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Abstract

Mass Composition and Dynamics in Quiet Sun Prominences

by

Gary K. Kilper

Solar prominences are transient phenomena in the solar atmosphere that display highly dynamic activity and can result in dramatic eruptions, ejecting a large amount of material into the heliosphere. The dynamics of the prominence plasma reveal information about its interaction with the magnetic field of the prominence, while the eruptions are associated with coronal mass ejections, which greatly affect space weather near Earth and throughout the solar system. My research on these topics was conducted via observational analyses of the partially-ionized prominence material, its composition, and the dynamics over time in prominences that range in activity from quiescent to highly active. The main results are evidence that (1) in quiescent prominences, neutral He is located more in the lower part of the structure, (2) a higher level of activity in prominences is related to a mixing of the material, and (3) an extended period of high activity and mixing occurs prior to eruptions, possibly due to mass loading. In addition, innovative modifications to analytical techniques led to measurements of the material's mass, composition, and small-scale dynamics.
Acknowledgments

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Finally, I greatly appreciate the operators and data teams for MLSO, SOHO, TRACE, Hinode, and STEREO for providing the observations, and the authors of the data analysis tools in the SolarSoftWare (SSW) package for IDL. SOHO is a project of international cooperation between ESA and NASA. TRACE is a NASA Small Explorer program mission of the Stanford-Lockheed Institute for Space Research and Lockheed Martin Solar and Astrophysics Laboratory (LMSAL). Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners, and operated in cooperation with ESA and NSC (Norway). STEREO/SECCHI is a collaborative effort by Johns Hopkins U. Applied Physics Laboratory, the Naval Research Laboratory, NASA GSFC, LMSAL, and several international institutions.
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Chapter 1

Introduction

Ever since they were first observed, prominences have puzzled scientists due to their transient existence, dynamic behavior, and periodic eruptions, which are dramatic events in the solar atmosphere that expel material and magnetic field from the corona into the solar system. These eruptions have long been associated with flares and coronal mass ejections (CMEs; Munro et al., 1979), which greatly affect the space weather at Earth. Space weather forecasting has already become a high priority due to the strategic importance of our satellites, spacecraft, and human explorers in space. This, combined with the potential for greater knowledge of the initial conditions (at the Sun) of interplanetary CMEs and a deeper understanding of plasma physics, makes research on prominences' magnetic structure, dynamics, and their eruptions a key component of heliophysics. This chapter provides the necessary background on solar prominences, which are the subject of my doctoral research that is described in the chapters that follow.
1.1 Prominences and Filaments

Prominences are condensations of cooler material in the hotter and less dense corona, supported against gravity and contained by a magnetic field that is anchored below (e.g. Tandberg-Hanssen, 1995). The material is surrounded by a relative void (less dense than the neighboring corona) and an overarching magnetic arcade. When viewed over the limb, the material and void are called a prominence and cavity, respectively; when observed against the solar disk, the material by itself is known as a filament, and the material together with the void is called a filament channel (see Fig. 1.1; note that filament channels can also lack material, consisting of only a void and magnetic arcade). In general contexts, the terms prominence and filament can be used interchangeably.

The cool prominence material is primarily composed of hydrogen and helium that is partially ionized, with the neutral atoms supported by interactions with the ions (Gilbert et al., 2002). Quiet Sun prominences and active region prominences are categorized by where they appear on the Sun and are generally considered to have very different magnetic structures and formation processes. Active region prominences are shorter (~10 Mm), short-lived (from minutes to hours), and low in the corona (1 Mm), while quiet Sun prominences are higher (50 – 100 Mm), longer (sometimes hundreds of Mm), and can persist for several days or weeks. Intermediate prominences are in the quiet Sun and exhibit behavior similar to those prominences, but they are sometimes grouped separately because they have a footpoint near an active
Quiet Sun prominences, on which this thesis is focused, differ in the amount of activity they display throughout their lifetime, ranging from quiescent, when the material shows little internal motion and has a stable size and shape, to active, when there are numerous small-scale motions and flows visible within the material,
an increase in the vertical height, a visible spine at the top, and often a deepening in absorption (Martin, 1998). Within this general context, activation is defined in this thesis as a transition from a level near quiescent to fully active, which has been observed to typically occur over a period of a few hours (Kilper et al., 2009). Eruptions are an extreme in the observed behavior of prominences, in which they rise in the corona and either expel some or all of their material off the Sun to form a CME, or the eruption fails and the material falls back to the Sun (e.g. Tandberg-Hanssen et al., 1980; Feynman & Ruzmaikin, 2004). Note that some of the terms above have been used in the past with some ambiguity, and the definitions outlined here are meant to reduce possible confusion within this thesis, which is primarily from an observational perspective.

The following sections contain more detailed information about the observations (§ 1.2), as well as the terminology and findings from previous research that is necessary to understand the prominence magnetic structure and formation (§ 1.3), composition and dynamics of the material (§ 1.4), eruption process (§ 1.5), and the direct motivation (§ 1.6) for the doctoral research conducted, which is described in later chapters.

1.2 Observations

Prominences and filaments are typically observed in near-infrared (IR), optical, and extreme-ultraviolet (EUV) spectral lines, while the cavity or filament channel is seen in white light, EUV, and soft X-rays (SXR). Observations of flaring in high
temperature lines and of the photospheric and chromospheric magnetic fields, derived from magnetically-sensitive optical lines, provide beneficial context information about the magnetic environment near prominences. Infrared, optical, and ultraviolet radiation is typically detected by instruments with a filter or multilayer coating (to select the wavelengths of photons that can pass through) and charge-coupled devices (CCDs), which efficiently convert the detected photons to electrical signals that can be processed and analyzed.

Prominences, visible over the limb, were first described in c.E. 1185 in Novgorod, Russia, when a total solar eclipse revealed the faint corona and "horns [that] came out somewhat like live embers." Not until the invention of the spectroscope in 1868 and the coronagraph in 1930 were prominences and filaments able to be clearly discerned, and on a regular basis. Now there are many ground-based observatories throughout the world that monitor the solar disk, allowing continuous temporal coverage of the Sun (weather permitting), and space-based observatories with a completely uninterrupted view for most or all of the year from their locations in low-Earth orbit or at the Sun-Earth Lagrangian point (L1).

Observations in chromospheric lines are those that form at chromospheric temperatures (~ 10^4 K), such as Hα (H Ic 6563 Å), He I (10830 Å), and Ca II H (3969 Å), which are at optical or near-infrared wavelengths and can be observed from the ground. Much of the prominence material is at chromospheric temperatures, and these lines are formed by complex combinations of collisions, photoexcitation
and photorelaxation. In chromospheric lines, prominences are observed as brighter than the dark background of space because the material emits radiation at these temperatures (Fig. 1.1(a)). Filaments are seen as relatively dark structures against the brighter background of the solar disk due to the absorption (and isotropic re-emission) of radiation from the chromosphere by the filament material (Fig. 1.1(b)). Such observations in optical lines have been obtained for more than a century, and now there are many observatories on the ground, and even one in space. Current optical instruments include the space-based *Hinode* Solar Optical Telescope (SOT) and ground-based instruments such as the Advanced Coronal Observing System (ACOS) at Mauna Loa Solar Observatory (MLSO) and the New Solar Telescope (NST) at Big Bear Solar Observatory (BBSO).

The transition region includes numerous lines between chromospheric and coronal temperatures that are below the photoionization limit for hydrogen or helium, and also have complex radiative transfer equations for prominence material. These lines show the same observing characteristics for prominences and filaments exhibited in chromospheric lines (Fig. 1.1(c)), and likely originate in the prominence-corona transition region (PCTR), which lies between the cool material and hotter corona and is often observed to have a larger spatial extent than is observed in chromospheric lines (since the PCTR surrounds the cool prominence). There are several hydrogen Lyman lines in this temperature regime, including Lyman-α (1215 Å), which can be observed by rocket flights into the Earth's mesosphere, such as the Extreme Ul-
traviolet Normal Incidence Spectrograph (EUNIS), or from space by the Ultraviolet Coronagraph Spectrometer (UVCS) or Solar Ultraviolet Measurements of Emitted Radiation (SUMER) on the Solar and Heliospheric Observatory (SOHO). The photoionization limit for ionized helium is much higher (well into the EUV), so shorter wavelength lines such as He II (304 Å) can be used, although these must be observed from space.

Coronal lines form at temperatures much hotter ($\sim 10^6$ K) than prominences, but the cool prominence material is still visible in these EUV lines via "continuum absorption" (Fig. 1.1(d)), which occurs when EUV photons are energetic enough to overcome the ionization potential to photoionize an atom or ion (primarily neutral hydrogen, neutral helium, and singly-ionized helium) and free an electron. Both prominences and filaments are observed via continuum absorption as dark objects embedded in the background coronal emission in lines such as Fe IX/X (171 Å), Fe XII (195 Å), Mg IX (368 Å), and Mg X (625 Å). EUV radiation is absorbed by the Earth’s atmosphere, so these observations must be taken by space-based instruments, including the Coronal Diagnostic Spectrometer (CDS) and Extreme-ultraviolet Imaging Telescope (EIT) on SOHO, the Transition Region and Coronal Explorer (TRACE), the Extreme Ultraviolet Imager (EUVI) on the Solar Terrestrial Relations Observatories (STEREO), and the EUV Imaging Spectrometer (EIS) on Hinode.

The interpretation of prominence observations at all of these wavelengths is augmented by spectral line diagnostics that relate the observed spectra to the promi-
nence's physical properties, such as depth, density, pressure, temperature, thermal velocity, line-of-sight velocity, and radial velocity. In these models, the original assumption of local thermodynamic equilibrium (LTE) was found to be inaccurate in stellar atmospheres (which must include a non-thermal component), so models without LTE (non-LTE or NLTE) were formulated, and subsequently applied to the Sun (e.g. Milkey et al., 1973; Heasley & Milkey, 1978). Current, highly sophisticated models include many atomic levels and ionization states, several moving prominence threads, and the PCTR (e.g. Anzer & Heinzel, 2005; Heinzel et al., 2008; Labrosse et al., 2008; Gunár et al., 2008); these spectral models can also be recalculated many times with a variety of input parameters to determine how those changes affect the synthetic spectra. The resulting information is critical in providing a basis for correctly interpreting prominence observations, including those used in my research.

1.3 Magnetic Structure and Formation

Prominences consist of a few basic magnetic components (that are assumed to also exist in empty filament channels). The structure has a spine along the top, with footpoints at both ends and often one or many barbs between the footpoints, all of which extend down from the spine to the chromosphere at oblique angles (see Fig. 1.1; Martin, 1998). In this thesis, each portion of the spine between neighboring footpoints or barbs (combined with those “legs”) will be referred to as a “section.” A magnetic arcade of several coronal loops typically arches over the prominence along
the length of the spine (e.g. Fig. 1.2(b)). The basic forces on a prominence are the
downward-directed gravity of the material and the magnetic tension of the overlying
arcade, countered by the upward magnetic buoyancy of the prominence structure due
to the higher magnetic pressure in the prominence than in the corona.

Importantly, prominences are always located above a neutral line or polarity in­
version line, which is where the radial component of the photospheric magnetic field
changes sign. This observational maxim has serious ramifications for prominence
models since it implies that horizontal field lines are essential to the extended pres­
ence of material suspended in the corona. In addition, almost all of the material
in a prominence must be added from the chromosphere. A calculation from several
years ago found that the amount of material in the entire corona is only a small frac­
tion of the observed amount of cool, dense material in a typical prominence (since
prominences are much denser than the corona; Saito & Tandberg-Hanssen, 1973).

Kippenhahn & Schlüter (1957) proposed the first model of a solar prominence.
This model assumes a pre-existing dip in the magnetic field, where coronal plasma
then collects and cools radiatively to chromospheric temperatures (Fig. 1.2(a)). In
this “dip model,” the gravity of the material is balanced by the magnetic tension due
to the dip in the field, but the actual formation process is unclear – i.e. whether the
dips exist first and cause the material to collect, or if the presence of material creates
the dips, which then cause more material to condense. More recently, Antiochos &
Klimchuk (1991) modeled a dipped prominence whereby heating near a footprint
Figure 1.2: Schematic diagrams showing the prominence magnetic field structure in the (a) dip model, (b) flux-rope model, and (c) wire model. In these diagrams, the overlying magnetic arcade (solid arcs, b), neutral line (dashed line, b & c), and filament material (shaded area, a & b) are displayed. Figures are from Kippenhahn & Schlüter (1957), van Ballegooijen (2000), and Lin et al. (2008), respectively.

ciauses material to rise into the structure, and as the density increases it cools more rapidly and forms the condensation in the dips.

The competing “flux-rope model” was first proposed by Kuperus & Raadu (1974), and developed further by van Ballegooijen & Martens (1989), Priest et al. (1989), Fan & Gibson (2004), and others. Flux-rope prominences are twisted tubes of magnetic field that do not require the material’s gravity to create any dips; the mass is simply located at the lowest part of the helical magnetic tube (Fig. 1.2(b)). The flux-rope is either created from a magnetic arcade that is sheared by solar differential rotation, in which the subsequent flux cancellation and reconnection creates the loops in the flux-rope, or a buoyant flux rope is created at the tachocline and then rises through the convection zone and photosphere, up into the corona. Once the structure has formed, chromospheric material can rise up through the ends, cool, and then settle into the series of dips within the flux-rope. Aside from clear formation processes, a further strength of the flux-rope model is its ability to explain the existence of
prominence cavities and the isolation of the prominence from the surrounding corona (Low & Hundhausen, 1995).

