen in AIA. The jet (in EUV) and the associated surge (in Hα and He I) are shown as the shaded vertical features in pink and grey colors, respectively. The reconnection site is marked by an “x” symbol, with small arrows illustrating the reconnection inflows (black) and outflows (red). Blue oval in (d) represents the RHESSI X-ray source at the root of the inner spine. Dotted lines outline the magnetic separatrix layer.

thermal conduction fronts, which propagate along the inner spine and result in strong footpoint X-ray emissions (blue patch in Figure 4.5d).

The clear detection of the fan-spine structure is attributed to not only NST’s superb sub-arcsec resolution, but also the special emission conditions for the 10830 Å
The fan is completely absent in all AIA and XRT bands but clearly visible in He I, suggesting that the fan should consist of plasma of upper chromospheric temperatures ($\leq 20000$ K) to which AIA and XRT are not sensitive. The He I emission is interpreted as being from the radiation of helium atoms in a metastable level excited by thermal collisions (i.e., the CM mechanism). The PR mechanism of He I emission is not favored for the case here since there is insufficient EUV emission in the fan.

In both steps, the outer spine is observed as a collimated jet consisting of both hot and cool material. This is likely associated with the magnetic reconnection site being embedded in the cool chromosphere: plasma is heated and propelled by the released magnetic energy and meanwhile, cool chromospheric plasma is ejected due to the sling-shot effect of the reconnected field lines. The inner spine, on the other hand, represents field lines directly connecting the opposite polarity footpoint with the magnetic null point. Its dark appearance in all filters (10830 Å, Hα, and EUV) suggests a density depletion at the locus of the inner spine. This is possibly associated with strong heating at the null point combined with efficient thermal conduction along the inner spine field line. This scenario is supported by the existence of a $>10$ MK X-ray source at the footpoint of the inner spine. However, it could not be completely ruled out the possibility that the dark inner spine is associated with a cool filament-like structure that is fortuitously aligned with the jet direction, causing an absorption feature in all bands.

To summarize, the sub-arcsecond resolution of the NST, combined with the unique sensitivity of the 10830 Å line to upper chromospheric plasma of certain temperatures, provide a clear view of a chromospheric jet event with a fan-spine geometry. Although numerous cases of chromospheric jets have been reported with an anemone or inverted Y-shape, the observations here, for the first time, reveal nearly every element of the fan-spine structure predicted in the theoretical jet model. The evolution of the jet observed in 10830 Å, Hα, EUV, and X-ray wavelengths
is consistent with a two-step reconnection scenario for jet formation. The results here will motivate further studies on chromospheric jets using high-angular-resolution observations, as well as more detailed modelling approaches.
CHAPTER 5

A FLARE OBSERVED IN CORONAL, TRANSITION REGION AND HELIUM I 10830 Å EMISSIONS

As discussed in Chapter 1, the formation mechanism for 10830 Å is complicated. Nonetheless, the strong helium emission during flares has seldom been studied. In the present chapter\(^1\), the mechanisms leading to the strong helium emission at flare footpoint is probed to understand the evolution of the emitting plasmas during flares through analysing the evolution of flare emissions in EUV and UV radiation and emission from neutral and ionized helium. On June 17, 2012, the evolution of a C-class flare is observed associated with the eruption of a filament near a large sunspot in the active region NOAA 11504. High spatial resolution filtergrams are obtained using the 1.6 m NST at the BBSO in broad-band TiO at 7057 Å (bandpass: 10 Å) and He I 10830 Å narrow-band (bandpass: 0.5 Å, centered 0.25 Å to the blue). The spatio-temporal behavior of the He I 10830 Å data is analyzed, which were obtained over a 90" × 90" FOV with a cadence of 10 sec. Simultaneous data from the AIA and EVE instruments on board the SDO spacecraft, and data from RHESSI and GOES spacecraft are analysed, as well. Non-thermal effects are ignored in this analysis. Several quantitative aspects of the data, as well as models derived using the “0D” EBTEL code [46], indicate that the triplet states of the 10830 Å multiplet are populated by photoionization of chromospheric plasma followed by radiative recombination. Surprisingly, the He II 304 Å line is reasonably well matched by standard emission measure calculations, along with the C IV emission which dominates the AIA 1600 Å channel during flares. This work lends support to some

of previous work combining X-ray, EUV and UV data of flares to build models of energy transport from corona to chromosphere.

### 5.1 Introduction

The spectra of helium atoms and ions in the Sun are not yet understood. The EUV resonance lines at He I 584 Å and He II 304 Å respectively are anomalously bright, under quiescent conditions, by factors of several when compared with many other lines [39, 40, 107, 71, 43]. Yet, these lines are some of the strongest EUV features in the solar spectrum, and as such they control to a significant degree the state of the earth’s thermosphere and ionosphere. Until a clear understanding of the formation of these lines is available, attempts to model the EUV irradiance using models based upon the standard assumption of ionization equilibrium are doomed to fail. In the present study, the evolution of flare emissions in EUV and UV radiation and emission from neutral and ionized helium are analyzed to probe the mechanisms leading to the strong helium emission. A broader goal of the present chapter is to understand the evolution of the emitting plasmas during flares. The narrow-band tunable filtergraph for the NST/BBSO [26, 10] is used to capture flare emission in the 10830 Å line. By combining these data with those of the adjacent chromosphere and corona seen at UV and EUV wavelengths with the AIA [53] and EVE [102] instruments on the SDO [70], the observed behavior is used to constrain the mechanisms by which helium emission can occur during flares.

Ground-based observations of helium lines that follow the evolution of flares are not common, the emission being confined to narrow kernels that are ill-suited to observation using slit spectrographs. Some important work [90] found that in the weaker flares He I 10830 Å shows absorption and only class 2B and larger flares show He I 10830 Å emission. Later, He I 10830 Å emissions were observed in a C9.7 flare with spectro-polarimetry [69]. Using an IR spectrograph with a spatial resolution of
1\".34 and a temporal cadence of 2.8 s, it is found that only when the GOES X-ray flux (which is integrated over the solar disk) reaches a threshold (about C6 class in their study) could they detect emission exceeding the continuum, which spatially corresponded to a bright Hα kernel [54].

Kleint [45] analyzed data of photospheric Fe I 6302 Å and chromospheric Ca II 8542 Å lines in a C3 class flare. She found that emission occurs only above the photosphere, within chromospheric plasma. It should be remembered that the chromosphere spans some 9 pressure scale heights between the quiescent (pre-flare) photosphere and overlying corona. These facts are suggestive that the He I 10830 Å emission should also arise from the chromospheric layers inside the flare footpoints.

Any process that can excite helium leading to line radiation requires a change in principle quantum number $n$ from the $n = 1$ ground levels. Thus helium excitation is unusually sensitive to \textit{high energy tails in distribution functions of the radiation field and/or plasma electrons and ions}. For example, the resonance lines ($2s - 2p$) of C IV have a 5x lower threshold than the resonance line of He II ($1s - 2p$) which form at similar temperatures, under ionization equilibrium conditions. One proposal uses “high energy photons” (shortward of 228 and 504 Å) to ionize ionized/neutral helium from which recombination populates the $n = 2, 3$ levels of helium [107]. By solving the standard non-LTE radiation transfer problem in 1D semi-empirical models of the solar atmosphere, it is found that the properties of the He I 10830 Å multiplet depend mainly on the density and the thickness of the chromosphere, as well as on the incoming EUV coronal back-radiation [72, 7, 14].