Some models do not have any material contained or supported within the prominence, removing the requirement of dips in the magnetic field, but instead require a continuous flow of material along a collection of magnetic field lines. The "wire model" of Martin & Echols (1994), based empirically on quiet Sun filaments, consists of several long, sheared loops without any dips (Fig. 1.2(c)). The spine is composed of the tops of the arches, and the barbs are inclined field lines that divert from the spine and extend sideways down to the chromosphere. By contrast, the "dynamical model" (e.g. Antiochos & Klimchuk, 1991; Karpen et al., 2001) is a numerical model inspired by the continuous flows seen most frequently in active region prominences, but sometimes also in active prominences in the quiet Sun (e.g. Zirker et al., 1998). In this model, material is continuously added, flows, and accumulates to form the prominence, all fueled by heating near the footpoints of a long, un-dipped coronal loop. If the heating is asymmetric, then small dips with lifetimes of several hours are repeatedly formed and destroyed, but the cool material occupies a much larger volume than these dips, which were found to not be necessary for condensations of material to form.
1.4 Composition and Dynamics

The physical processes important in the solar atmosphere and in prominences are driven by the physical properties. The low density ($\sim 10^9 \text{ cm}^{-3}$) and high magnetic field strength ($\sim 10 \text{ G}$) yield a low plasma beta in the corona, meaning that the magnetic field pressure dominates gas pressure, so charged particles must move mostly along field lines. At $10^4 \text{ K}$, the prominence plasma is partially ionized – i.e. a mix of neutral atoms, ions, and free electrons. The composition of the material is assumed to be similar to the photosphere, which is about 92% hydrogen, 8% helium, and 0.1% heavier elements, but both the composition and the ionization fractions are unknown for the material in prominences. Spectral line modeling has calculated the helium abundance in prominences before (for example, $0.10 \pm 0.025$ in Heasley & Milkey, 1978), but it has not been measured directly. From NLTE models of prominences, the material is estimated to have around 50% of the hydrogen and 10% of the helium ionized (e.g. Anzer & Heinzel, 1999; Labrosse & Gouttebroze, 2004). Neutral atoms are not directly affected by the magnetic field and presumably would simply fall due to gravity. However, the neutrals are supported in prominences by frictional interactions with the ions – specifically charge exchange between the neutral and ionized states of each element, i.e. $H^0$ with protons and $He^0$ with $He^+$ (Gilbert et al., 2002). Charge exchange in hydrogen is strong because of its relatively low first ionization potential (FIP; 13.6 eV), but the effect is much less for noble elements like helium (which has a high FIP of 24.6 eV).
The material in prominences is very dynamic – even in the most quiescent prominences. Active and pre-eruption prominences show a high degree of motion along the spine and vertically in the legs, with speeds up to 70 km s\(^{-1}\). In addition, separate Dopplergram observations were utilized to detect "counter-streaming" flows of 5–20 km s\(^{-1}\) in both directions along the spine of quiet Sun prominences (e.g. Zirker et al., 1998; Lin et al., 2003), and Okamoto et al. (2007) measured a flow speed averaging 39 km s\(^{-1}\) in an active region prominence. Furthermore, in a high-resolution Hinode/SOT observation of a quiescent prominence, Berger et al. (2008) measured downflows of material at 10 km s\(^{-1}\) and upflows of small voids (possibly material heated outside the bandpass of Hinode/SOT H\(\alpha\)) to be around 20 km s\(^{-1}\) (discussed more in § 4.0).

Material also moves in and out of prominences, and mass draining (i.e. mass loss) is often observed to occur along apparent magnetic field lines. Neutral atoms can also diffuse across field lines in a process called "cross-field diffusion" (Gilbert et al., 2002). Heavier atoms with larger FIPs diffuse much faster than neutral hydrogen,
which effectively is coupled to $H^+$ and barely diffuses at all (see § 1.6 below). Mass can also be added to the prominence via several mass loading mechanisms, which explain how chromospheric material is caused to rise against gravity, up into the prominence. In “injection models”, material is propelled up the legs of the prominence by magnetic reconnection low in the solar atmosphere (Fig. 1.3(a); e.g. Wang, 1999; Chae, 2003). “Levitation models” have material lifted from the chromosphere by low-lying dips in the prominence, either by relaxing loops in the prominence (Deng et al., 2000), flux-ropes emerging through the chromosphere (Rust & Kumar, 1994), or after reconnection of loops in the chromosphere that then rise (Fig. 1.3(b); e.g. van Ballegooijen & Martens, 1989). In evaporation-condensation models, such as “chromospheric evaporation” (Fig. 1.3(c); Antiochos & Klimchuk, 1991), localized heating near a footpoint causes chromospheric material to rise into the prominence, and then radiatively cool and condense near the middle of the structure. Aside from these mechanisms of overall mass variation, gravitational settling of ions could redistribute the material within prominences such that heavier elements would be preferentially located lower in the structure due to their greater weight, with the scale height of the settling depending inversely on the ion’s mass. These mechanisms of mass variation feature heavily in the motivation for and interpretation of the doctoral research (described below).
1.5 Eruptions and CMEs

Prominence eruptions are dramatic events in the corona, and most start with an initial slow rise, followed by a sharp change to a fast rise when they are high in the corona (Sterling & Moore, 2001). Prominence eruptions can be full, when all of the material is expelled, partial, when only some of the mass erupts, or failed, if the material resettles or falls back to the surface and does not result in a CME (e.g. see Gilbert et al., 2007b).

Full and partial eruptions expel the prominence material as part of a CME, which typically consists of a bright leading shell, a dark cavity, and an inner core associated with the prominence material (Crifo et al., 1983; Hundhausen, 1988). A general model of prominence-related CME initiation has the prominence (sometimes rising) in the corona, and the magnetic fields are strained until reconfiguration of the field (presumably due to magnetic reconnection) releases a vast amount of stored magnetic energy, which expels some material outward to form a CME, and flings other material downward to slam into the chromosphere and cause flaring (Forbes et al., 2006). In the same vein, the types of prominence eruptions can be explained by reconnection occurring below, within, or above the prominence material (Fig. 1.4; e.g. Gilbert et al., 2001).

Many models of prominence eruptions have been formulated (see Low, 1996; Klimchuk, 2001), and they all involve a loss of equilibrium in the forces on the prominence (as outlined in § 1.3 above). The “mass loading model” requires an increase in promi-
Reconnection below flux rope

Reconnection above the prominence (within flux rope)

Reconnection within the prominence

Figure 1.4: Schematic diagrams showing the possible reconnection sites in an inverse polarity flux-rope prominence, which would form a full eruption (left), a failed “cavity-only” eruption (middle), and a partial eruption (right). Note that left and right could also result in failed eruptions if the rising prominence is constrained by or experiences further reconnection with fields higher in the corona, and all three reconnection sites apply in a similar way to the dip model. Figure is from Gilbert et al. (2001).

nence mass to allow the storage of additional magnetic energy, then a sudden shift or draining of mass results in a decrease in gravity, causing the prominence to rise and erupt, despite the dominance of the magnetic fields in the low plasma beta corona (e.g. Low et al., 2003). An increase in the upward buoyancy is described in two types of models. The mechanism of “flux cancellation” is a natural way to construct a prominence flux-rope, but as the process continues, the magnetic pressure in the flux-rope could exceed the surrounding magnetic tension, leading to an expansion of the flux-rope and a buoyant rise of the prominence (e.g. Lin et al., 1998). A more impulsive version is the “flux injection model”, in which the poloidal magnetic flux is increased by sub-photospheric motions (or possibly via coronal sources) that
wind up the flux-rope, increasing magnetic pressure until the system destabilizes and the prominence erupts (Chen, 1989). The remaining models involve a decrease in the downward magnetic tension of the overlying magnetic arcade. In the “magnetic breakout model”, there is a quick decrease in the tension due to reconnection between the arcade above and neighboring flux systems, which would result naturally from a multi-polar magnetic topology (Antiochos et al., 1999). Finally, the “tether-cutting model” involves a fast reconnection of the lower part of the prominence due to flux emergence that decreases in the magnetic tension of the arcade until the prominence rises and erupts (e.g. Moore et al., 2001). A more gradual version that incorporates flux cancellation, dubbed “tether-weakening”, has been found to be more in line with observations of large or small-scale flux emergence (see below).

Several past observational studies have centered on the detection of precursors to eruptions – such as the behavior during the build up, the rise speed and acceleration, and brightenings in high-temperature lines (e.g. SXR or EUV) – all with the goal of understanding the importance and timing of the relevant forces and energy release mechanisms (Alexander, 2006). Several lines of work are particularly relevant to the research on filament eruptions presented below (in § 2.4). In the first, observations of eruptions over a range of wavelengths (and temperatures) provided evidence for heating, seen as an increase in emission, both during the eruptions (e.g. Engvold et al., 2001; Kucera & Landi, 2008) and beforehand when the filaments are rising and expanding (e.g. Cirigliano et al., 2004; Kucera & Landi, 2006). In another study,
Gibson et al. (2006) found that a cavity is present for all CME-related filament eruptions considered and that its size increases before and during an eruption. Finally, recent work utilizing magnetic field data during eruptions detected the emergence of magnetic flux in a localized regions near the legs, starting several hours before the eruption and occurring simultaneously with the slow rise phase and microflaring in SXR, which possibly indicates tether-weakening (e.g. Feynman & Ruzmaikin, 2004; Sterling et al., 2007). In a separate case study, Schmieder et al. (2008) found high activity and a strong decrease in the photospheric magnetic field network near a filament, starting more than 24 hours prior to eruption, but no flux emergence nor small-scale brightenings, leading them to suggest that a gradual decrease in magnetic tension from flux cancellation via photospheric diffusion slowly destabilizes the system. All of these findings provide clues for the importance of the several possible eruption mechanisms, and also provide a framework for the interpretation of the results from my research on filament eruptions.

1.6 Motivation for Studying Prominence Mass

Much work has been done to apply the observed movement of material in prominences to infer its magnetic structure, but the material itself can also convey important information in ways that are seldom explored. The amount of mass in a prominence, the abundances, and the ionization fractions are all unknown, yet these values are critical for understanding the interaction between the magnetic field and
the plasma. Order-of-magnitude estimations for the density and mass of the prominence material have been deduced, often via estimations of the electron density, but the composition and ionization fractions are completely unmeasured. Due to the dominance of hydrogen and helium, the desired numbers are the percentages of the material that is \( H^0 \), \( H^+ \) or protons, \( He^0 \), and \( He^+ \). The amount of \( He^{2+} \) and all heavier elements is assumed to be negligible.

Furthermore, changes in prominence mass and composition can tell us a great deal about the importance of the various mass variation mechanisms, or point to the possible causes of eruptions – especially when compared to advanced theoretical models (such as Roussev et al., 2007; Fan & Gibson, 2007; Karpen & Antiochos, 2008). For example, in the models of mass loading from the chromosphere (described in § 1.4), mass injection and chromospheric evaporation would cause flows up the prominence legs, but in levitation models, the material would be pulled up directly into the lower part of the spine, bypassing the legs.

Differentiating between the types of mass draining could be discerned by the direction of movement by the material, but changes in the composition yield additional information. Mass draining along field lines is inferred when material is moving down along apparent field lines, and it should generally not change the composition. However, neutral atom cross-field diffusion predicts the diffusion of neutral helium down through the prominence, leaving behind the neutral hydrogen. Therefore, a net decrease in the amount of neutral helium (relative to hydrogen) or a change in the
composition over the height of the prominence material would indicate that cross-field diffusion may be affecting the prominence material. Gravitational settling of ions could also cause heavier elements to be located lower in a prominence, but ions would presumably need to move across field lines within the prominence, and the scale height of heavy ions would be significantly smaller than for hydrogen (e.g. the scale height for $Ca^+$ would be 40 times smaller), which should be detectable.

Observational signs of possible mass variation were present in the data, but a focused analysis of the composition in prominences had not yet been attempted. My doctoral research was later expanded to include highly active and pre-eruption prominences, but the initial aim was to explore the mass composition in quiescent filaments and determine whether cross-field diffusion was playing any role in the dynamics.

**My Starting Point: Cross-Field Diffusion**

The main line of work in my Ph.D. research has been to study the mass and composition of prominences and how it relates to their overall behavior – especially their formation, dissipation, and eruptions. The first study (described in § 2.3) was directly motivated by the results of Gilbert et al. (2002), who formulated the process of cross-field diffusion in a partially-ionized prominence plasma. They set out to address the question of how the neutral component is supported against gravity, and they found that, theoretically, neutral helium should diffuse across the magnetic field much faster than neutral hydrogen.
Their results were obtained by modeling a five-component hydrogen-helium plasma (composed of $H^0$, $H^+$, $He^0$, $He^+$, and $e^-$) subjected to gravity and a horizontal magnetic field. The charged particles primarily drift laterally along the magnetic field, and the various frictional forces – specifically, the relatively large upward-directed frictional force due to charge exchange – causes the neutral atoms to be supported against gravity to differing degrees, due to differences in FIPs and mass. For approximate values of filament height and density (noted in the equations below), they calculated cross-field vertical diffusion times for neutral hydrogen and neutral helium of 520 hours and 24 hours, respectively, which are directly proportional to the vertical column density:

$$\tau_H \approx 520 \left[ \frac{h_{fil}}{0.01 R_\odot} \right] \left[ \frac{n}{10^{10} \text{ cm}^{-3}} \right] \text{hours}$$

$$\tau_{He} \approx 24 \left[ \frac{h_{fil}}{0.01 R_\odot} \right] \left[ \frac{n}{10^{10} \text{ cm}^{-3}} \right] \text{hours}$$

Here $h_{fil}$ is the vertical extent of the filament structure (in solar radii, $R_\odot = 700 Mm$), and $n$ is the total number density (including the neutrals, ions, and electrons; in $\text{cm}^{-3}$).

Therefore, cross-field diffusion of neutral atoms could play a significant role in modifying the relative abundance of helium to hydrogen, assuming the filament does not undergo significant thermal or dynamical evolution over a period of several hours. They suggested a comparison of the relative absorption in filaments between neutral hydrogen and helium lines, such as $H\alpha$ and $He\ I\ 10830 \ \text{Å}$, to look for a helium deficit (relative to hydrogen) in the degree of absorption or the filament size. A preliminary examination of co-temporal $H\alpha$ and $He\ I$ full-disk images from MLSO found possible
indications of such abundance effects.

The second study of filament eruptions (described in § 2.4) was directly motivated by preliminary findings from my first study, but required an expansion of the sample size and the data set to better test the initial trends found. The third study of direct calculations of the prominence mass and helium abundance (Chapter 3) was motivated both by a suggestion in Kucera et al. (1998) that if prominence mass could be measured in several EUV lines then the composition could be calculated, and also by the improved mass measurement technique of Gilbert et al. (2005, 2006). Finally, the fourth study utilizing the newer observatories (Chapter 4) was conducted to obtain much better data and definitively test my initial results. These aims were what led me (and my collaborators) to design and conduct the research described below; as the reader may notice in the coming chapters, these studies yielded some novel and significant results, and also led to some unexpected and surprising conclusions.
Chapter 2

He/H Absorption Ratio Studies

Prominences are composed almost entirely of hydrogen and helium, and a comparison of hydrogen and helium image observations with good spatial resolution and cadence can provide detailed information about the prominence mass composition and how it changes over time. The method (described in § 2.2), is based on the preliminary results and recommendations in Gilbert et al. (2002), and has been modified to test for the effects of cross-field diffusion in the first study (§ 2.3), and for the increased homogenization of the composition prior to eruption in the second study (§ 2.4). The results of both analyses have also inspired several possible follow-up projects for the future (outlined in § 2.5).

2.1 MLSO Observations

The Mauna Loa Solar Observatory (MLSO) on the active volcano of Mauna Loa in Hawaii observes the Sun in several optical and near-infrared wavelengths on a daily basis from 17:00 to 02:00 UT, depending on the duration of daytime and the weather conditions. The two instruments used in my studies were installed as part of the
Advanced Coronal Observing System (ACOS) in 1996-1997, and are operated by the High Altitude Observatory (HAO), a division of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. The Polarimeter for Inner Coronal Studies (PICS) instrument observes the Hα 6563 Å line with a bandpass (i.e. a spectral width or resolution) of 0.5 Å and a resolution of 2.9 arcsec per pixel (Fig. 2.1(a)). Concurrent to the PICS observations, the Chromospheric Helium-I Imaging Photometer (CHIP) instrument observes He I 10830 Å (at line center and in red and blue Doppler wings) with a bandpass of 1.4 Å and resolution of 2.29 arcsec per pixel (Fig. 2.1(b)). Note that the actual, measured spatial resolution is roughly double the pixel size, and 1 arcsec at the center of the Sun is equivalent to 725 km. The observations of both instruments include the full-disk and the limb, and are taken every three minutes for the years used in these studies (2000-2006).

The observations used here are of the full solar disk, corrected for p-angle (i.e. the relative tilt of Earth's axis to the Sun's), and “flat-fielded” to eliminate inconsistencies in instrument response over all pixels, and also correct for limb darkening, which is done by multiplying the pixel value by a factor depending on the distance from disk center, in order to normalize the pixel values in the quiet Sun background over the entire solar disk (see Fig. 2.1). The set of observations analyzed were selected to avoid poor seeing (e.g. bad weather or clouds) and atmospheric distortion, which is a problem only at the very beginning and end of daylight hours, when the depth of Earth's atmosphere through which the Sun is observed is greatest. Context infor-
Figure 2.1: Examples of corrected images of the solar disk in (a) \( \text{H} \alpha \) 6563 Å, with the uncorrected observation for comparison, and (b) \( \text{He I} \) 10830 Å, as observed by MLSO on 2004 Feb 18 at 17:24 UT, when six quiet Sun filaments are visible. Note that the scaling in the \( \text{H} \alpha \) image is 1.27 times smaller than in \( \text{He I} \) due to the difference in pixel resolution between the PICS and CHIP instruments.

Information is provided by the \( \text{He I} \) velocity data, for which the observations of the \( \text{He I} \) Doppler wings are subtracted to yield qualitative information about the line-of-sight velocity of the filament material.

2.2 Analysis and He/H Absorption Ratio

The key observational quantity in understanding the composition of filament material is the \( \text{He}/\text{H} \) absorption ratio, which is obtained by comparing absorption in co-temporal observations in \( \text{H} \alpha \) and \( \text{He I} \). This section explains its calculation, physical meaning, and discusses the possible associated errors.

The MLSO observations comprising each pair of \( \text{H} \alpha \) and \( \text{He I} \) being compared
are as close together in time as possible, and are carefully aligned to ensure a proper measurement of the absorption ratio. The analysis is done via a code written using IDL and the SolarSoftWare (SSW) package, which are common tools for solar data analysis. The code reads in the observational parameters and image arrays for each pair, rescales and aligns the two images, selects the subset of pixels containing the filament, and compares the absorption in the two lines at each pixel in the filament. The alignment is done by shifting and then re-binning the pixels in the He I image to fit the Hα image. The pixels included as part of the filament must show a certain degree of absorption in Hα, which was determined by the threshold in trial runs that best selected the filament material without including too much random absorption in the background; Hα is used to identify the filament because in He I, active regions are also seen in absorption, which would confuse the pixel selection process in intermediate filaments. For each of the co-aligned pixels comprising the filament, the relative percentages of absorption from the average brightness values are calculated in the two lines and then compared to yield the He/H absorption ratio:

\[
(He/H \text{ absorption ratio})_{\text{pixel}} = \frac{1 - (H_{\text{pixel}}/H_{\text{avg}})}{1 - (H_{\alpha_{\text{pixel}}}/H_{\alpha_{\text{avg}}})},
\]

where \(H_{\text{pixel}}\) and \(H_{\alpha_{\text{pixel}}}\) are the numerical values of that pixel in the two lines, and \(H_{\text{avg}}\) and \(H_{\alpha_{\text{avg}}}\) are average pixel values, which are set as a constant for each wavelength and were estimated from the average pixel values in the quiet Sun over many observations. The resulting absorption ratio values are plotted to give a spatial
map of the composition, as seen in the figures in the following sections. Note that the maps show the absorption ratios on a logarithmic scale, so even small variations are readily apparent in the figures. In addition, the total absorption in Hα and He I, the average He/H absorption ratio, and (for the study on filament eruptions) the root-mean-square (RMS) deviation of the absorption ratio are calculated and plotted.

The physical meaning of the absorption ratio is that it provides a relative measure of the column density of neutral helium, as compared to the column density of neutral hydrogen, because of how the two lines are formed at $10^4$ K. He I 10830 Å is formed by photoexcitation between the lowest triplet states of neutral helium ($1s2l\,^3S$ and $^3P$) at a rate nearly unchanged for typical temperatures in a filament (e.g. Andretta & Jones, 1997; Labrosse & Gouttebroze, 2001, 2004). Hα is formed in neutral hydrogen by a mix of photoexcitation and collisions between the $n = 2$ and $n = 3$ states, with only a square-root dependence of their population levels on the temperature (e.g. Wiik et al., 1992; Gouttebroze et al., 1993; Heinzel et al., 1994). Aside from slightly different logarithmic slopes for an optically thin or thick filament, the amount of absorption in both lines is directly dependent on the electron density, and thus on the column density of the atom that forms the line. The NLTE models do find some scatter in this relation (because of the range of input parameters, besides density), so the column density can only be estimated to within half an order of magnitude or less in any individual observation of any particular filament. However, comparisons in observations of the same filament are much more accurate since the prominence
parameters would be consistent and not random variables. Therefore, by comparing these spectral lines, meaningful relative values of the absorptions can be determined (between different observations, or among different parts of a filament in the same observation), and thus relative values of the column densities and abundances. In the maps of the He/H absorption ratio, a darker pixel means there is a relative helium deficit, compared to the amount of hydrogen, while a brighter pixel indicates a relative helium surplus. In addition, the plots of the total absorption and the absorption ratio only show relative changes over time in the column densities and composition, respectively.

In the study on filament eruptions, the RMS deviation of the pixels’ absorption ratio values (from the average absorption ratio) in each observation is also calculated, and it is used to quantify the relative degree of the composition’s homogenization and its change over time. While there is some scatter in this measure of the homogenization, a decrease in the RMS deviation is a good indicator of a general normalization of the composition over the whole filament structure.

He/H Absorption Ratio Error Analysis

Errors in the He/H absorption ratio could result primarily from three sources. The effects of weather and atmospheric distortion are mitigated by removing affected pairs of images from the data set. Problems could also result from a comparison of different parts of a filament between the two spectral lines, caused by a misalignment due either to solar rotation during the time difference between the pair of observations, or to
incorrect values of the Sun center and radius listed in the parameters of an observation (which happens rarely: occurring in only 3 of 289 pairs of images in the initial study, or \(\sim 1\%\)). Finally, a change in the material's temperature or its motion could modify the spectral (i.e. wavelength) distribution of the material, causing a different amount of absorption to be measured when there is no actual change in the column density; this is especially important in a narrow wavelength filter, since only a fraction of the line profile is within the narrow bandpass, so smaller shifts in the spectral distribution could affect the amount of absorption measured.

The images in the two spectral lines are never taken at exactly the same time, with the separation ranging from less than a minute (for the majority of our data) up to almost six minutes, when necessary to avoid using a poor-quality image. By tracking surface features, the maximum possible "pixel speed" due to solar rotation is found to be 0.07 pixels per minute at disk center, while the average pixel speed for the observations analyzed is just 0.02 pixels per minute (at around 30° latitude and 35° longitude). Therefore, in six minutes a surface feature will move 0.12 pixels on average, and a maximum of 0.42 pixels due to solar rotation. Filaments are suspended above the solar surface and would thus have a greater pixel speed, but for the tallest filaments observed here, this effect would only increase the maximum pixel speed to 0.076 pixels per minute, corresponding to a distance of 0.46 pixels – less than half a pixel.

To fully check on the possibility of misalignment, features on the surface of the
Sun (not in the filament material in the corona) were compared between Hα and He I for each pair of images. Surface features used were, for example, the pixels of maximum emission or absorption in active regions or plage regions. In the data, the boundaries and brightest/darkest pixels were clearly aligned around 95% of the time, and the remaining minority of the pairs were removed from the data set. These failures in alignment were due to either: no surface feature being significant enough to be compared with absolute confidence, an image in the pair was too blurry for the features to be identified clearly, or the observational parameters in the image files were incorrect. In order to test this method of confirming the alignment, I took a well-aligned pair and increased the size of just the He I image by one pixel in the x-direction in the first case, and by one pixel in the y-direction for the second case. By using a viewer that centers all of the images it displays, and then comparing the normal Hα image with the two shifted He I images, it was possible to see whether a misalignment of half a pixel could be detected. The half-pixel shift (which corresponds to 1.45 arcsec) was detectable for both cases, implying that this process of confirming the alignment is reliable to that scale, and it could also correct for any effect of solar rotation. Therefore any features in the He/H absorption ratio maps (that are at the resolution limit of two pixels wide or larger) are real features and not due to a misalignment.

The NLTE models play a crucial role in understanding the error due to changes in the plasma temperature or the velocity distribution. An increased temperature of
the prominence plasma causes more electrons to be excited out of the ground state to populate the lower energy levels of the Hα and He I transitions, which increases the number of absorbers of those wavelengths. For Hα, this is a slow increase, with the $n = 2$ population level dependent on the square root of the temperature (Heinzel et al., 1994). For He I, the temperature does not affect the He level populations much at all since the temperature must rise rather high (for a quiet Sun prominence) for electrons to be ionized out of the singlet ground state, which can then recombine into the triplet states (Labrosse & Gouttebroze, 2004). In both lines, the absorption in an optically thin filament increases faster with density than in an optically thick filament, but filaments with reasonable geometries (similar to those analyzed here) are expected to be optically thin in both Hα and He I.

A change in the velocity distribution of the filament material can affect the amount of absorption in two main ways. If the line-of-sight velocity increases, then the spectral distribution will broaden due to Doppler shifting, and some of the material may be shifted far enough from line center so that it does not absorb within the observing instrument's bandpass, causing the amount of absorption to decrease. Likewise, if the line-of-sight motion decreases, then more material will absorb within the bandpass and the amount of absorption will increase. A second possibility for changing the observed absorption is the Doppler-brightening effect (DBE), which is caused by strong radial velocities and is especially important for erupting prominences. Affecting absorption lines (such as Hα and He I), DBE occurs when the amount of the photospheric-
chromospheric radiation incident on a prominence in the wavelength range of its line absorption profile increases due to the relative motion of the filament material to the solar surface, which increases the photoexcitation rate for that line transition, and would therefore cause an increase in observed emission from a prominence (e.g. Heinzel & Rompolt, 1987; Gontikakis et al., 1997; Labrosse et al., 2008). In filaments, since DBE would cause the filament material to emit more, then there would be less absorption observed; however, this signal is superseded in filaments by the line-of-sight Doppler shift, which causes the absorption to decrease much faster with the radial velocity. Since the filaments analyzed here have small radial velocities (and the line-of-sight velocities are mostly radial with only small contributions from the lateral flows along the spine), these velocity effects (on the absorption in both Hα and He I) play only a minor role, except after the filament eruptions have already been initiated, when the material Doppler shifts out of the instrument bandpass.

2.3 Results from Long-Duration Filament Study

This first study was initially designed to examine quiescent filaments over an entire disk crossing to search for long-term changes in the composition and determine if cross-field diffusion has any effect on filaments. All of the filaments selected are from 2004, which is between solar maximum and minimum, providing many quiet Sun filaments whose absorption is uncontaminated by nearby active regions. Of forty-four candidates identified, the twenty filaments selected have good temporal coverage in
the observations over the thirteen-day disk crossing, and the entire sample of filaments includes a variety of sizes, behaviors of the material, and locations on the Sun relative to active regions (see Table 2.1). For each filament, a pair of Hα and He I images were selected and analyzed from the beginning and end of each day that the filament was on the solar disk and observations were being taken at MLSO – yielding a cadence of two per day, which would be sufficient to identify any effects due to cross-field diffusion. In addition, two full days of observations were analyzed with three-minute cadence to search for shorter timescale variations during an eruption (on Aug 11) and during the disappearance of part of the filament spine (on Sept 19; Table 2.2).