Another appeals to the diffusion of helium atoms and ions up steep temperature gradients where the locally higher temperature can excite the $n = 2$ levels faster than occurs for transitions such as the C IV resonance lines [39]. Yet another uses unresolved plasma motion to achieve the same result [1]. Flare spectra of EUV helium emission lines, observed with the SO82A (spectroheliograph, or “overlap-ogram”)
instrument, were analyzed in terms of a “burst” model by Laming et al. [49]. They assumed that, during flares, “ionizing plasma” conditions exist in the Sun’s transition region, permitting the excitation of \( n = 2, 3 \) levels before ionization occurs. Pietarila et al. [71] showed that all of these mechanisms can be unified into a common picture of excitation, by considering the conditions experienced by the motions of individual atoms and ions of helium (Lagrangian picture).

No matter the precise mechanism at play, helium may be expected to shed light on processes requiring much higher energies (> 10 eV) than are present throughout the bulk of the chromosphere (\( \sim 0.6 \) eV). Near simultaneous observations of various photospheric and chromospheric lines show that the chromosphere is the location of the footpoint emission from at least moderate (C-class) flares [45].

Furthermore, the importance of He I 10830 Å triplet is being realized from monitoring dynamical activity in the chromosphere and measuring the chromospheric magnetic fields. Trujillo et al. [93] have modelled the scattering polarization by interpreting the observed polarization in terms of the Zeeman and Hanle effects.

It is proceeded by combining high angular resolution observations of the He I 10830 Å multiplet with lower resolution measurements of He II 304 Å obtained with SDO. Other observables from SDO, as well as X-ray emissions from the RHESSI [56] and GOES will be used to understand the changing conditions in the emitting chromospheric and coronal plasma.

### 5.2 Observations

With the advent of the 1.6 meter NST at the BBSO, ground based IR observations with high resolution (\( \frac{D}{F} \sim 0''.14 \) in 10830 Å are now regularly acquired. The off-axis design of NST reduces stray light since there is no central obscuration, and the site’s good seeing conditions combined with the high order AO have enabled us to obtain observations with a spatial resolution close to the diffraction limit of the telescope.
On June 17, 2012, a small filament eruption and the associated flaring activity was observed. One footpoint of the filament was embedded in a small pore near a large sunspot in the active region NOAA 11504. High spatial resolution filtergrams were obtained in a broad band (bandpass: 10 Å) containing well-known TiO lines, and in a narrow band (bandpass: 0.5 Å) in the blue wing of the He I 10830 Å multiplet. The latter images enabled us to establish the photospheric underpinning of the filament in the chromosphere and corona.

5.2.1 Infrared Data

The TiO images have a cadence of 30 seconds, with a FOV of 70″ × 70″. The image scale is 0″.0375/pixel. TiO molecular bands are unusually sensitive to the photospheric temperature, they exhibit enhanced intensity contrast in the photosphere due to the stronger absorption of these bands in cool intergranular lanes. The 10830 Å Lyot filter was made by the Nanjing Institute for Astronomical and Optical Technology. This narrow-band filter was tuned to -0.25 Å relative to the two blended strongest components of the multiplet (at 10830.3 Å), making the filtergram more sensitive to upward moving features. A high sensitivity HgCdTe CMOS IR focal plane array camera [9] was employed to acquire the 10830 Å data with a cadence of 10 seconds. The pixel size of the filtergrams is 0″.0875, and the FOV is 90″ by 90″. With the aid of high order AO [10] and KISIP [101], images with diffraction limited resolution at different bands were achieved. All NST data used in this chapter are speckle reconstructed. More technical detail in data acquisition and reduction can be found in Cao et al. [11].

With the NST, the active region was observed continuously for a few hours in good seeing conditions, providing a unique opportunity to follow the entire evolution of the flare with high spatial and temporal resolutions. Observations started before 17:00 UT, well before the flaring activity. Figure 5.1 is a snapshot of the 10830 Å
filtergram during the maximum of the flare, with the bandpass shown in the lower right panel. Since the bandpass is tuned to the blue wing of 10830 Å, the filtergram captures some underlying continuum radiation, with photospheric features including sunspots, pores, and granules clearly visible in the image. The filament appears as a dark feature lying between two large sunspots. During the flare, impulsive brightenings in this bandpass are observed at a few locations, marked as patches 0 to 8 in the figure; these patches will be described as P0 - P8 in the following analysis.

5.2.2 Supporting Data from SDO and RHESSI

Taking advantage of the SDO’s unique continuous coverage of the Sun, UV and EUV images observed by AIA, and full disk continuum images and line-of-sight (LOS) magnetograms from the HMI [80] are used. AIA takes full-disk images in 7 EUV bands with a cadence of 12 s and spatial scale of 0''.6. These EUV telescopes observe emission from coronal plasmas at temperatures from 1 to 10 MK. Apart from these EUV channels, AIA also takes full-disk images at the UV 1600 Å broadband at 24 s cadence. During flares, the C IV doublet is significantly enhanced to dominate emission in this band [73], also confirmed in the present analysis. The C IV line emission is produced by plasmas near 100,000 K, typical of the mid transition region.

Spatial co-alignment among these data is done by first co-aligning the HMI continuum images with the NST TiO data. Using the granular patterns and sunspots, it is straightforward to precisely align the HMI/SDO continuum images with the NST TiO images. Then the TiO data with the 10830 Å filtergrams are co-aligned using the sunspots and bright granules. AIA and HMI observations are co-aligned with each other using satellite pointing information, and the HMI continuum images serve as the intermediary for co-alignment between the AIA images and the NST images. The accuracy of the co-alignment is better than 0''.5.
Figure 5.1 Snapshot of the He I 10830 Å observation. The bandpass of the narrow-band filter is illustrated by a vertical strip in the solar spectrum on the lower right corner, and three vertical dashed lines depict the line centers of the He I 10830 Å triplets. The FOV is 64 Mm × 64 Mm. The 9 small boxes with digits encompass the footpoints of the flare during its second peak.

Finally, X-ray emission of the flare are also observed by GOES and RHESSI. Using the standard RHESSI software package, RHESSI X-ray light curves and images were obtained with pixel size of 2″.26 by 2″.26 (subcollimators 1, 3, 4, 5, 6, 8 are used). The RHESSI data are co-aligned with the SDO data according to the coordinates provided in the FITS header. Light curves and images of the flare in the X-ray, EUV,
UV, and IR wavelengths are illustrated in Figures 4.2 and 4.3 respectively, derived as discussed below.

![Diagram of radiation fluxes](image)

**Figure 5.2** Light curves of the 2012 June 17 C3.9 flare. Both soft X-ray 1-8 Å from GOES and some X-ray flux from RHESSI are shown in panel a. Time profiles in UV 1600 Å and EUV 171 Å and 94 Å by AIA/SDO are plotted in panel b. Also plotted is the light curve of 10830 Å.