The desired results were a determination of whether any effect due to cross-field diffusion could be observed in the composition, a better estimate of the level of activity within quiet Sun filaments, and how often filaments transition from quiescent to active, and vice versa. The actual results of the study confirmed that cross-field diffusion could be playing a significant role in the dynamics in quiescent filaments, and we also found trends in the composition of varying material (i.e. increasing or decreasing in absorption) and in pre-eruption filaments. These findings were published in the Astrophysical Journal (Gilbert et al., 2007a).
Table 2.1. Quiet Sun Filaments Analyzed Over a Disk Crossing

<table>
<thead>
<tr>
<th>Filament Designation</th>
<th>Avg. Lat.</th>
<th>Dates Visible</th>
<th>Filament Category</th>
<th>Edge Effects</th>
<th>Varying Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-01-3</td>
<td>25° N</td>
<td>Jan 19-23-27</td>
<td>Large QS</td>
<td>Switch (3)</td>
<td>Appearance</td>
</tr>
<tr>
<td>2004-02-1</td>
<td>50° S</td>
<td>Feb 7-12-15</td>
<td>Small QS</td>
<td>Part (3)</td>
<td>App. &amp; Dis.</td>
</tr>
<tr>
<td>2004-02-2</td>
<td>40° S</td>
<td>Feb 12-17-22</td>
<td>Small QS</td>
<td>Same (4)</td>
<td>Appearance</td>
</tr>
<tr>
<td>2004-02-5</td>
<td>35° N</td>
<td>Feb 16-20-24</td>
<td>Large QS</td>
<td>Switch (2)</td>
<td>Disappearance</td>
</tr>
<tr>
<td>2004-03-2</td>
<td>20° N</td>
<td>Mar 6-11-15</td>
<td>Intermed.</td>
<td>Switch (3)</td>
<td>Variation</td>
</tr>
<tr>
<td>2004-05-1</td>
<td>20° N</td>
<td>May 2-7-11</td>
<td>Erupting</td>
<td>Switch (4)</td>
<td>Appearance</td>
</tr>
<tr>
<td>2004-05-3</td>
<td>20° N</td>
<td>May 19-24-30</td>
<td>Erupting</td>
<td>Part (1)</td>
<td></td>
</tr>
<tr>
<td>2004-06-1</td>
<td>15° N</td>
<td>May 29-Jun 3-7</td>
<td>Erupting</td>
<td>Switch (4)</td>
<td></td>
</tr>
<tr>
<td>2004-07-2</td>
<td>30° S</td>
<td>Jul 9-14-18</td>
<td>Large QS</td>
<td>Part (5)</td>
<td>Variation</td>
</tr>
<tr>
<td>2004-08-2</td>
<td>30° S</td>
<td>Aug 6-11-13</td>
<td>Erupting</td>
<td>Part (3)</td>
<td>Variation</td>
</tr>
<tr>
<td>2004-09-2</td>
<td>25° S</td>
<td>Sep 5-10-14</td>
<td>Intermed.</td>
<td>Part (2)</td>
<td>Appearance</td>
</tr>
<tr>
<td>2004-10-2</td>
<td>25° S</td>
<td>Oct 7-10-14</td>
<td>Intermed.</td>
<td>Same (3)</td>
<td>Appearance</td>
</tr>
<tr>
<td>2004-12-2</td>
<td>35° N</td>
<td>Dec 6-11-14</td>
<td>Large QS</td>
<td>Same (3)</td>
<td>Appearance</td>
</tr>
</tbody>
</table>

a Identifies each filament by the year, month, and order within that month in which it was recognized.

b Observation dates (during 2004) of the filament when nearest the east limb, 0° longitude, and the west limb, respectively.

c Filament categories: intermediate (near an active region), small-size in the quiet Sun, large-size in the quiet Sun, and erupting.

d Types of edge effects: dark edge switches sides during the disk crossing, dark edge remains on the same side, or dark edge is visible only for part of the disk crossing. The number of days showing edge effects is given in parentheses.

e Types of varying material: appearance of new material, disappearance of existing material, or a variation in the amount of material within a section that persists.
Table 2.2. Individual Full Days Analyzed

<table>
<thead>
<tr>
<th>UT Date</th>
<th>Start Time</th>
<th>End Time</th>
<th>Lat.</th>
<th>Long.</th>
<th>Associated Filament</th>
<th>Dynamic Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Aug 11</td>
<td>16:37</td>
<td>02:28</td>
<td>30° S</td>
<td>5° W</td>
<td>2004-08-2</td>
<td>Eruption</td>
</tr>
<tr>
<td>2004 Sept 19</td>
<td>17:31</td>
<td>01:52</td>
<td>30° N</td>
<td>5° W</td>
<td>2004-09-3</td>
<td>Disappearance</td>
</tr>
</tbody>
</table>

2.3.1 Separation of H and He in Quiescent Filaments

Filaments are quiescent when the material is relatively inactive and the shape of the filament structure is mostly stable and unchanging. The twenty filaments in this study were found to be quiescent for at least a day during their disk crossing, and sometimes for a majority of the time. Periods of higher activity were observed to come and go, with the transition between quiescent and fully active lasting at least several hours, and longer for the transition back from active to quiescent. Properly measuring these timescales and the frequency with which they occur was not a primary goal of this study, but would be a good follow-up project for future work.

Edge Effects

The focus of this study was to search for observational signs of cross-field diffusion, and the most striking pattern in the He/H absorption ratio distributions is seen at the edges of the filaments. There are often dark bands (of relative helium deficits) along one side and brighter than average bands (showing relative helium surpluses) along the opposite edge. These "edge effects" are seen more frequently in filaments away
from the disk center, nearer to the solar limb. All twenty filaments exhibit this effect to some degree, with many of them displaying a dramatic contrast in the absorption ratios from one edge to the other (see Edge Effects in Table 2.1).

Nine of the filaments show edge darkening on one side initially, no noticeable edge darkening at some time during the event (usually near disk center, but not precisely), and then switch to have darkening along the opposite edge when the filament is near the west limb. For example, filament 2004-01-2 initially shows clear bands of helium deficit and surplus along the northern and southern edges, respectively (Fig. 2.2(b)), while the opposite orientation is present later (Fig. 2.2(g)), and no edge darkening is visible when the filament is near disk center. Three filaments show edge darkening consistently on the same side throughout the disk crossing, and all of them have rather stable shapes and are above 25° latitude. The edge effects are not discernible for at least a day when the filaments are near disk center, but are visible when near both limbs. The remaining eight filaments have some edge effects on the same side for part of the disk crossing (i.e. at least one day; Fig. 2.2(b)), but do not show clear edge effects at all while on one of the hemispheres (Fig. 2.3(j)).

There are some inconsistencies in the orientation of the edge effects. Over all twenty filaments, there are seven cases (2.4% of the total) that show a clear irregularity over sequential observations in the presence or location of edge darkening (despite seemingly good image alignment) that cannot be explained, except by an unexpectedly quick change and reversion in the compositional distribution or the orientation
Figure 2.2: Series of He/H absorption ratio maps of an intermediate filament (2004-01-2) from January 2004. A co-temporal Hα disk image is inlaid in (e). The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. The arrows point to edge effects, ellipses identify filament sections increasing in absorption, and rectangles identify sections decreasing in absorption. All times are UT.
Figure 2.3: Series of He/H absorption ratio maps of a large quiet Sun filament (2004-07-2) from July 2004. An Hα disk image is provided in (e) for context. The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. The arrows point to edge effects, ellipses identify filament sections increasing in absorption, and rectangles identify sections decreasing in absorption. All times are UT.
Evidence for Cross-Field Diffusion

The prevalence of edge effects in observations of quiescent filaments indicates that the responsible physical process has a large effect on the filament material when there is a low amount of activity and a stable structure. Since the edge effects are stronger when the filaments are near the limbs, and many show the darker edge switch sides as the Sun rotates (to be closer to the nearest limb), then the composition is likely stratified in the vertical direction of the filaments, which could not be seen as well when viewed from directly above (see Fig. 2.4). Therefore, the observed He/H absorption ratio distributions show a relative surplus of He I absorption, as compared to Hα absorption, in the lower part of the filament and a corresponding helium deficit in the upper part. Both neutral atom cross-field diffusion and gravitational settling can cause a concentration of helium in the lower part of the filament, but their mechanisms do this in different ways.

Cross-field diffusion explains how neutral helium, with its greater mass and higher FIP, diffuses out of the filament in around one day, while neutral hydrogen is supported against gravity almost entirely via charge exchange with protons (Gilbert et al., 2002). The calculated timescale of one day for neutral helium diffusion was for a filament with no internal activity in the material. Filaments are typically more active, however, and do not remain quiescent for too long. The observed timescale for the separation of neutral helium and hydrogen is on the order of a few days, which
Figure 2.4: Cartoon showing the typical orientation of the edge effects in the He/H absorption ratio on a north-south oriented vertical-ribbon-like filament as it crosses the solar disk, when near the (a) east limb, (b) disk center, and (c) west limb. These distributions show a relative surplus of He I absorption (compared to Hα absorption) in the lower part of the filament and a helium deficit in the upper part. Therefore, the observations imply that neutral helium is more concentrated in the lower part of quiescent filaments than neutral hydrogen. Figure is from Gilbert et al. (2007a).

compares well to the theoretical calculation of Gilbert et al. (2002). A decrease in the overall He/H absorption ratio, i.e. a decrease in the amount of He I absorption without a decrease in Hα absorption, would support cross-field diffusion as a viable mechanism for mass loss, and such a trend is discussed more in § 2.3.2.

Gravitational settling would cause the redistribution of the heavier element (helium) into the lower part of the filament due to gravity. The ions are supported against gravity by the Coulomb force, so the scale height for hydrogen settling is four times larger than for singly-ionized helium. However, to switch from a homogenized composition to a distribution with He and H separated, gravitational settling would
need to move the ions across field lines, which is only possible if there is a higher-than-expected plasma beta in filaments, such that the magnetic fields do not dominate. New Hinode observations of vertical flows in prominences are questioning whether it is a magnetically-dominated environment (e.g. Berger et al., 2008), but as of now, the movement of neutrals to create the edge effects seems much more likely.

Further study would require the measurement of the rate of redistribution of the absorption ratio and the rate of change in the He I absorption. Newer observatories put this objective within reach, and an observing campaign using instruments with high resolution and cadence could yield results confirming the importance of cross-field diffusion in filaments that are quiescent.

2.3.2 Changing Composition in Varying Filaments

Despite selecting the twenty filaments for their long lifetimes on the disk to better test for the importance of cross-field diffusion, they show a great deal of variability in the filament material. Some are quiescent, and many are active with increased movement by the material; interestingly, a few even show different levels of activity among their separate sections of filament material. Recall that each portion of the spine, combined with its neighboring legs, is defined here as a “section.” Although there is a great deal of apparent motion in the barbs and footpoints, no significant structure in the composition was found via the absorption ratio analysis, except that the ratios remain roughly constant in the legs.
Relations Between Changes in Absorption and Absorption Ratio

Eighteen of the filaments show changes in the amount of absorption due to the filament material, including the appearance or disappearance of entire sections. The absorption ratios of the varying parts of the filament often seem to change in association with variations in the amount of absorption, but not always. The three general types of varying material observed in these filaments are (1) the appearance of new sections of material, (2) the disappearance of existing sections of a filament, and (3) variations in the amount of material within a filament section (see Varying Material in Table 2.1).

The appearance of new sections, both large and small, occurs in fourteen of the filaments. These new sections sometimes are attached to the ends of the filament, but usually they appear as separate structures in a different part of the filament channel. For all new sections, the same trend was found for a large majority of the appearing material. As the absorption increases in Hα and He I, the absorption ratio is approximately constant throughout the new section for the duration of the absorption increase, and the constant value of the absorption ratio is roughly the same across all of these appearing sections (e.g. Fig. 2.2(g)). The period of simultaneously increasing absorption and constant absorption ratio ranges from several hours to a few days, although the actual lower bound could not be determined because only two image pairs were analyzed per observing day.

In nine of the filaments, existing sections disappear and become no longer visible
in Hα and He I. The amount of absorption decreases in both lines for the disappearing sections, but not always at the same rate. In around a third of the disappearances, the absorption ratio varies little, meaning that Hα and He I absorptions decrease at around the same rate (e.g. Fig. 2.5(m)). For another third, as the amount of absorption decreases, the absorption ratio also decreases, which means the absorption in He I decreases faster than in Hα (e.g. Fig. 2.2(e)). For the remainder, an irregular mixture of absorption ratios or a lack of sufficient data made the categorization unclear (e.g. Fig. 2.3(j)). These disappearances typically take between one day to a few days, but more frequent observations would need to be analyzed to find anything on the order of minutes or hours. One such quick disappearance of a section occurred in a filament on 2004 Sept 19, which was analyzed in detail with three-minute cadence observations. The section slightly increases in absorption and then disappears completely a few hours later, when the material seems to move out of the spine toward both legs, leaving behind a gap in the spine (Fig. 2.5). Note that the absorption ratios in the disappearing section remain fairly constant throughout the day, and the total absorption over the entire filament increases about 30% over the first half of the observing day before a gradual, steady decrease totaling 15%, which starts 3.5 hours prior to the disappearance of the section.

In three of the filaments, no section newly appears nor disappears, but there are variations in the amount of absorption within a section of the spine. In particular, these sections initially decrease in both absorption and absorption ratio, so the He I
Figure 2.5: Series of He/H absorption ratio maps of a small quiet Sun filament (2004-09-2) from 2004 Sept 19-20. The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. Note that the pixel threshold was not used here to ensure a complete picture of the ratio variations, so the background noise due to the chromosphere is still present. The ellipses signify when the filament section is increasing in absorption, and the rectangle identifies when it starts disappearing. All times are UT.
absorption is decreasing faster than Hα (Fig. 2.3(g)). Then as the absorption increases again in both lines, the absorption ratio also increases back to around the same constant value (Fig. 2.3(i)), which is similar for all three of these varying sections in addition to the newly appearing sections described above. Therefore, when starting from absorption ratio values that indicate a helium deficit, as the absorption increases in both lines, the absorption ratio rises up to a constant value, which lies between the helium deficit and surplus ratio values from the edge effects, and is roughly the same for all of the varying material.

Mass Loading and Draining

Since the varying material, especially in active filaments, has a higher velocity, it is possible that some of the changes in absorption and absorption ratio are due to Doppler effects. However, as described in § 2.2, these effects would be minor, and the Hα absorption would be expected to decrease more quickly due to Doppler shifting than absorption in He I since its bandpass is narrower. Furthermore, a line-of-sight velocity large enough to induce a Doppler shift would be expected to decrease the amount of absorption in Hα first, increasing the absorption ratio slightly, as occurs right before an erupting filament disappears in Hα. Therefore, the assumption that increases and decreases in the amount of Hα or He I absorption are directly related to changes in the column density of neutral hydrogen or helium is valid for varying material, as well.

The observed trends have ramifications in regards to models of mass loading and
draining (introduced in § 1.4). The behavior of the absorption ratio in association with increases in the absorption indicates that mass loading may be adding material with a constant composition. Newly appearing sections are observed to have a near-constant, average He/H ratio as they increase in absorption, as well as some noticeable activity of the material in the legs and along the spine, implying that mass is being loaded into the filament through the legs. For the three filaments that show "variations" in the amount of material in a section, the absorption ratio initially shows a helium deficit. When the filament absorption starts increasing, the He/H ratio also increases (from a helium deficit) up to near the average value, and then remains approximately constant. Some type of mixing could be involved, but it appears that a good amount of mass (with an average composition) is being added to the filament that overwhelms the previous helium deficit (which was possibly caused by cross-field diffusion; see below). Both of these trends point to mass loading in filaments being a process of material being transferred from the chromosphere up into the filament structure, likely through the legs and then along the spine. All three mechanisms of mass loading could possibly explain these observations, but the levitation model would not naturally cause the increased activity in the legs and spine, as opposed to the injection model or chromospheric evaporation. A follow-up study that included magnetic field data (that could identify the locations of flux emergence) would be necessary to distinguish which process of mass loading is dominant.

The trends for disappearing sections and material are less strong, and thus the
interpretation is more complicated. The observation that the He I absorption is
decreasing more quickly than Hα would be explained directly by cross-field diffusion.
This category of disappearing sections (and the three persisting sections that show
variations) appears to be more quiescent than the others, but the cadence makes it
difficult to determine conclusively without further work. When the absorption ratio
does not decrease as a section disappears, then the material is most likely moving
along field lines to other parts of the filament (as in the example from 2004 Sept 19)
or draining down the legs to the chromosphere. There are indications that this group
of filament sections are more active, with more movement along the spine, and that
the material disappears faster than the previous group, but again, a higher cadence
follow-up study would be needed. The more complex behavior of the absorption ratio
in the remaining disappearing filament sections is not surprising, given the dynamic
nature of filaments. It in unclear whether these changes represent a mixture of cross-
field diffusion and field-aligned movement or draining, or if some other process is
occurring. Overall, this array of findings on the small-scale dynamics in filaments
is important for understanding the physical processes of mass variation, and further
research following up on these results are described below (§ 2.5) and in the remaining
chapters.
2.3.3 Pre-Eruption Signature in the Composition

The inclusion of five erupting filaments in this study was intended as the first exploratory step in a search for any trend in the composition related to eruptions. A possibility was that cross-field diffusion could reduce the amount of mass from heavy neutrals, allowing the entire filament to buoyantly rise and erupt. The sample included a partial and a full eruption of two small quiet Sun filaments (2004-05-1 and 2004-05-3), failed partial eruptions of a small and a large quiet Sun filament (2004-06-1 and 2004-08-2), and a full eruption of a large intermediate filament (2004-12-3). For the eruption on 2004 Aug 11, a detailed analysis of observations with three-minute cadence was done to search for any effects visible on smaller timescales.

Combined Trends Including Homogenization of the Absorption Ratio

The results from these five filament eruptions show a distinct pattern: a day or more before the eruption starts, the erupting portion of all five filaments increases in both Hα and He I absorption, and at the same time, the absorption ratios change to a near-constant value over the entire section. That is, any helium deficit or surplus is wiped out as the absorption ratios nearly homogenize to an average value throughout the erupting section. There is also a high degree of activity in the pre-eruption material during the period of increasing absorption and homogenization. For example, filament 2004-05-3 shows edge effects initially (Fig. 2.6(c)), until it starts increasing in absorbing and the absorption ratios become more homogenized (Fig. 2.6(d)), starting
Figure 2.6: Series of He/H absorption ratio maps of an erupting filament (2004-05-3) from May 2004. An Hα disk image is provided in (f) for context. The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. The pre-eruption trends start between (c) and (d). The arrows point to edge effects, and the erupting section is circled in (g). All times are UT.

more than 1.5 days prior to the initiation of eruption (Fig. 2.6(h)).

The particular behavior of the absorption and absorption ratios observed prior to the eruptions varies slightly among the filaments. The three filaments that erupt while MLSO was taking observations (2004-05-3, 2004-06-1, and 2004-08-2) show a small asymmetry in the location of the eruption, in that the material expelled seems to start rising nearer to one leg a few minutes earlier than on the other side. Filament
2004-06-1 starts rising and then erupts only the highest portion of its material and settles back down in the corona, while in filament 2004-05-1, newly-appeared sections erupt less than a day after a visible connection is formed to the rest of the filament. The analysis of the full day of observations of the eruption on 2004 Aug 11 did not show anything significant in the absorption ratio immediately prior to, nor during, the eruption.

**Possible Sign of Mass Loading**

The period of concurrent increases in homogenization of the absorption ratio, increases in Hα and He I absorption, and a high level of activity by the filament material suggests a few possible physical explanations, and a potentially powerful tool for space weather prediction.

The active motions within the filament could continually mix the material and therefore increase the homogenization of the absorption ratios, and the increased absorption may be partially caused by temperature increases. Still, the highly active motions must be caused by something, with mass loading up the legs a strong possibility (although mass levitation could also be occurring to some degree). Chromospheric evaporation models have shown that increased flows up the legs cause more material to condense and load onto the filament, increasing the mass (Karpen et al., 2001), but it seems counterintuitive that filaments would undergo an extended period of mass loading, increasing their gravity, just prior to their rise and ejection from the corona. However, the corona is magnetically-dominated, so an increase in mass may be offset
by changes in the magnetic field. In addition, this pre-eruption trend of increasing absorption in Hα and He I and a near-constant absorption ratio is very similar to that for varying material (§ 2.3.2); it is possible that both are undergoing the same process of mass loading, maybe just to differing degrees or durations.

The potential importance of this initial finding of possible pre-eruption mass loading, which was inconclusive because of the small sample size, directly motivated the follow-up study described in the next section. It was hoped that better statistics on the length of the period of time in which homogenization and absorption increase, or better measurements of the amount that either parameter increases, might lead to a quantitative physical precursor to eruptions, allowing more accurate predictions about exactly when a filament will erupt and how massive it will be, which is highly valuable information for space weather forecasting.

2.4 Results from Filament Eruptions Study

The goal of this follow-up study on quiet Sun filament eruptions was to fully test the initial finding of possible pre-eruption mass loading, and to improve the statistics and method to yield quantitative results that could at least be partially compared to the various filament eruption mechanisms. Out of sixty-nine possible filament eruptions that were observed by MLSO between 2000 and 2006, thirty-eight were identified as good candidates due to the availability of sufficient observations. The nineteen eruptions selected for analysis have the most complete sets of observations
in both the Hα and He I spectral lines for several days preceding the eruptions, and they also span a range of sizes, shapes, locations on the disk, and eruption types, which was done with the intention to fully test and broaden the impact of any results (see Table 2.3).

Due to an improved technique in the modified IDL code that sped up the data processing, it was possible to analyze all pairs of observations from every day these filaments were visible in MLSO observations, so the cadence is three minutes instead of two per day. The method is largely the same as in the previous study, except that for partial eruptions, only the pixels in the erupting portion are included in the final calculations. In addition, to quantify the degree of homogenization and its change over time, the root-mean-square (RMS) deviation of the pixels' absorption ratios from the average value was calculated in each observation. While there is some scatter in this measure of the homogenization, a decrease in the RMS deviation is a good indicator of a general normalization of the relative abundances over the whole erupting structure. For context information post-eruption, observations from SOHO/EIT and the Large Angle and Spectrometric Coronagraph (LASCO) on SOHO were used to view the entire eruptions and connect them to the resultant CMEs. Most of the measured CME parameters are obtained from the CDAW LASCO CME catalog, although it was necessary to measure one CME using the MLSO/Mk4 K-coronameter (on 2003 June 11).

The expected results were to determine the strength of the pre-eruption trends

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<table>
<thead>
<tr>
<th>Event</th>
<th>Date &amp; Time of Eruption (UT)</th>
<th>Eruption Location (arcsec)</th>
<th>Filament Size</th>
<th>Homogenization Time Prior to Eruption (hr)</th>
<th>Percentage Change in Absorption</th>
<th>Eruption Type</th>
<th>Related CME, Position Angle &amp; Angular Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000-02-19, 21:00</td>
<td>[150, 750]</td>
<td>Medium</td>
<td>$t \approx 29$</td>
<td>+100%</td>
<td>Partial</td>
<td>00:30, 327°, 88°</td>
</tr>
<tr>
<td>2</td>
<td>2000-04-11, 19:30</td>
<td>[600, -600]</td>
<td>Large</td>
<td>$96 &gt; t &gt; 47$</td>
<td>+40%</td>
<td>Partial</td>
<td>20:30, 210°, 45°</td>
</tr>
<tr>
<td>3</td>
<td>2001-06-10, 18:00</td>
<td>[250, -550]</td>
<td>Medium</td>
<td>$94 &gt; t &gt; 46$</td>
<td>+120%</td>
<td>Failed</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>2001-08-17, 19:00</td>
<td>[-300, 450]</td>
<td>Small</td>
<td>$t &gt; 75$</td>
<td>+200%</td>
<td>Failed</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>2002-04-26, 16:45</td>
<td>[100, -550]</td>
<td>Large</td>
<td>$67 &gt; t &gt; 24$</td>
<td>+180%</td>
<td>Partial</td>
<td>18:52, 209°, 96°</td>
</tr>
<tr>
<td>6</td>
<td>2002-06-10, 18:55</td>
<td>[150, 450]</td>
<td>Large</td>
<td>$93 &gt; t &gt; 50$</td>
<td>+230%</td>
<td>Failed</td>
<td>None</td>
</tr>
<tr>
<td>7</td>
<td>2002-07-23, 09:00</td>
<td>[350, 600]</td>
<td>Large</td>
<td>$83 &gt; t &gt; 64$</td>
<td>+220%</td>
<td>Full</td>
<td>19:31, 319°, 116°</td>
</tr>
<tr>
<td>8</td>
<td>2003-06-11, 16:30</td>
<td>[-250, -600]</td>
<td>Large</td>
<td>$t &gt; 72$</td>
<td>+110%</td>
<td>Partial</td>
<td>18:50, 150°, 45°</td>
</tr>
<tr>
<td>9</td>
<td>2003-07-11, 20:30</td>
<td>[100, -600]</td>
<td>Medium</td>
<td>$t &gt; 67$</td>
<td>+80%</td>
<td>Partial</td>
<td>00:30, 196°, 118°</td>
</tr>
<tr>
<td>10</td>
<td>2003-07-11, 22:00</td>
<td>[350, 350]</td>
<td>Small</td>
<td>$t \approx 29$</td>
<td>+220%</td>
<td>Failed</td>
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</tr>
<tr>
<td>12</td>
<td>2004-06-02, 22:20</td>
<td>[-100, 250]</td>
<td>Small</td>
<td>$t \approx 27$</td>
<td>+10%</td>
<td>Failed</td>
<td>None</td>
</tr>
<tr>
<td>13</td>
<td>2004-08-11, 22:15</td>
<td>[200, -500]</td>
<td>Medium</td>
<td>$t \approx 29$</td>
<td>+90%</td>
<td>Failed</td>
<td>06:00, 195°, 40°</td>
</tr>
<tr>
<td>14</td>
<td>2004-12-24, 04:15</td>
<td>[250, 800]</td>
<td>Large</td>
<td>$t \approx 101$</td>
<td>+40%</td>
<td>Full</td>
<td>05:36, 291°, 92°</td>
</tr>
<tr>
<td>15</td>
<td>2005-06-07, 09:00</td>
<td>[-350, 450]</td>
<td>Medium</td>
<td>$t &gt; 65$</td>
<td>+40%</td>
<td>Full</td>
<td>10:24, 65°, 77°</td>
</tr>
<tr>
<td>16</td>
<td>2005-07-09, 20:40</td>
<td>[-500, 550]</td>
<td>Small</td>
<td>$43 &gt; t &gt; 28$</td>
<td>+5%</td>
<td>Partial</td>
<td>21:54, 75°, 62°</td>
</tr>
<tr>
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<td>2005-08-15, 17:50</td>
<td>[-300, -550]</td>
<td>Small</td>
<td>$42 &gt; t &gt; 25$</td>
<td>+780%</td>
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<td>23:54, 117°, 78°</td>
</tr>
<tr>
<td>18</td>
<td>2005-09-06, 10:00</td>
<td>[450, 400]</td>
<td>Large</td>
<td>$t \approx 60$</td>
<td>+30%</td>
<td>Full</td>
<td>21:12, 289°, 55°</td>
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<tr>
<td>19</td>
<td>2006-06-02, 03:00</td>
<td>[400, -550]</td>
<td>Small</td>
<td>$115 &gt; t &gt; 106$</td>
<td>+130%</td>
<td>Full</td>
<td>04:24, 246°, 42°</td>
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</table>
observed in the initial study, and possibly to probe the validity of filament eruption mechanisms. The broadened sample of filaments with a diverse set of physical properties severely reduced the possibility of any circumstantial conditions negating the trends. The actual findings confirmed our previously observed trends in the absorption ratio, absorption in both lines, and the level of activity prior to eruption. The increased likelihood that an extended period of pre-eruption mass loading is truly occurring is addressed in detail by a discussion including other observational pre-eruption trends, and how eruption models fit all of these observations. These results have been submitted to the Astrophysical Journal in a paper currently under review (Kilper et al., 2009).