5.2.3 **Overview of the Flare**

In the top panel of Figure 5.2, X-ray light curves in several RHESSI channels and in GOES 1-8 Å channel are plotted\(^2\). Colored curves in panel (b) of Figure 5.2 show normalized light curves in several wavelengths: the IR 10830 Å from NST, EUV bands at 94 Å and 171 Å from AIA/SDO, and UV band at 1600 Å also from AIA/SDO. In panel (b), the 1600 Å light curve (green) is created from total counts of selected footpoint pixels that exhibit strong emission, or more specifically those pixels with

\(^2\)Note that 10 keV corresponds to a photon wavelength of 1.23 Å.
a count rate greater than five times the median count rate \( I_q = 71 \, DN s^{-1} \) of the quiescent region. Since the AIA data and NST data have been well co-aligned, the light curve of He I 10830 Å (black) is made from the counterpart of the footpoint pixels in 1600 Å. The light curves in EUV 94 Å (blue) and 171 Å (red) are made from pixels of the entire FOV shown in Figure 5.3. Each curve is subtracted by its minimum values and then divided by the residual maximum. As seen in Figure 5.2, flaring occurs in two phases, with the SXR emission in GOES 1-8 Å peaking at 17:28 UT and 17:39 UT, respectively. Each phase is usually characterized by a rapid rise of the emission, followed by a more gradual decay. Remarkably, it is found that emission in the IR and UV bands peaks first, along with a peak in the 171 Å channel, immediately followed by SXR emissions by relatively high temperature plasmas, and then by lower temperature EUV emissions in 94 Å (6 MK) and 171 Å (1 MK). For the EUV 171 Å light curve, the first two peaks coincide with the UV and IR peaks while the following ones correspond to the cooling of the post-flare coronal loops.

Figure 5.3 shows the evolving morphology of flaring plasma observed in several wavelengths. Before the flare onset, twisting of the dark filament can be seen in the 10830 Å filtergrams (see panel a1 of Figure 5.3). Before the flare is seen in X-ray, the filament is dark in 10830 Å filtergram as shown in panel a1 and there are no obvious signals in EUV images. However, in UV 1600 Å images (b1), there are brightenings right in the middle of the filament, indicating the ongoing activity at upper chromosphere prior to the filament eruption and flare. These small events account for a minor emission peak at 17:22 UT before the flare as shown in Figure 5.2. Next, the filament brightening and eruption (second column in Figure 5.3) are coincident in time with the first major abrupt rise in the light curves. Ten minutes later, a second abrupt brightening phase (third column in Figure 5.3) was observed as the emission of the footpoint dramatically increases. The intensity of 10830 Å is significantly enhanced by more than 50% of pre-flare state.
Figure 5.3 Snapshots of the flare in a few bands at a few moments with the same FOV. Rows from top to bottom: He I 10830 Å, UV 1600 Å, EUV 304 Å, 171 Å and 131 Å. Left panels (a1-e1): snapshots before the filament eruption. Middle panels (a2-e2): snapshots during the first peak of the flare. Panels (a3-e3): snapshots during the second peak of the flare. Right panels (a4-e4): snapshots after the flare. The contours on the 10830 Å filtergrams are from RHESSI images with channels of: 6-15 keV (green) and 25-50 keV (red). The RHESSI images are made from 17:28:10 UT with 10 seconds integration and from 17:38:30 UT with 1 minute integration, respectively. The contour levels are 90%, 75% and 60% of the peak intensity of each image.
In the top panels of Figure 5.3, contours of the X-ray images by RHESSI are overlaid on the 10830 Å images. Strong soft X-ray (SXR) emission at photon energies from 6-15 keV (green contours) is observed during both phases of the flare, from an extended coronal emission source lying above the foot-point patches significantly larger than the SXR RHESSI angular resolution (∼2 – 3″), also shown in Figure 5.3(a2-a3). There is also a small amount of X-ray emission above 25 keV, most likely the hard X-ray (HXR) emission (red contours), which is present for only a short time. So these weak signals above 25 keV suggest that the non-thermal effects are not significant in this event [22, Section 2.4]. The SXR emissions below 25 keV and in GOES 1-8 Å channel are usually produced by flare plasmas heated to over 10 MK [31].

During these two major phases of the flare, emissions in IR, UV, and EUV bands occur in the localized patches, P0-P8, which are connected by coronal loops brightened later on in 131 Å (e4) and 171 Å (d4). Therefore, these IR and UV bright kernels most likely correspond to footpoints of flare loops. The counterpart in the corona is shown in both 171 Å and 131 Å images (d1-e4), reflecting the loop structures with million degree plasma. EUV flux observed by AIA are saturated in 171 Å and 131 Å, especially during the first impulsive phase. In the first impulsive phase, the saturations are in the middle of the filament which is shown in the column a2-e2 of Figure 5.3, and they coincide with both the RHESSI SXR contour and chromospheric brightenings in 1600 Å and 10830 Å. Then during the second peak, the footpoints become bright. These observations strongly suggest that the filament eruption starts from chromosphere (early activity in AIA 1600 Å inside filament) and when magnetic reconnection happens, the released energy heats the plasma to the coronal temperature (SXR and EUV brightening in the first impulsive phase). Later, magnetic reconnection takes place in the disturbed corona, giving rise to more energy.
release and formation of new coronal loops as well as brightened foot-points; this generates the second phase of the flare.

Figure 5.4 shows the TiO images during the flare as well as one HMI photospheric magnetogram, showing only LOS components of the magnetic field. Blue contours superimposed in these images are IR foot-point patches brightened during the flare. The TiO images exhibit lots of small-scale bright points, but barely any enhanced flare emission at the locations of the bright IR patches. Therefore, it could be asserted that the foot-point brightening observed in the He 10830 Å band is not produced in the photosphere. The panel (c) in Figure 5.4 shows one (typical) HMI LOS magnetogram. The blue and red contours are footpoint patches of the 10830 Å filtergram and coronal loop of the AIA 131 Å image, respectively. Further, the IR footpoint patches are located in penumbral magnetic fields with different polarity and most of them are seen to be connected by coronal loops. Patches P0, P1, P2, and P5 are located in magnetic fields of negative polarity, while P3, P4, P6, P7, and P8 are located in positive polarities. The loops in the AIA 131 Å seem to connect P0-P2 to P3-P4, and P5 appears to be connected with P6. These loops are significantly inclined relative to the magnetic polarity inversion line.

5.2.4 Light Curves of Flare Foot-point Emission

In Figure 5.5, light curves of P0, P4, and P6 in 10830 Å, AIA 1600 Å and 304 Å are plotted as typical examples. The GOES 1-8 Å light curve is not plotted since it is not spatially resolved. The patches are rectangular areas containing a combined 906 AIA pixels (each with scale of 0″.6) that are centered over the enhanced 10830 Å regions brightened during the flare (see Figure 5.1). In Figure 5.5, the minimum values for each curve are subtracted and then the curves are divided by their residual maximum.
Figure 5.4  Panel (a) and (b): TiO images from NST/BBSO during the two impulsive phase. Blue contours on panel (b) are regions of emission measured in He I 10830 Å. Panel (c): HMI LOS magnetogram overlaid with foot-point contour in 10830 Å (Blue) and loop contour in 131 Å (Red). The boxes encompass the patches indicated in Figure 5.1. Three panels have the same FOV of 76″ × 76″.

In this chapter, the IR filtergram contains both line wing and part of the line center of the He I 10830 Å and the line profile before the flare is in absorption. Approximations at the footpoint are made as follows:

1. Before the flare, the clear view of the penumbra indicates the absorption is optically thin and only a small fraction of continuum flux is absorbed. Hence the observed flux before flare may be approximated as continuum.

2. The flare in this chapter is not a white-light flare so the quiescent (pre-flare) continuum is the same as continuum during flare, which means that the emission enhancement is due to He I 10830 Å;

3. Therefore, it is assumed that the flare enhancement with respect to pre-flare flux is approximately the same as enhancement over the quiescent continuum.