2.4.1 Related Trend in Absorption Ratio and Absorption

The nineteen filaments analyzed in this study range in their size and shape, and they culminate in a mix of full, partial, and failed eruptions (Table 2.3). The key finding is that, in all cases, the He/H absorption ratio is nearly homogenized within the erupting part of the filament starting at least one full day before the eruption. Additionally, over the same time period, the filaments are active, with visible small-scale motions and an increase in vertical extent, and the amount of absorption in Hα and He I due to the filament material increases continuously (in most cases) from “activation” (which is a transition from a quiescent to an active state) up to the initiation of eruption.
A typical example of this behavior is the filament eruption from 2002 July 23, which is a full eruption of a large filament. On July 19, the filament is quiescent, showing a low level of activity and a stable size and shape (see Fig. 2.7(b)). The distribution of neutral H and He is slightly separated (Fig. 2.8(b)), with edge effects showing a relative helium deficit along the top and a surplus at the bottom. By July 20, two and a half days before the eruption, the filament has become active, with noticeable movement of the material within, and an apparent increase in vertical extent (Fig. 2.7(c)). During the period of high activity, the absorption ratio (and implicitly the composition) quickly homogenizes to approximately the same value throughout the filament (Fig. 2.8(c)); this effect is evident in the initial decrease of
Figure 2.8: Series of He/H absorption ratio maps of a large quiet Sun filament that erupts on 2002 July 23 at 09:00 UT. The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. The erupting filament is circled in (e). The absorption ratios become more homogenized spatially during the nighttime between (b) and (c). All times are UT.

the RMS deviation of the absorption ratio, which then changes little over the next three days (Fig. 2.9(d)). In addition, the total absorption in Hα and He I increases sharply at the time of homogenization and continues increasing up to the time of the eruption (Figs. 2.9(a) and 2.9(b)). The filament erupts fully on July 23 at 09:00 UT (as observed by EIT), and the resultant CME appears in LASCO/C2 later that day at 19:31. This eruption shows a clear and steady increase in absorption in Hα and He I, but aside from an initial decrease in the RMS deviation, the amount of homogenization in the absorption ratio does not continue increasing throughout the active period.
Figure 2.9: Six-day plots of the total absorption in Hα and He I, the average He/H absorption ratio, and its RMS deviation over the entire filament that erupts on 2002 July 23 at 09:00 UT. The total absorption is the sum of the erupting filament pixels’ percentages of absorption for each line. The brackets indicate the nighttime during which the absorption ratios become more homogenized, and the arrows denote the start of the eruption. The daily observing window at MLSO is between 17:00 and 02:00 UT.
Figure 2.10: Series of MLSO Hα 6563 Å images of a medium-sized quiet Sun filament during its failed eruption on 2004 Aug 11 at 22:15 UT, reformation on Aug 12, and second failed eruption on Aug 15 at 01:30 UT. The erupting filament is circled in (e) and (i). All times are UT.
Figure 2.11: Series of He/H absorption ratio maps of a medium-sized quiet Sun filament that erupts on 2004 Aug 11 at 22:15 UT, reforms on Aug 12, and erupts again on Aug 15 at 01:30 UT. The absorption ratio is plotted on the same log-scale for all maps, where a brighter pixel corresponds to a relative surplus of absorption in He I as compared to Hα, and a darker pixel shows a relative helium deficit. The erupting filament is circled in (e) and (i). The absorption ratios start becoming highly homogenized in (d). All times are UT.
A comparison of this eruption with the failed eruption on 2004 Aug 11 of a medium-sized filament better illustrates the range of the trends observed. This filament is initially quiescent, and Aug 7 shows clear edge effects (Fig. 2.11(a)). Early on Aug 9 there is a small increase in activity, and during Aug 10 the activity greatly accelerates during the build up to the eruption the next day at 22:15 UT (Fig. 2.10). The absorption ratios start changing slowly on Aug 9 (soon after Fig. 2.11(b)), but do not become significantly more homogenized until Aug 10 (Fig. 2.11(d)), as evidenced by the steep decline in the RMS deviation that day (Fig. 2.12(d)). There is a slow decrease in the RMS deviation from Aug 9 to 10 during a period of slightly higher activity, although this is partially caused by the Sun's rotation since a view from above would not see the vertical stratification of neutral H and He in quiescent filaments (discussed in § 2.3.1). The absorption in Hα increases slightly for several days prior to Aug 10 (Fig. 2.12(a)), and the He I absorption actually decreases (Fig. 2.12(b)), before a sharp increase in absorption in both lines that is concurrent with the increasing homogenization on Aug 10. EIT observations show the post-eruption filament rising high in the corona, draining its material down apparent magnetic field lines, then resettling with the footpoints and barbs in the same positions. A faint CME (with a weak leading edge and no discernible inner core) is observed in LASCO on Aug 12 at 06:00. The filament reforms about one day later (Fig. 2.10(g)), and maintains a high level of activity while again increasing in Hα and He I absorption, concurrent to decreases in the RMS variation. This high activity leads up to another failed
Figure 2.12: Six-day plots of the total absorption in Hα and He I, the average He/H absorption ratio, and its RMS deviation over the entire filament that erupts on 2004 Aug 11 at 22:15 UT, reforms on Aug 12, and erupts again on Aug 14 at 23:30 UT. The total absorption is the sum of the erupting filament pixels' percentages of absorption for each line. The *brackets* indicate the time period of slightly higher activity from Aug 9 to 10, after which the activity greatly accelerates, and the *arrows* denote the two eruptions. The daily observing window at MLSO is between 17:00 and 02:00 UT.
eruption on Aug 15 at 01:30 UT, which is quickly contained by overlying field. This filament shows only slight initial increases in homogenization and Hα absorption, and a decrease in He I absorption, for the two days of low activity, before a sharp increase in activity, homogenization, and absorption in both lines the day before the first eruption. The short period of high activity cannot illustrate well the long trend of increasing absorption, but the sharp decline in the RMS deviation during Aug 10 shows the rate of homogenization and its simultaneous start with the increase in absorption at around 20:00 UT. The second eruption provides a more typical example with the start of the observed trends approximately 50 hours prior to eruption initiation, and more gradual changes in the increasing absorptions and homogenization of the absorption ratio.

The combined trends of filament activation, near-homogenization of composition, and increases in absorption all start within about an hour of each other and at least one day prior to eruption for all nineteen of the filaments considered, regardless of size and type (Fig. 2.13). The RMS deviation of the absorption ratio decreases monotonically for twelve filaments during the active period, and three others show a decrease after a short initial increase, with the increase occurring simultaneously with a jump in the absorption. Although a high degree of homogenization is clear in the remaining four filaments (2001 Aug 17, 2003 July 11 22:00, 2005 Aug 15, and 2006 June 2, which are all small in size and greatly increase in Hα absorption; see Fig. 2.13), the value of the RMS deviation increases slightly during the active period.
Figure 2.13: Semi-log scatterplot for the nineteen filament eruptions, classified by size, of the percentage increase in the total absorption in Hα versus the number of hours prior to eruption when homogenization of the absorption ratio starts. The total absorption is the sum of the erupting filament pixels' percentages of absorption for each line. Note that the two small filaments in the lower-left erupted only a minor fraction of material, and the other four small filaments exhibited slight increases in the RMS deviation during their active periods.

However, these four filaments are quite small and appear to be already homogenized before activation (while they are still forming), and thus they had a relatively low RMS deviation at the start.

Between activation and eruption, the absorption increases in Hα and He I for seventeen of the nineteen filaments, with the exceptions being eruptions of only a small fraction of the material (2004 June 2 and 2005 July 9; see Fig. 2.13). The smallest filaments show a tendency to erupt the soonest after activation – about two days on average – while the largest filaments erupt no earlier than two days after
activation, with an average of about three days (see Table 2.3). However, the wide
spread in these times indicates that size is not a dominant factor in determining the
length of time between activation and eruption.

2.4.2 Possible Mass Loading Prior to Eruption

The combined trend of a high degree of spatial homogenization of the He/H ab-
sorption ratio, high level of activity, and increases in Hα and He I absorption, all
starting at least one day prior to every eruption considered, is a compelling result.
The spatially near-constant ratio supports the idea that the composition is approxi-
mately the same throughout the filament, which is clearly different from the separated
distribution of He and H for quiescent filaments showing edge effects. The change
from a separated distribution to a near-homogeneous composition could be partially
caused by a mixing of the material due to the motions that are readily apparent
in highly active filaments, but the combined trend (including absorption increases)
suggests the correct interpretation could be mass loading.

Several factors imply that the observed pre-eruption trends are unlikely to be arti-
facts of the data or the selected sample of filament eruptions. Current NLTE models
do not provide a viable alternative explanation for the large absorption increases in
pre-eruption filaments, since the average temperature would need to increase much
higher than is expected in filaments (recall § 2.2, and see discussion in Kucera &
Landi, 2008). In addition, the similar observational trend found for non-erupting
filament sections increasing in absorption (discussed in § 2.3.2) suggests that there could be a common physical process responsible for both. Finally, the range of sizes, shapes, locations relative to active regions, positions on the solar disk, and eruption types mean that none of these factors are likely to be affecting the observed results. The advantages of the mass loading interpretation for these pre-eruption filament sections are that it could cause the simultaneous increases in homogenization, activity, and absorption in both Hα and He I, with the added mass overwhelming the previous distribution of material and also causing some mixing as it moves within the filament. The continual increase in absorption up to the start of the eruption (for most of the filaments) would then mean that a day or more of mass loading precedes the initiation of eruption, and thus a significant increase in the weight of the filament material.

Comparing the Results to Eruption Models

The observed simultaneous trends of increased activity, absorption, and homogenization of composition – and its interpretation as an extended period of pre-eruption mass loading – have serious ramifications on the possible models to explain these eruptions. By combining these results with previous studies, a new explanation for eruptions is formulated here and discussed.

A large degree of mass loading could greatly increase the downward gravitational force on the filament, allowing a build up of stored magnetic energy prior to eruption, as described by Low et al. (2003). However, their picture requires significant mass loss to initiate the slow rise, and no such draining is observed in the filaments considered.
here, with an insignificant signal in the MLSO He I velocity data and little or no reduction in the amount of absorption in Hα and He I until the eruptions are well into their slow rise phases and high in corona.

Alternatively, "tether-weakening" of the overlying magnetic arcade would decrease the downward magnetic tension and, since flux cancellation converts the magnetic arcade into field lines wrapped around the filament, also increase the buoyancy of the flux-rope structure, countering gravity and allowing the filament to rise (Moore et al., 2001). Observations of localized newly-emerging flux could cause small-scale reconnection with the magnetic arcade, increasing the net upward force on the filament and possibly also allowing the cavity to expand, with the microflaring a signature of this tether-weakening reconnection (Sterling et al., 2007). However, most of the observational research on flux emergence have been case studies, and a recent statistical study of the relationship between CME initiation and flux emergence found that 40% of the CME source regions show flux decreases (Zhang et al., 2008). In a separate case study, Schmieder et al. (2008) found high activity and a strong decrease in the photospheric magnetic field network near the filament starting more than 24 hours prior to eruption, but no flux emergence nor small-scale brightenings, leading them to suggest that flux cancellation via photospheric diffusion slowly destabilizes the system. These studies on the pre-eruption magnetic field suggest that it plays some role in eruption initiation, possibly through different scales of tether-weakening and flux cancellation.
Flux cancellation and tether-weakening of the magnetic arcade may indeed contribute to the slow-rise prior to eruptions, and in combination with previous studies, there is a potential explanation for mass loading prior to eruption. In this picture, the small-scale reconnection causes the heating observed before and during eruptions (Kucera & Landi, 2008). If a low level of heating occurs near the footpoints, then the resultant mass loading via chromospheric evaporation (Antiochos & Klimchuk, 1991) would affect the amount of absorption and the He/H absorption ratio as described above. The flux cancellation would also increase the magnetic field strength of a flux-rope, both increasing its buoyancy and the size of the cavity, which was observed by Gibson et al. (2006). Therefore, the possible mass loading observed in this study might not be a direct cause of the eruption (e.g. as a mechanism to increase the downward force and spur reconnection below the filament as it sags), but rather a byproduct of some scale of tether-weakening, provided that the decrease in magnetic tension and increase in buoyancy, when combined, are greater than the increase in gravity. Once the net force on the filament is upward, it could rise buoyantly and erupt to form a CME, as modeled by Fan & Low (2003).

A confirmation and measurement of pre-eruption mass loading (e.g. using high temperature EUV observations, described in Chapter 3), along with a comparison of a measured rate of mass increase and a theoretical rate from chromospheric evaporation (under similar conditions) need to be calculated to fully test this scenario. A future study of the timing between various precursors to eruption – including increases in
cavity size, homogenization of composition, increases in absorption, heating, and flux emergence – would significantly advance the understanding of the physical mechanism of filament eruptions.

**Predicting Filament Eruptions and Space Weather**

The day or more of lead time between the homogenization of the He/H absorption ratio and the eruption suggests that this analytical method, in principle, could be used to predict when and where a filament eruption may occur. A real-time analysis of co-temporal observations of neutral H and He lines could be implemented with minimal user interaction to assist space weather forecasters or any observers wishing to capture an eruption with their instruments.

There are two main caveats that currently limit the effectiveness of such an approach. The spatial homogenization is also observed to occur in many non-erupting filaments, especially those that are forming or increasing in size (§ 2.3.2), making any prediction very uncertain, although a systematic study of varying filaments and a refinement of the method should improve the predictive capability. Secondly, the large spread in the amount of time between the start of homogenization and the actual initiation of eruption observed in this study (even when the eruptions are grouped by size) means that it would be difficult to pinpoint the time of eruption much in advance. Indeed, the method of a real-time analysis of the He/H absorption ratio is more suited to determine when eruptions will not occur, allowing advanced forecasting of “All Clear” periods when space weather conditions will be safe, instead of
when there is imminent danger.

2.4.3 Reformation in Failed and Partial Eruptions

Although not the main focus of the study on filament eruptions, there were also some preliminary findings regarding the reformation of non-erupting sections after partial or failed filament eruptions. Reformation of the erupting sections occurs only in failed eruptions (i.e. with no CME), and only for three of the six filaments in that category. The key difference is that for those that reformed, the material rises and at least partially disappears in Hα, but is still contained, producing no CME, and simply resettles with the footpoints and barbs in the same positions. This reformation happens rapidly in the failed eruption of the small filament on 2004 June 2 (after a few hours; Fig. 2.14) and takes much longer for the medium-sized one on 2004 Aug 11 (about 23 hours; Fig. 2.10(g)). In addition, about eight hours after the Aug 11 eruption, there is a "cavity-like" CME in LASCO/C2 from the correct position angle that lacks the inner core of filament material of a typical three-part CME (Fig. 2.15). The three failed eruptions that do not reform show indications that the material rises and then falls back down different field lines to other parts of the solar surface.

None of the full and partial eruptions, which do have related CMEs, show material reforming in the sections that erupt. For partial eruptions, the non-erupting filament sections do remain behind, including some that lifted during the eruption process and disappeared in Hα, yet quickly reformed, as in the filament on 2003 June 11
Figure 2.14: Series of MLSO Hα 6563 Å images of a small quiet Sun filament during its failed partial eruption on 2004 June 2 at 22:20 UT and reformation. The filament is starting to settle back down and reform in (c). The erupting material is circled in (c). All times are UT.

Figure 2.15: SOHO LASCO/C2 coronagraphs of a faint “cavity-like” CME following the failed eruption of a medium-sized quiet Sun filament on 2004 Aug 11 at 22:15 UT. The two images show at different times the (a) C2 coronagraph from 1.5 to 6 solar radii and (b) a difference image constructed from C2 observations. The faint CME is outlined. All times are UT.
Figure 2.16: Series of MLSO Hα 6563 Å images of a large quiet Sun filament that has a partial eruption on 2003 June 11 at 16:30 UT. The erupting section is circled in (a). The non-erupting filament sections reform by the next day in (d). All times are UT.

(Fig. 2.16). At other times the non-erupting sections seem barely disturbed by the nearby eruption.

Reconnection and Eruption Types

These initial findings on the reformation of filament sections after eruption indicate a few possibilities. Since the erupting sections in full and partial eruptions do lead to a CME (i.e. are not failed eruptions), and these sections do not reform, then their entire magnetic structure must be completely disrupted in the eruption, and is possibly expelled from the Sun along with the filament material (Gilbert et al., 2007b). In addition, because in partial eruptions the non-erupting sections remain
and reform very quickly (if they disappear at all), then the different sections of a filament may be mostly disconnected magnetically. When there is some effect on the non-erupting sections by the eruption, it could be caused either directly by changes in a common magnetic structure, or indirectly, by coronal MHD waves, for example.

The failed eruptions seem to come in two varieties, depending on whether or not the filament reforms. Some erupting filaments simply lift high in the corona and are either seemingly constrained above (2001 June 10), or there is possible reconnection within the material (2004 June 2; Fig 1.4, right) or above the material within the cavity (2004 Aug 11; Fig 1.4, middle), causing the portion below the reconnection point to resettle in the corona. Others rise into the corona and seem to reconnect with overlying field lines, down which the erupting filament material flows back to the solar surface.

A more complete study of filament reformation in partial and failed eruptions could do much to improve the understanding of magnetic connectedness among filament sections, which would help to distinguish between the various models of filament magnetic structure.

2.5 Future Studies Utilizing the Absorption Ratio

Several ideas have already been mentioned above for future work using the He/H absorption ratio. These and other possible studies involving similar techniques are listed here.
• In order to measure the rate at which the edge effects appear for comparison to the predictions of cross-field diffusion and gravitational settling, the He/H absorption ratio would need to be calculated in a few quiescent filaments with three-minute cadence (from MLSO) or the optimal cadence from optical instruments at other observatories, such as BBSO. Longer continuous coverage would also significantly improve the results, and the Global High-Resolution Hα Network can provide good Hα observations from Hawaii, California, New Mexico, France, Germany, Italy, China, and Japan. Obstacles remain in that not all observatories measure He I 10830 Å, and calibrating the many instruments would be a major challenge.

• Instead of increasing the duration of the observations, better temporal cadence and spatial resolution could be used to make measurements over shorter baselines. An observing program using Hinode/SOT Hα Dopplergrams in conjunction with He II 304 Å observations from STEREO/EUVI or from the Atmospheric Imaging Assembly (AIA) instrument on the Solar Dynamics Observatory (SDO; scheduled for launch in October 2009) would have a cadence under a minute for both. The He II line showing ionized helium emission would be useful, despite being a transition region line, because gravitational settling predicts that ionized He would be more concentrated in the lower part of the filament than neutral H, while cross-field diffusion does not. In addition, to remove potential problems from comparing plasma at very different temperatures,
Lyman-α could be compared with He II.

- In a similar idea, the vertical distribution of emission in He I could be compared with He II to determine whether there is a separation between neutral and ionized helium. Comparisons between a neutral calcium line (e.g. Ca I 8542 Å from SOLIS VSM at the National Solar Observatory) and ionized calcium (e.g. Ca II H 3969 Å on Hinode/SOT) should produce the same effect, presumably at a much faster because of its heavier mass and smaller FIP. Ca II H could also be compared to Hα to search for possible differences caused by gravitational settling (see § 4.2.2).

- Results from a comprehensive study on varying filaments using the He/H absorption ratio with three-minute cadence could impact several different lines of research. Calculations of mass draining and mass loading would improve the understanding of the physical mechanisms for mass variation. In addition, better knowledge of the behavior of the He/H absorption ratio for non-erupting varying filaments might allow better predictions on which filaments will erupt and after how long, leading to better estimates of the eruption time and the amount of erupting material, and yielding more accurate space weather forecasts. Such a study is now being carried out by two undergraduate students (advised by Dr. Alexander and assisted by me), who are collecting a large sample of 30+ varying filaments in MLSO, which will be analyzed by the improved IDL code and method used in the follow-up study on filament eruptions.
• An immediate goal is to conduct a study with disk, magnetic field, and cavity observations to compare the timing between various precursors to eruption – namely the increases in cavity size, homogenization of composition, absorption in H\(\alpha\) and He I, high activity, heating, photospheric diffusion, and flux emergence. New observations from Hinode, SDO, and especially the STEREO spacecraft, which provide two more vantage points for good observations of limb cavities during the build up to eruptions of filaments on the disk (from the Earth’s viewpoint), make it possible to study the timing between these various precursors to eruption, and to do so with good cadence and spatial resolution. In addition, tests of the newly proposed eruption mechanism could be conducted by comparing a measured rate of mass increase to a theoretical rate from chromospheric evaporation (under similar conditions), or by comparing measured changes in the magnetic field data to possible reconnection rates that would theoretically cause enough heating to induce chromospheric evaporation.

• Finally, a large statistical study of filament reformation in partial and failed eruptions could be performed to improve our knowledge of magnetic connectedness among filament sections and help determine the plausibility of the various models of filament magnetic structure. For example, the wire model, with its overlapping of coronal loops to compose the filament, would fit poorly with observations that show adjacent filament sections (separated from one another by barbs) to be largely disconnected at the legs. Likewise, a model proposing dis-
tinct (disconnected) flux-ropes for each filament section would be contradicted by observations of a partial eruption that also clearly pulls apart a neighboring, non-erupting section.
Chapter 3

EUV Continuum Absorption Study

Prominences are observed in extreme-ultraviolet lines as dark structures embedded in the brighter background of coronal radiation. Since prominence material is much cooler than coronal temperatures (at which the EUV spectral lines are formed), the usual complicated combination of atomic processes is reduced to the relatively simple process of continuum absorption, which is photoionization via photons energetic enough to overcome the ionization potential of the species (Osterbrock, 1970). For prominences, the main absorbers are neutral hydrogen, neutral helium, and singly-ionized helium, for which the cutoff wavelengths are 912 Å, 504 Å, and 228 Å, respectively. The photoionization cross-section is inversely proportional to the photon energy (Keady & Kilcrease, 2000); a plot of the average cross-section per atom/ion for an assumed prominence composition is provided in Fig. 3.1. The composition we use is based on spectral line models that calculate the helium abundance and ionization fractions, yielding our assumption of 45% $H^0$, 45% $H^+$, 9% $He^0$, and 1% $He^+$ (Heasley & Milkey, 1978; Anzer & Heinzel, 1999; Labrosse & Gouttebroze, 2004); note that protons do not contribute to the photoionization cross section because they are
Figure 3.1: Plot of the average photoionization cross-section per atom/ion in a prominence with an assumed composition (45% H$^0$, 45% H$^+$, 9% He$^0$, and 1% He$^+$). In this plot, the contributions to the total photoionization cross-section are separated by the absorbing species: those due to H$^0$ (below the blue line), He$^0$ (between the red and blue lines), and He$^+$ (between the black and red lines) start at 912 Å, 504 Å, and 228 Å, respectively.

already fully ionized. Since the vast majority of electrons are in the ground state in H and He (Heinzel et al., 1987b; Milkey et al., 1973), only the ground state photoionization cross-sections are used in these calculations. When analyzing EUV absorption, an important distinction must be made between the amount of emissivity blocking that is due to the lack of coronal emission (e.g. from a cavity or coronal hole) and the continuum absorption due to photoionization of the prominence material.

Based on previous work measuring the column densities and total mass (§ 3.1), the observations at several EUV wavelengths (described in § 3.2) were analyzed using
a method that calculates the absorption at every data pixel to create spatial maps of
the column densities and mass (§ 3.3). The results show neutral helium concentrated
in the lower part of quiescent prominences, and an active prominence with similar
spatial distributions for neutral hydrogen and helium (§ 3.4). These findings are
interpreted as possible indications of the effect of cross-field diffusion in quiescents
and mass loading in relation to higher activity (§ 3.5), in agreement with the results
of the He/H absorption ratio studies (in Chapter 2). This work is being prepared for
submission to the Astrophysical Journal.

3.1 Mass Measurements in EUV Lines

The earliest observations of continuum absorption in the EUV were done by Orrall
& Schmahl (1976) via the Harvard EUV spectrometer on ATM Skylab, and since then
a large number of prominences have been observed in the EUV by SOHO, TRACE,
STEREO, and Hinode. Measurements were first attempted by Kucera et al. (1998)
using several spectral lines observed with SOHO/CDS to estimate a column density
of neutral hydrogen on the order of $10^{18} \text{ cm}^{-2}$. They also found that continuum
absorption in a prominence on 1997 May 14 did not fit a model of absorption due
purely to photoionization, and calculations by Engvold et al. (2001) showed that
emission in hot lines from the PCTR can decrease the amount of measured absorption
in an erupting or heated prominence that could explain the deviation noted by Kucera
et al. (1998). Gilbert et al. (2005, 2006) were first to measure the total prominence
mass, and importantly took into account coronal radiation in front of the prominence
material, correcting an underestimation of the column densities; in a sample of 23 prominences, the total mass values ranged $1 \times 10^{14} - 2 \times 10^{15}$ g. These papers form the basis for the analytical technique used in this study (described below in § 3.2).

In particular, accounting for foreground radiation in front of the prominence is an important step in obtaining correct values of the column densities and masses (full derivation is in Gilbert et al., 2005). The percentage of coronal radiation in the foreground can be calculated via the 3-D position of the prominence, but only if the distribution of coronal radiation is well known. The technique of Gilbert et al. (2005) reduces the number of unknowns (and allows the separate determination of the foreground radiation) by using prominences “straddling” the limb – i.e. with material both on the disk and over the limb (see Fig. 3.2). Since little coronal radiation is emitted beneath the prominence nor from within the prominence material (i.e. $I_{1,p} \approx 0$), then there is no background radiation ($I_b$) behind material on the disk (i.e. $I_b^D \approx 0$), and the foreground radiation ($I_f$) and the amount of continuum absorption can be calculated from four intensity values ($I_b^L$, $I_b^D$, $I_f^L$, and $I_f^P$) and the scale height of the coronal emission, since the foreground radiation should decrease with altitude. In addition, geometrical measurements of the prominence height and depth are utilized to reduce error by better estimating the emission from beside the prominence material (in the cavity; $I_{0,p}$); note that this emission is relatively low anyway since the cavity has less material – and emits less radiation – than the average corona.

Related lines of work have contributed greatly to the understanding and interpre-
Figure 3.2: Schematics showing the different regions of coronal radiation from the side (top) and the observer's point-of-view (bottom) used in the calculation of foreground radiation. The different intensities are from the background ($I_b$), prominence region ($I_p$), or foreground ($I_f$), either along ($I_1$) or beside ($I_0$) the line-of-sight to the prominence, and on the disk ($I_D^D$) or over the limb ($I^L$). Figures are from Gilbert et al. (2005).

tation of the results presented here. Observations of several transition region lines were used to calculate a neutral He/H ratio of $N_{He I}/N_{H I} = 0.1 \pm 0.2$ (Del Zanna et al., 2004; Chiuderi Drago, 2005), which is comparable to the photospheric helium abundance and the calculation by Heasley & Milkey (1978). In another line of study, theoretical models of NLTE radiative transfer indicate a much larger opacity (sometimes 1-2 orders of magnitude) for continuum absorption in some EUV lines than the Hα opacity, corroborating observations of extended filament structures in EUV images, and implying the presence of more filament material than is visible in Hα.
Further research utilized these findings to determine the vertical extent of material in prominences, its 3-D structure, and the amount of emissivity blocking, which is due either to the lack of coronal emission in the cavity or to the continuum absorption of prominence material (e.g. Anzer & Heinzel, 2005; Schwartz et al., 2006). In an alternative approach to our technique, Heinzel et al. (2008) used Hinode/XRT observations to determine the cavity blocking and isolate the continuum absorption, and then calculated optical thicknesses at various wavelengths and a neutral hydrogen column density of $1 - 5 \times 10^{19} \text{ cm}^{-2}$. All of this previous research has contributed greatly to (and motivated) the study presented here.