Figure 5.6 shows the histogram of the peak intensity, normalized to the pre-flare emission, of these 906 pixels in different wavelengths. The UV 1600 Å and EUV 304 Å flare emissions have increased by up to two orders of magnitude, and the IR intensity has grown by a factor of 1.2 to 2.5 over the pre-flare emission. It is
Figure 5.5  Light curves in He I 10830 Å, AIA 1600 Å and 304 Å. Panel a to c represent for patches 0, 4 and 6 noted in Figure 5.1, respectively. The minimum value is subtracted from each light curve, which then normalized to its maximum.

noteworthy that, previous flare observations in the He I 10830 Å bandpass have shown IR darkening [34] and only when the GOES X-ray flux reaches a threshold could they detect emission [90, 54]. However, in this flare, almost all flaring pixels exhibit IR emission even during the first phase when GOES 1-8 Å emission is only at C1 level.
Figure 5.6  Histogram of peak intensities for all the footpoint pixels: x axis shows peak intensities as how many times the pre-flare intensity; y axis is in percentage. For the He I 10830 Å, the pre-flare intensity is approximated by the quiescent continuum.

Figure 5.7  Histogram of 10830 Å, 1600 Å and 304 Å rise and decay timescales. Upper panels: rise timescales. Bottom panels: decay timescales. As shown in Figure 5.5, the emissions from P0, P4, P6 in 10830 Å, 1600 Å and 304 Å all rise rapidly on the same timescale, and peak at the same time; they then decay more gradually but with quite different timescales: the 304 Å emission decays slightly slower than the 1600 Å emission, and the 10830 Å IR intensity decays
most slowly. Similar behavior is seen in individual pixels but with lower signal to noise ratios. The statistics of rise and decay timescales of all pixels are plotted in Figure 5.7. For each pixel, the maximum of light curve is recorded. Then the light curve from the onset of the flare to the time of maximum is fitted using a half Gaussian function. The rising timescale is calculated as half of the full width at half maximum of the fitted Gaussian function. Then the curve from maximum is fitted to an e-slope. The decay timescale is calculated from the time of its maximum to the time when it decays to \( \frac{1}{e} \) of its maximum.

The flux of most pixels rise impulsively within one minute. The UV 1600 Å flux typically decays within a few minutes while the decay timescale of the 304 Å flux is around 10 minutes. The flux in 10830 Å decays on longer timescales of a few tens of minutes.

5.3 Analysis

5.3.1 Summary of Critical Observations

There are several critical aspects to IR 10830 Å narrow-band and other data (refer to Figures 4.1-4.7) which is highlighted and drawn upon below:

1. The 10830 Å emission is confined to patches that are morphologically a mixture of bright fibril-like structures (P1, P5, P7), and bright amorphous patches (P0, P2, P3, P6, P8) (Figure 5.1).

2. These patches lie mostly over penumbral regions, on large scales they are associated with bright UV/EUV emission (Figure 5.4), but pixel-to-pixel comparisons reveal little correlation (which is not shown in this chapter).

3. The 10830 Å emission often has sharp edges (e.g., P0), close to the resolution limit of the observations (0\(\text{"}.14\)) (Figure 5.1).
4. The SXR emission observed below 15 keV by RHESSI is from a much extended source: in contrast to the sharp edges in 10830 Å (Figure 5.3).

5. The simultaneous steep rise at AIA 304 Å, 1600 Å, and 10830 Å footpoint emissions suggests that the IR and UV/EUV emissions are related during this phase (Figure 5.5).

6. The 10830 Å emission decays an order of magnitude more slowly than other UV/EUV emission, but has some similarity to the RHESSI and GOES decay curves (Figure 5.2).

5.3.2 Physical Picture

In previous work, Qiu et al. [73] has found a simple physical picture which can account for the UV and EUV data of flares that are qualitatively similar to the new observations presented here. Some process to be identified transfers energy rapidly out of the corona. When this energy is directed towards the lower solar atmosphere then this atmosphere responds by trying to deal with the excess energy through ionization, radiation losses, fluid motions and perhaps other modes (MHD waves, particle acceleration).

Evolution of plasma at the feet of flare loops begins with a highly dynamic response to impulsive heating. In work by Qiu et al. [73], the “impulsive rise” of the UV 1600 Å light curves at the flare foot-points is used to estimate empirical heating rates through a “0D” model. The method, using only two free parameters, has been applied to analyze and model heating of thousands of flare loops in a few flares with agreeable comparison between synthetic and observed X-ray and EUV spectra and light curves [73, 61, 55]. Using UV signatures to build heating rates, these studies not only resolve heating in individual loops but are not confined to flares that have

3 Not to be confused with the “impulsive” phase of many flares seen at radio and gamma ray wavelengths.
significant thick-target HXR emissions. In the present chapter, two further simplified assumptions are made based upon previous work [73] and upon the weakness of HXR emissions: (1) the 1600 Å emission during the flare is dominated by C IV emission and not the underlying continuum; (2) there are no significant non-thermal particles impacting the solar chromosphere from above.

The thermal conduction from the site of energy deposition will generate a downward propagating shock front, which most likely produces the impulsive spike in the UV and EUV light curves [20]. On the other hand, the cooling of the overlying corona governs the gradual decay. Such two phase evolution in the UV emissions has been reported by Hawley et al. [35] in stellar flare observations, and they found that during the cooling phase, a few lines including C IV can be used as a transition region pressure gauge monitoring the coronal plasma evolution in overlying flare loops. The DEM throughout the transition region is proportional to the equilibrium coronal pressure since the entire loop is in approximate hydrostatic balance in the cooling phase [19, 30, 36]. In this “pressure-gauge” approximation, the decay phase of UV/EUV emission in solar flares [61, 74] also compares favorably with the observations. Here, this model is adopted to compute decay-phase flare foot-point emission in EUV He II 304 Å, and UV C IV bands. The IR He I 10830 Å emission is then studied in the context of this model. Below, plasma evolution is modelled in hundreds of flare loops observed in this flare to find the coronal/transition region structure overlying the IR patches. Then He I 10830 Å enhancement due to different physical processes is estimated in these patches to compare with observations.

5.3.3 Calculations with EBTEL

For loops during the decay phase in approximate hydrostatic balance, the DEM throughout the transition region is proportional to the equilibrium coronal pressure and the optically thin radiative losses are balanced by the downward conductive heat
from the cooling coronal loops. With the plasma flow neglected, the DEM along the leg of the flux tube is computed analytically \[19, 30, 36\] as

$$\xi_{se}(T) = \overline{P} \sqrt{\frac{\kappa_0}{8k_B^2}} T^{\frac{3}{2}} Q^{-\frac{1}{2}}(T)$$

(5.1)

where

$$Q(T) = \int_{T_0}^{T} T'^{\frac{3}{2}} \Lambda(T')dT'$$

(5.2)

and \(\Lambda(T)\) is the optically thin radiative loss function. \(\kappa_0\) is the thermal conductivity coefficient and \(k_B\) is Boltzmann constant. Expressing the temperature-dependent scaling constant as \(g_{se}(T)\), the transition region DEM can be computed as \(\xi_{se}(T) = g_{se}(T)\overline{P}\), which is directly proportional to the mean pressure \(\overline{P}\) calculated using the zero-dimensional loop heating model, the EBTEL model \[46, 12, 13\]. Qiu et al. \[74\] and Liu et al. \[61\] have already confirmed that this pressure-gauge approximation can re-produce observed gradual decay reasonably well.

The spatially resolved AIA 1600 Å light curves are used to determine the empirical heating rates of the observed flare loops. With these heating rates, a zero-dimensional EBTEL model is used to compute mean temperature and density of plasmas in these flare loops. EBTEL solves an energy equation and a mass equation, taking into account an ad-hoc heating term which is inferred from foot-point UV light curve, coronal radiative loss, the loss through the transition region which in this study is scaled to the pressure of the coronal plasma, and thermal conduction and enthalpy flow between the corona and transition region. The synthetic coronal radiation in SXR and EUV bands are then computed and compared with observations by GOES and AIA to verify the very few parameters in the method.

Results of EBTEL calculations for the present datasets are shown in Figure 5.8. Using the 906 UV brightened pixels seen with SDO, 906 half loops anchored to these
pixels have been modelled. The lengths of these half loops are estimated from the EUV images, which range from 16 to 41 Mm. The heating rates of these loops are assumed to be proportional to the rise of the UV light curve at the foot-point pixel with a constant scaling factor which can be adjusted by best matching synthetic and observed EUV light curves. For this flare, the inferred heating rate in the 906 half loops ranges from $1 \times 10^8$ to $7.5 \times 10^{11}$ erg s$^{-1}$ cm$^{-2}$, and the total heating rate is plotted as dashed line in the top left panel of Figure 5.8 together with the UV total counts light curve. By assumption, beam heating scenarios are ignored and (non-radiative) magnetic heating primarily occurs in the corona. The other panels in the figure show synthetic SXR and EUV light curves in comparison with those observed by GOES 1-8 Å and 6 EUV bandpasses of AIA. Light curves in these passbands reflect evolution of coronal plasmas that are heated to over 10 MK and then gradually cool down to 1-2 MK. As shown in Figure 5.8, the synthetic light curves reflect the cooling of the flare, with high temperature emissions (131 and 94 bands) peaking earlier than low-temperature emissions (211, 193, and 171 bands). The synthetic and observed light curves coincide with each other quite well: they exhibit very similar time profiles and the magnitude of the total counts are comparable by within a factor of 2. The good comparison indicates that the method is able to reproduce mean properties of the corona during the flare.

In these models, the plasma pressure at the coronal base increases from a pre-flare state between 0.1 and 1 dyne cm$^{-2}$ up to pressures of several times $10^{1-2}$ dyne cm$^{-2}$ during the flare. Accordingly, the emission from lines such as C IV increases by similar factors. The underlying UV continuum near 1600 Å, however, forms near pressures closer to $1 - 2 \times 10^3$ dyne cm$^{-2}$ under quiescent conditions [94], over an order of magnitude higher. Thus, downward propagating flare energy is expected to be attenuated before it can reach such high pressures, associated with the much deeper “temperature minimum” region below the chromosphere.
Figure 5.8  Comparison of observed and synthetic flux calculated through EBTEL model. The dotted and solid lines are the synthetic and observed light curves, respectively. The heating rate is given as the dashed light curve in the top left panel. The corresponding passbands are noted by the number on the right corner of each panel.

Observations in this chapter show that the brightest IR 10830, UV 1600, and EUV 304 emission are generated in the lower-atmosphere at the footpoints of flare loops. Light curves in these wavelengths exhibit an impulsive rise, followed by a gradual decay. Using the transition region DEMs computed as above, it is found, as a post-facto confirmation of the initial assumption, that the UV 1600 Å band is indeed dominated by the C IV line. The emissivity $\epsilon(T)$ (radiated power in erg cm$^{-3}$ s$^{-1}$ divided by $N_e^2$) of the optically thin C IV multiplet is derived from CHIANTI 7.0 with ionization equilibrium [16, 50]. Using the DEM, the total C IV photon flux is computed in units of photons cm$^{-1}$s$^{-1}$sr$^{-1}$ and by convolving with the AIA instrument response function, the flux is converted to observed count rate in units of...
DN s\(^{-1}\). The right panel of Figure 5.9 shows the synthetic light curve of the C \textsc{iv} total counts summed up from foot-points of all flare loops, in comparison with the observed UV 1600 Å total counts. It is seen that, during the decay phase, the synthetic light curve agrees very well with the observed light curve in both the evolution timescale and the magnitude. However, the impulsive phases are significantly underestimated by the model calculations, because the equilibrium approximation is not adequate during the rise (heating) phase of the flare.

![Figure 5.9](image)

**Figure 5.9** Dotted lines: computed light curves for 304 and 1600 Å with pressure gauge assumption. Solid lines: observed data.

The He \textsc{ii} 304 Å line is usually formed in mid transition region temperature plasma (in equilibrium conditions this would be close to 80,000 K). To understand the observed He \textsc{ii} emission at the flare foot-points, the contribution function of the He \textsc{ii} line is calculated, as well, under conditions of statistical equilibrium, and convolved it with the transition region DEM and the AIA instrument’s response function in this band. In Figure 5.9, the left panel shows the synthetic He \textsc{ii} total counts light curve, which evolve along with the observed light curve with comparable amount of emission during the decay phase.

The successful comparison between the synthetic and observed C \textsc{iv} light curve during the decay phase confirms that the pressure-gauge approach reasonably
describes the transition region during this phase. The similarity of the observed and computed light curves of He II 304 Å emission is remarkable, given the earlier work, particularly that of Laming et al. [49], cited in the introduction.

5.3.4 He I 10830 Å

The observations indicate that the He I 10830 Å line is formed somewhere in the stratified chromosphere. During the flare, this layer must be significantly heated to enhance the He I line against the core from above ionized the neutral helium atoms. Then the recombination of the electrons and He II generates populations of the upper levels \((1s2p^3P_{0,1,2})\) of the multiplet [107]. The second is the “burst model” advocated by Laming et al. [49].

The observed enhancements of 10830 Å range from 1.2 to 2.5 times the pre-flare emission (Figure 5.6): the median value is close to 1.3, which is now adopted. As mentioned above, most flare footpoints locate in the penumbra. Before the flare, the clear view of the sunspot penumbra indicates the shallow absorption in 10830 Å. Therefore, most flux comes from the photosphere in these area, which means that emission during this stage could be approximated by the continuum emission. The total emission is estimated in physical units from 10830 Å as follows. The estimated continuum formation temperature at 10830 Å is around 6000 K at disk center as shown by Maltby et al. [63]. 5600 K is adopted since the flare footpoints locate in penumbra. Assuming that the continuum is generated by black-body radiation, the excess intensity could be written as

\[
I_{ex} \approx (1.3 - 1.0) \times B_\lambda(5600K) \times \Delta \quad \text{erg cm}^{-2}\text{sr}^{-1}\text{s}^{-1}, \tag{5.3}
\]

where \(\Delta\) is an (unknown) width of the excess emission line profile in wavelength units. Let \(\Delta = fw\) where \(f\) is the ratio of the radiation emitted by all 10830 Å transitions divided by the fraction that is observed, which covers a width \(w = 0.5\) Å. Values of
$1 \leq f < 10$ seem reasonable values, $f = 2$ is used since the bandpass cover almost half of the red component of $10830 \text{ Å}$ spectrum. Using a photospheric radiation temperature near $5600 \text{ K} = 8 \times 10^5 \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ Å}^{-1} \text{ s}^{-1}$, and $w = 0.5 \text{ Å}$,

$$I_{ex} \approx (0.3) \times (0.5) \times 8 \times 10^5 \text{ erg cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1},$$

or a total $10830 \text{ Å}$ energy flux out of the optically thin slab of

$$F_{ex} = 2\pi I_{ex} \approx 1.5 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}.$$ 

Since the energy of one $10830 \text{ Å}$ photon is $1.83 \times 10^{-12} \text{ erg}$, the photon flux is then

$$N_{ex} \approx 0.8 \times 10^{18} \text{ ph cm}^{-2} \text{ s}^{-1}.$$ 

**Photoionization-recombination picture** If the typical $10830 \text{ Å}$ enhancements are produced via the photoionization-recombination mechanism, the required energy flux of ionizing EUV photons is simply determined by computing the photoionization rate and the number of photons emitted in $10830 \text{ Å}$ per ionization [107, e.g.,]. Unlike Zirin’s work, there is no need to consider photoexcitation by the photosphere since the photospheric radiation cannot generate emission above its own continuum. Using the HAOS-DIPER package [42], it is found that between 32 and 62% of all recombinations lead to $10830 \text{ Å}$ emission, depending on whether the $504 \text{ Å}$ continuum is assumed optically thin or thick respectively. A value of 50% is adopted for optical depths close to unity where the bulk of the helium material will be photoionized, compared with 8.5% which lead to emission in the $\text{He I}$ resonance line at $584 \text{ Å}$. EUV photons at wavelengths below $504 \text{ Å}$ are needed for photoionization of $\text{He I}$. The photon energy flux at $500 \text{ Å}$ could be estimated, which is the minimum required flux to generate the observed enhancement in the photoionization-recombination picture, as

$$N_{EUV} = N_{ex}/0.5 = 1.6 \times 10^{18} \text{ ph cm}^{-2} \text{ s}^{-1},$$
for an energy flux of

\[ F_{EUV} \approx 6 \times 10^7 \text{ erg cm}^{-2}\text{s}^{-1}. \]

When distributed over an area of 906 AIA pixels, it is found that a total luminosity of the flare at wavelengths close to and below 504 Å of \(1.1 \times 10^{26}\) erg s\(^{-1}\). If distributed across the 9 patches, the average luminosity per patch is \(1.2 \times 10^{25}\) erg s\(^{-1}\).

The solid lines in Figure 5.10 shows the estimated photon energy flux from the observed IR enhancement in each of the 8 patches. P5 is not plotted since its emission is blended with the absorption from the nearby filament. With the transition region DEM computed for every pixel, the total optically-thin radiation energy is estimated by transition region plasmas of up to 2 MK, as plotted in dotted lines in Figure 5.10. It is seen that, in most of these patches, the estimated radiation energy is comparable with the required photon energy to generate the enhanced IR emission during the decay phase for as long as observed. It is concluded that photoionization by EUV photons in the overlying transition region is a viable mechanism for the prolonged He I emission at the flare foot-points.

An independent EUV photon energy flux produced in this flare can be estimated from observations by the EVE [102] on SDO. Two EVE spectrographs measure the whole-Sun solar extreme ultraviolet (EUV) radiation spectrum from 10-1050 Å with a resolution of approximately 1 Å and a cadence of 10 seconds. During this flare the “A” spectrograph on EVE acquired data in the range 60-380 Å, no data above 380 Å were obtained with the “B” spectrograph. The net EUV flux from the flare, obtained by subtraction of pre-flare emission, is shown in Figure 5.11. The solid line is the total flux observed by EVE from 60-380 Å while the dotted line is the calculated total optically-thin radiation by plasmas of up to 2 MK. The observed and measured fluxes are within ± a factor of three. Given the crude nature of the calculations and complex geometry of the flaring plasmas at various wavelengths, these measurements
provide reassurance that the photon fluxes in the model are broadly compatible with the data.

Laming et al. [49] estimates $2 - 8 \times 10^{16}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for the EUV ionizing intensity in the He I and He II continua. The number directed towards the chromosphere is $2\pi$ larger, or $\sim 3 \times 10^{17}$ photons cm$^{-2}$ s$^{-1}$. This is a factor of 7 smaller than the estimation here. This difference may be real, reflecting different flares, or it may reflect differences in the resolution of instruments used. The data used here has a far higher angular resolution, necessarily leading to higher intensities as smaller flare kernels are better resolved.

Figure 5.10  Total estimated optically-thin energy flux from the transition region (dotted line) compare with estimation from 10830 Å enhancement (solid line). The number on the upper right conner of each panel denotes the patches showed in Figure 5.1. The patch P5 is not plotted here because the emissions are blended with the filament absorption.
Burst picture The essence of this picture is that a burst of heating is assumed to occur in cool (chromospheric) plasma on time scales small compared with the time taken to ionize a given ion. During the burst the electron temperature is raised above the quiescent state, the hotter electrons lead to line emission before the ions involved become ionized. Heuristic arguments for this model have been given for EUV/UV helium lines by Laming et al. [49]. It has been placed on firmer theoretical grounds by Judge et al. [41]. In the work of Laming and Feldman, burst temperatures near $1.8 \times 10^5$ K were needed to reproduce spectra of He II which are consistent with spectra of He I.

This picture seems unlikely to be able to explain the 10830 Å line’s behavior reported here for the following reasons. The He I ionization times for pre-flare electron densities of around $5 \times 10^{10}$ cm$^{-3}$ [94, the value in the pre-flare upper chromosphere from] are about 100, 2 and 0.05 s for burst electron temperatures of $2.3 \times 10^4$, $4.6 \times 10^4$, and $9.3 \times 10^4$ K ($\equiv 2$, 4 and 8 eV), respectively. These values are simply scaled from Laming & Feldman’s Figure 1. Excitation of the 1s2p $^3P^o$ levels by electron collisions naturally requires time scales with a similar temperature dependence because these
levels lie at 21 eV, close to the continuum which is at 24.5 eV. Thus, populating these levels also leads to significant ionization. Further, a mere 1-2 eV is sufficient to ionize 50% of He I when photoionization from the $n = 2$ levels is considered (Laming & Feldman table 4). There are two difficulties: there is “little room in temperature space” where electron collisions from below can provide significant populations of the $1s2p^3P^o$ levels - if they are excited, the He I is also readily ionized; for electron temperatures equivalent to 4 eV or more, needed to provide significant populations of these levels, the ionization times are so short so that one must invoke very many bursts to maintain the observed light curves, even during the “impulsive” rise phases (many tens of seconds for 10830 Å, see Figure 5.7).

Thus, recombination appears the only way to significantly populate the $1s2p^3P^o$ levels. If this occurs via EUV photons, helium is selectively enhanced by the process outlined above. If however electron collisions are responsible, then one would expect very bright UV and EUV emission from trace species such as C, N, O, Si... from the upper chromosphere. Simultaneous observations of UV emission lines of various ions, for example from the new IRIS spacecraft, would be needed to see if pictures involving electron impact excitation of He I from the $1s^2 1S$ level can be refuted or must be considered further.

### 5.4 Discussion and Conclusions

With the NST’s high spatial resolution imaging observations as well as simultaneous space data from AIA on board SDO, a detailed analysis of a C class flare is given, which is observed continuously by all instruments at the cadence of 10-24 s (30 s for the TiO NST data). Specifically, this chapter has tried to identify the dominant mechanism that produces the observed He I 10830 Å emissions.

The picture that the flare energy released in the corona propagates downwards by heat conduction and radiation into the underlying chromosphere is adopted.
Particle beams seem insignificant on the basis that HXR fluxes are very small for this flare. Furthermore, analysis in this chapter focus on the decay phase of the flare, when the thermal model is sufficient for fitting the RHESSI spectra [60]. The conductive downflow is computed by determining heating rates which is inferred from 906 UV brightened pixels. And the zero-dimensional EBTEL model is utilized to compute mean plasma properties in the corona and transition region of flare loops anchored within these pixels. Remarkably, the method can reproduce not only the C IV emission generated in the transition region at the flare foot-points, but also He II 304 Å emission, at least during the decay phases, to within a factor of two or so. This is remarkable agreement given the need to appeal to different mechanisms for bigger flares in previous work [49].

In terms of the He I 10830 Å multiplet, it is argued that the downward propagation of energy via EUV photons is an important mechanism for excitation during the flare. Thus, PR model [107] appears to be a prominent component exciting the 10830 Å multiplet during this event. Several pieces of evidence support this picture. Firstly, the morphology of the footpoint 10830 Å emission is qualitatively similar to a mixture of EUV channels observed with AIA. Secondly, the light curve of 10830 Å emission is, during the rise phase, similar to the (E)UV transition region light curves (304 Å and C IV which dominates the 1600 Å channel); during the decaying phases, it is perhaps more similar to the coronal SXR and EUV light curves. Thirdly, photon budgets are in reasonable agreement, as measured against both EVE data as well AIA data. Fourthly, the EUV radiation computed from the EBTEL models is also compatible with the photon budget for exciting 10830 Å via PR, during the decay phase.

In Andretta et al. [2], the calculated helium spectrum is strongly affected by the spectral distribution and overall level of EUV coronal back-illumination, which is consistent with the result here. They also found that He I 10830 Å is
not sensitive to chromospheric helium abundance. In calculation of this chapter, the helium abundance merely needs to be large enough so that it dominates most of the absorption of some EUV radiation, these photons being converted to longer wavelengths such as the 10830 Å line computed down to the layer where EUV no longer penetrate. The calculations are therefore insensitive to modest changes in the abundance of helium.

But there is perhaps one problem with the PR mechanism: if this were the only source of photons in 10830 Å, then there should be a close correspondence between the spatial distribution of the EUV photoionizing radiation and the underlying 10830 Å flare emission. However, this is not always the case. Scatter plots of peak intensities of the light curves in AIA 1600 Å, AIA 304 Å and He I 10830 Å show little correlation. One cause of the enormous scatter might be the fact that only a 0.5 Å wide part of the 10830 Å line is observed, which is shifted by 0.25 Å blueward of the line center. Therefore, the morphology and light curves might contain velocity-dependent information that is not present in the broad band (E)UV channels.

Nevertheless, a “burst” picture is also examined which depends on non-equilibrium ionization to explain the large populations of the \( n = 2 \) triplet levels of helium. It is concluded that this seems unlikely for the He I 10830 Å multiplet on several grounds, at least for the decay phases. Occam’s Razor would compel us to accept the PR mechanism as perhaps the “simplest answer compatible with the data”.

The assumed steady-state and equilibrium conditions are not adequate for calculations during the impulsive phases with durations of 10-100 seconds or so. In this period, the 10830 Å have identical rapid enhancement with the (E)UV lines. Perhaps a “burst” picture would be successful during this phase. Further observations including more UV lines, such as can be observed with IRIS, would be desirable, since to leading order the lines would respond to bursts but not the PR mechanism.
Flares, as the most energetic explosive events, have been of great importance for space weather. Numerous researches of flares have been done to study the formation mechanism of them. The morphology of magnetic fields is essential for the formation of flares, because it is closely associated with magnetic reconnection. In the solar atmosphere, plasma are “frozen” together with magnetic fields since the magnetic diffusion term is rather small and could be ignored. Thus, the morphology of the observed plasma outlines the structure of magnetic fields. Taking advantage of multi-wavelength observations, complemented by data in He I 10830 Å, topology of the magnetic fields could be investigated through tracing the plasma of varies temperatures from photosphere to corona, which helps elucidate the formation of flares. In this chapter, the 10830 Å observations in two studies of flares are presented.

6.1 Study of Two Successive Three-ribbon Solar Flares on 2012 July 6

10830 Å data is of great importance for diagnosing the temperature of plasma and investigating the structures of the flares. Two three-ribbon flares (M1.9 and C9.2) have been studied, using observations of both Hα and 10830 Å from the NST, as well as Ca II H images from Hinode. The two flares occurred on 2012 July 6 in NOAA AR 11515, with time interval between them of half an hour. The morphology of the magnetic fields at the flaring site is characterized by an intriguing “fish-bone-like” structure. There are 3 jets associated with the flares, which are surge-like flows,

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This chapter is based on the following papers:
labelled as jet 1-3. In Figure 6.1, the jets 2-3 are shown, right after the C9.2 flare. Jet 2 can be observed in the Hα center line, 10830 Å, as well as EUV, while jet 3 (indicated by dotted lines) is only identified in Hα. Jet 3 cannot be distinguished from the brightened hot EUV loops connecting the flare to the remote region, i.e., region S (yellow contour in panel (d)), and it is missing in 10830 Å filtergrams. Thus, it is surmised that jet 3 moves along closed loops containing cooler ejecta of chromospheric temperature since there is no observation of higher temperatures, e.g., it is missing from 10830 Å. In contrast, jet 2 is probably launched outward along hot open magnetic field lines as modelled in this area.

6.2 Witnessing Magnetic Twist with High-resolution Observation from the 1.6-m NST

Magnetic flux ropes consist of a group of highly twisted, current-carrying magnetic fields which are writhing about each other and rotating around a common axis. The structure of magnetic flux ropes are important to and often associated with solar eruptions i.e., flares and CMEs. The flux ropes are usually observed in SXR and EUV, which reflect the magnetic fields and hot plasma in corona. However, the previous coronal observations of the evolving flux ropes are of low resolution, which hampers an unambiguous and detailed identification of flux ropes and their relation to eruptions. Moreover, the evolution of flux ropes has not been observed in the low solar atmosphere such as the chromosphere. Using the highest resolution chromospheric images from the 1.6-m NST at BBSO, the observations of magnetic twist in a flare are studied, supplemented by a magnetic field extrapolation model.

As shown in Figure 6.2, before the flare eruption, an inverse S-shaped flux bundle is clearly observed in both H-alpha off-bands(±0.6 Å; panel a,b) and 10830 Å (panel c), which appears as an integrated single structure. It is noticeable that the 10830 Å filtergrams are transparent so that the background features in the photosphere coexist with the overlying loops. Then, the overall inverse S-shaped flux bundle appear
Figure 6.1  Jets 2 and 3 observed in NST 10830 Å and Hα after the C9.2 flare. (a) NST He I 10830-0.2 Å, (b) Hα line center, (c) SDO/AIA 335 Å, and (d) 131 Å images. In panel (d), the dashed box is the FOV of panels (a)-(c). And the yellow contours are LOS magnetic fields at -700 and -300 G of the remote region, S. Courtesy Wang et al. 2014 [98].

Partially being ripped off, while the brightening in 10830 Å has extended into two bright ribbon-like patches in the horizontal direction (Figure 6.2c-f).

Before the onset of the flare, three-dimensional magnetic field structure is constructed using a non-linear force-free field (NLFFF) extrapolation model based on the surface vector magnetogram taken by the HMI. The extrapolated magnetic fields coincide with the observed S-shaped flux bundle observed in He I 10830 Å as well as H-alpha off-bands. Using the TiO images, photospheric shearing motions are
Figure 6.2  BBSO/NST observation on 11 August 2013. (a) and (b) shows the VIS images at the H-alpha red-wing (+0.6 Å) and blue-wing (-0.6 Å), respectively. (c-f) Time evolution of infrared imaging magnetograph (IRIM) images at the He I 10830 Å line. It is notable that right before the event onset, there exhibit an inverse S-shaped flux rope structure at the centre in both H-alpha off-bands (a,b) and He I 10830 Å (c) images. The active flux rope on top of the extending flare ribbons are clearly seen in 10830 Å images (d-f). Note that some linear and thin features running at an angle across the centre of the flux rope in c-f are artifacts produced by the infrared camera. Courtesy Wang et al. 2015 [96].

also detected, which contributes to the energy build-up of the twisted S-shaped flux bundle.
The high-resolution images obtained by BBSO/NST provide a first opportunity to witness the detailed structure and evolution of twisted flux ropes in the low solar atmosphere. Moreover, The 10830 Å filtergrams not only provide a good intermediate for co-alignment with other observations in different wavelengths, but also shows the magnetic flux ropes in the chromosphere, with background features in the photosphere. In this way, high resolution 10830 Å observations are valuable in the studies since the structures could be traced from photosphere to the upper chromosphere.
CHAPTER 7
SUMMARY AND DISCUSSION

This dissertation is focused on the study of small-scale solar activity observed in He I 10830 Å with NST which leads to a new era of high resolution observations. The knowledge of the small-scale solar activity will benefit the prediction of space weather, since they are thought as not only epitomes of major solar activity i.e., major flares and CMEs, but also processes of energy built-up before eruptions. All the events investigated in this dissertation occurred between 2011 and 2013, during which observations made with NST have been successful and a large amount of well observed data has been obtained. In the following, the major results of the presented observational studies are summarized and listed below, which help extend the understanding of the topology and triggering mechanism of small-scale solar activity and shed light on the future studies.

7.1 Major Results of this Dissertation
First, surges could be triggered by motions of large granules. In a special case study, before the occurrence of the surge, the motion of a slightly larger granule is detected right at the root of the surge. The granule squeezes the intergranular lanes with outstanding advection speed of 2 km s\(^{-1}\) (compared to average velocity of 0.5 km s\(^{-1}\) for granules) at its front. Then the ejection starts, accompanied with changes of magnetic fields in the photosphere. The estimated mechanical energy of the surge is comparable to the energy loss of the magnetic fields, and this close association indicates the surge is produced from magnetic reconnection. Therefore, the surge is resulted from magnetic reconnection initiated by the motion of a large granule in the photosphere.
Second, in the study of a limb jet event, clear evidences suggest that the event is generated through two-step magnetic reconnection. Fan-spine topology is one signature of magnetic reconnection. Every element of the fan-spine topology predicted by magnetic reconnection model are observed, including the inner spine. In 10830 Å, the inner spine of the jet is clearly visible, supported by strong X-ray source at the footpoint of the inner spine, which is a post facto confirmation of the null point fan-spine topology. In the high resolution NST observations, the footpoints in AIA EUV images turn out to consist of loop structures in 10830 Å filtergrams. The fan of the jet could be observed in Hα blue wing and 10830 Å while there is no EUV signal, which indicates the temperature of plasma is cool, i.e., < 20,000 K. Moreover, there are bi-directional flows originated from a common region which should be the magnetic reconnection site.

Third, at the flare footpoint, photoionization of chromospheric plasma followed by radiative recombination is of great importance for populating the 10830 Å multiplet during the cooling phase. During the decay phase of a C-class flare, the mean gas pressure of loops are estimated using EBTEL model. And the DEM throughout the transition region is calculated as proportional to the equilibrium coronal pressure since the entire loop is in approximate hydrostatic balance (pressure-gauge). The results are constrained by comparison between synthetic coronal radiation and observation in the SXR and EUV bands. Furthermore, the synthetic He II 304 Å, as well as the C IV, emissions computed by standard DEM calculations are reasonably well matched to observations, which is a confirmation of validity of the pressure-gauge approach. Then the EUV radiation computed using the calculated DEM is also compatible with the photon budget for exciting 10830 Å via PR during the decay phase.

Finally, the studies of surge and jet show that the 10830 Å is not produced by PRM at some stages. In the study of the granule triggered surge, there are not enough EUV photons to raise the strong He I 10830 Å absorption in the first stage.
Meanwhile, super hot plasma is found which could be the key for the formation of 10830 Å. Moreover, the 10830 Å emission is neither co-spatial nor co-temporal with the EUV enhancement along the spine during the second stage of the limb jet studied. Actually, there is also super hot plasma found in the spine. Therefore, the PRM could be ruled out for the formation of the 10830 Å during these stages.

He I 10830 Å observations provide us valuable tools to investigate the solar activity. Based on the above results, following conclusions are made. (1) The photospheric motions are important for triggering the solar activity in the chromosphere, which is certified by the granular advection triggered surge. This relationship will benefit the prediction of chromospheric events by observing the activity in the photosphere. (2) Surge and jet studied in this dissertation are produced via magnetic reconnection, which is indicated by comparable energy of the surge to the magnetic field energy loss, bi-directional flow originated from magnetic reconnection site, as well as the super hot (> 1 Mk) source at the footpoint of the inner spin observed in 10830 Å. (3) At the flare footpoint, the PRM plays an important role in the 10830 Å formation. (4) There are some parts of the jet that PRM could be ruled out for the formation mechanism of 10830 Å, i.e., the fan, since there is not sufficient EUV photons inside the fan. Since these lines are used to study solar activity, a clear picture of its formation mechanism will consequently lead to diagnose the phenomena and better understanding of the events.

7.2 Foreseeing the Future Work

As a concluding remark to this dissertation, following studies based on results in this dissertation are expected to be done in the future:

Statistical studies are needed to extended study of triggering mechanism of surges. The photospheric motions will be tracked around the surges to see if the motions are indispensable for triggering the surges. Furthermore, a number of surges
will be investigated to study the relationship between granule’s motion and magnetic reconnection rate.

A much more comprehensive picture will be investigated about the 3D topology of surges or jets. More limb events will be studied combining the data from Hinode X-Ray Telescope. For large events, HXR data observed by RHESSI will be used to locate thermal and non-thermal electrons. Together with AIA EUV images, the jets will be investigated from top to bottom and from $\sim 10^4$ to $\sim 10^7$ K. Fan-spine topology will be focused on to see if the inner spine and bi-directional flows could be observed in other events.

The formation mechanism of He I $10830$ Å triplet on the Sun will be further studied, which is essential for understanding the observation. Quantitative estimation of the EUV radiations could be made through varies DEM calculation. The He I $10830$ Å emission via pure PRM could be computed and compared to observations. More cases will be studied in flaring regions, and when and why the PRM does not take effects should be found out. Especially, if PRM is the formation mechanism, why the edge of the flaring regions are so sharp.

In general, the PRM is the widely accepted physical mechanism for He I $10830$ Å excitation, which requires EUV back irradiation from the corona. Thus, He I $10830$ Å absorptions should be not easy to be observed in the corona holes due to the lack of EUV emission. And this is indeed the case with low resolution observations. However, with the high resolution data achieved with the NST, there are actually small-scale He I $10830$ Å absorptions in intergranular lanes inside the corona hole. Studying the formation mechanism of these small absorption in corona holes would lead to fundamental improvement of the knowledge about the complex forming mechanism for the He I $10830$ Å absorption in quiet regions.

Large-scale shear motions have been observed before filament eruption, which contribute to energy build-up and release process. The shear motions will be studied
using simultaneous TiO data to verify its role in twisting and destabilizing a filament. The accompanying micro-flares will be analysed to locate the initial site of energy release.

Furthermore, high resolution spectro-polarimetry in He I 10830 Å will be carried out, after the Near-Infrared Imaging Spectro-polarimeter (NIRIS) is available in the near future, which offers both velocity fields and vector magnetic fields of upper chromosphere. Magnetic fields play a fundamental role in defining the structure, mass and energy flows in the chromosphere and corona [100]. Therefore, observations of small-scale magnetic fields with the highest resolution are crucial to understand physics of small-scale activity.
BIBLIOGRAPHY


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