### 3.2 EUV Observations

The observations used in this analysis are from SOHO/CDS (Mg X 625 Å and Mg IX 368 Å), SOHO/EIT (Fe XII 195 Å and Fe IX/X 171 Å), and TRACE (171 Å); see the summary in Table 3.1. This data set allows the determination of continuum absorption due to $H^0$ alone (at 625 Å), a mix of $H^0$ and $He^0$ (at 368 Å), and a combination of $H^0$, $He^0$, and $He^+$ (at 195 Å or 171 Å). These three instruments have been in operation several years, building up a sizable archive of prominence observations.

SOHO was launched in 1995 to the first Lagrangian point (L1) along the Earth-
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength</th>
<th>Spectral Bandpass</th>
<th>Resolution (arcsec/pixel)</th>
<th>Field-of-view (arcsec)</th>
<th>Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDS NIS1</td>
<td>368 Å</td>
<td>0.08 Å</td>
<td>4.06 × 1.68</td>
<td>120 × 240</td>
<td>68 mins</td>
</tr>
<tr>
<td>CDS NIS2</td>
<td>625 Å</td>
<td>0.14 Å</td>
<td>4.06 × 1.68</td>
<td>120 × 240</td>
<td>68 mins</td>
</tr>
<tr>
<td>CDS a</td>
<td>Both</td>
<td>&quot;</td>
<td>2.03 × 1.68</td>
<td>244 × 240</td>
<td>105 mins</td>
</tr>
<tr>
<td>CDS b</td>
<td>Both</td>
<td>&quot;</td>
<td>4.06 × 3.36</td>
<td>244 × 240</td>
<td>44 mins</td>
</tr>
<tr>
<td>EIT</td>
<td>195 Å</td>
<td>13 Å</td>
<td>5.25</td>
<td>Full Disk</td>
<td>12 mins</td>
</tr>
<tr>
<td>EIT</td>
<td>171 Å</td>
<td>12 Å</td>
<td>2.63</td>
<td>Full Disk</td>
<td>6 hours</td>
</tr>
<tr>
<td>TRACE</td>
<td>171 Å</td>
<td>6.4 Å</td>
<td>0.5</td>
<td>384 × 384</td>
<td>60 s</td>
</tr>
</tbody>
</table>

a Program for the CDS observations of a prominence on 1996 July 31.
b Program for the eighteen successive CDS observations on 2005 May 18.

Sun line, and it includes a wide array of telescopes and particle detectors on board — twelve instruments total. The Coronal Diagnostic Spectrometer (CDS) was designed to observe EUV emission lines with high spectral resolution (to separate lines) and spatial resolution good enough to identify smaller features of the solar atmosphere. It is comprised of the Grazing Incidence Spectrometer (GIS; primarily shorter wavelengths) and the Normal Incidence Spectrometer (NIS; Harrison et al., 1995). The most useful CDS prominence observations were done via a narrow slit (of a few arcseconds) by the NIS instrument. To construct 2-D images, several adjacent slit observations (with exposure times of 1 — 2 minutes) were rastered and combined. The Extreme-ultraviolet Imaging Telescope (EIT) on SOHO has a full-disk field-of-view (FOV) and images the corona with wide bandpass filters in four EUV channels.
(Delaboudinière et al., 1995). The improved capabilities of the focused Transition Region And Coronal Explorer (TRACE) mission, launched in 1998, were designed to provide observations of coronal dynamics at finer scales (Handy et al., 1999). TRACE observes the solar atmosphere in UV and EUV channels with very high spatial resolution, marking an improvement over EIT, but its FOV only covers a fraction of the full Sun. Note that the wide-bandpass imagers in EIT and TRACE detect a mix of spectral lines and cannot determine temperatures as well as a spectrometer, but their advantages include larger FOVs and a higher cadence. The specific parameters of the observations from these instruments vary, depending on the observing program (Table 3.1).

An examination of CDS observations from 1996-2007 identified sixty-eight prominences as possible candidates for our absorption study. Twenty of these were selected for analysis, based entirely on the availability of sufficient observations in the desired CDS wavelengths, good signal-to-noise in the data, the full prominence within the FOV, and the presence of prominence material straddling the limb, which is necessary to utilize the method of Gilbert et al. (2005). Of the prominences analyzed, eleven had either insufficient background coronal radiation on either side of the prominence material (and within the FOV), or inconsistencies in the background coronal radiation on the disk or limb due to active regions, coronal holes, or an irregular cavity shape; in only nine could the background coronal radiation (minus the emissivity blocking of the cavity) be correctly interpolated from the observations.
Most of the CDS observations analyzed here were organized by T. Kucera via SOHO Joint Observing Program 63, in which the NIS $4 \times 240$ arcsec slit was rastered over 30 steps to create an image with a FOV of $120 \times 240$ arcsec. The limited FOV meant that only small prominences were targeted. Two of the prominences used were observed with other programs: one observation of a medium-sized prominence on 1996 July 31, and eighteen observations of a large active prominence on 2005 May 18 (denoted in Table 3.1). EIT 195 Å observations simultaneous to the CDS observations were available for most of the prominences, but in 171 Å, only synoptic EIT observations from every six hours were available. Only one of the prominences with good CDS data was also observed by TRACE, on 1999 Mar 20 at 171 Å. This lack of high resolution, coordinated EUV observations helped to motivate a follow-up study (described in Chapter 4).

### 3.3 Constructing Maps of Prominence Mass

The analysis of the EUV observations was done using an IDL code developed specifically for this project. First, the observations are read and prepped (i.e. cleaned, dark-corrected, flat-fielded, and despiked to remove cosmic ray hits) using procedures and calibrated images in the SSW package. A common FOV and color table is used for all of the images so that consecutive observations can be compared more accurately (Fig. 3.3(a)). Note that the observations are not aligned among the different instruments at this point since the alignment would need to be done manually, via the iden-
tification of similar features in each image, which can be done post-processing. The user then selects the pixels in the image containing prominence material (Fig. 3.3(b)), determines the limb radius, and estimates the depth of the prominence and the mean altitude of the material from the solar surface.

The remainder of the procedure is repeated ten times to reduce statistical error since the mass calculation is highly sensitive to the values of the pixels chosen (see below). The scale height of the coronal emission is calculated as the slope of a semi-log plot (versus the radius). Positions on each side of the prominence are selected from which the background radiation will be interpolated. It is very important to remove any bias in these points that may occur due to increased or decreased local emission (e.g. from a small active region, plage region, or a coronal hole), and to interpolate from points within the cavity, otherwise the emissivity blocking from a cavity will be incorrectly attributed to continuum absorption by prominence material. Since the amount of coronal radiation along a radial scan of the quiet Sun generally follows a symmetric logarithmic distribution that is peaked at the edge of the limb, we were able to correct for small deviations in coronal emission by using a power law to smooth over these inconsistencies and provide a much better estimate of the coronal radiation around the prominence material. The code automatically interpolates the amount of coronal emission at all data pixels of the prominence between these two corrected radial scans, effectively "deleting" the prominence material (Fig. 3.3(d)).

Next, the method of Gilbert et al. (2005) is used to determine the foreground
Figure 3.3: Series of images showing the steps in the process of interpolating the coronal emission around the prominence material so that accurate calculations of the continuum absorption and column densities can be made at each data pixel. This small quiet Sun prominence was observed by SOHO/CDS in Mg X 625 Å on 1999 Mar 20 at 14:05 UT.
radiation by selecting data pixels both on the disk and over the limb that contain prominence material with the same column density. The foreground radiation, combined with the depth of the prominence (estimated from its width and inclination), is used to infer the amount of coronal radiation behind the prominence material, and the formula for continuum absorption provides the column density in each data pixel (of the atoms/ions absorbing at the wavelength of the observation). Using the assumed composition, a column mass for each data pixel is calculated, and these masses are summed over the prominence area to obtain a total mass. Finally, a 2-D map of the column mass at each data pixel is plotted.

Some results can be obtained without any assumptions about the helium abundance or ionization fractions. For prominences observed simultaneously in 625 Å and 368 Å, a ratio between the amount of neutral helium to neutral hydrogen can be obtained directly. Since both of these are CDS lines (and therefore co-aligned), a map of the neutral ratio is constructed by comparing the continuum absorption in these two lines at every data pixel. Note that in the assumed composition the ratio would be $He^0/H^0 \equiv n_{He^0}/n_{H^0} = 0.09/0.45 = 0.2$. For simultaneous observations of 625 Å, 368 Å, and either 195 Å or 171 Å, the ionization fraction of helium ($x_{He} = n_{He^+}/n_{He^0}$) can also be calculated, but problems arise because of possible misalignment between instruments, and especially from vastly different line opacities. If 625 Å and either 195 Å or 171 Å observations are available and a helium ionization fraction is assumed, then the ratio of the total amount of all helium to neutral hydrogen ($n_{H^0}/n_{He_{total}}$)
can be calculated. However, the same problems of possible instrument misalignment and different line opacities surface in the analysis.

**EUV Absorption Error Analysis**

There are many possible sources for large errors in this analysis, but most of them have been mitigated by careful data selection, repetition of the calculations, and testing for possible instrumental effects. Significantly reducing the remaining error would require a sophisticated NLTE model that could, for example, correct for high opacities and infer the actual column density from the observed, possibly underestimated amount of continuum absorption. Note that the TRACE and CDS observations have not been aligned to the full-disk observations of EIT, since the highly different opacities makes it difficult to compare any lines except for the two from CDS. However, manual distinction of features is sufficient to allow comparisons in the mass distributions in observations from different instruments.

The analytical code used here was designed to be fast and easily repeatable, and to remove random error as much as possible. The main source of error results from the comparison of pixels at the limb/disk interface, which is used to determine the foreground radiation. The resulting column density measurement depends logarithmically on changes in the intensity of those pixels, and is therefore very sensitive to the comparison of those values. By repeating the calculation ten times while using several pairs of data pixels to estimate the foreground radiation, interpolating the background slightly differently, and recalculating the scale height of the coronal
emission, this error was markedly reduced. The repetitions mean that the foreground radiation (and the column densities and total mass) is calculated from a larger sample of the pixels comprising the prominence, so the effect of individual pixel fluctuations in the data is mitigated. Trial runs showed that ten repetitions were enough to reduce this source of error; a greater number of repetitions did not continue decreasing the spread in the calculated masses.

Error was also reduced by prudent data selection and the analysis of a larger set of prominences. Excluding prominences near active regions, coronal holes, or with an unclear cavity shape decreased possible effects from an incorrect determination of the coronal radiation around the prominence. In addition, any prominences showing a large amount of emission from the prominence material were excluded from the analysis (625 Å, 368 Å, and 171 Å are all at $10^6$ K), although note that a relatively small amount of emission was tolerated (e.g. the 1997 May 14 prominence; discussed by Engvold et al., 2001).

Instrumental effects were tested by several comparisons, and all were found to be relatively insignificant. Analyses of simultaneous TRACE and EIT observations (at either 171 Å or 195 Å) measured similar mass values, despite different resolution, exposure times, instrumentation, etc. There were also no changes detected between: different exposure times and pixel sizes for EIT 195 Å observations, different pixel binnings for identical STEREO/EUVI 195 Å observations, comparable prominence observations before and after loss of communication with SOHO in June 1998, and
the different observing programs used for the CDS observations. Furthermore, even though 171 Å is formed at the same temperature as the two CDS lines, it always yields a much higher mass, indicating that the spectral line temperature is not the dominant factor. The only parameter that really affects the mass calculations is the EUV wavelength, either because of different temperatures for the spectral lines, or due to higher opacities in lines with larger photoionization cross-sections (see Fig. 3.1 above).

Indeed, the pattern of different relative masses measured among the spectral lines may be due to different opacities in these EUV lines. Theoretical models have calculated the opacity in 195 Å to be similar to Hα, but the opacity in 625 Å is approximately 33 times larger (Anzer & Heinzel, 2005; Heinzel et al., 2008). The analysis presented here might also be sensitive to possible saturation of the continuum absorption in 625 Å, which results in the smaller mass calculations from 625 Å (see below). Therefore the total mass measurements from the 195 Å observations are the most trustworthy quantitatively, but there is still important qualitative information in the spatial maps of the mass measured from the other spectral lines.

3.4 Results of Mass Determinations

The results from the continuum absorption mass calculations of the 82 observations (in four spectral lines) of the nine prominences are summarized in Table 3.2. Note that these total prominence masses are calculated using the assumed compo-
sition of 45% $H^0$, 45% $H^+$, 9% $He^0$, and 1% $He^+$. The prominences average the lowest mass values in 625 Å and the highest in 195 Å. For each set of observations in the various lines, a pattern emerges: the lowest mass is always measured in 625 Å, followed 368 Å, and then usually 171 Å before 195 Å. As documented in previous studies, the prominences appear more extended in the CDS lines than in the shorter wavelengths.

The values for the neutral abundance ratio $He^0/H^0$ are all higher than 0.2 – i.e. the ratio expected from previous studies (§ 3.1). In multiple observations of the same prominence, the ratio values are generally consistent, except for a 19% decrease in the prominence’s neutral abundance ratio on 1999 March 23. More telling is the spatial distribution of this ratio. Of the seven prominences observed in both CDS lines, four clearly show more 368 Å continuum absorption in the lower part of the prominence than in 625 Å (1996 July 31, 1997 May 9, 1999 March 20, and 1999 Oct 12), while one shows a slight indication of this same pattern (1997 Aug 7). In addition, the prominence on 1999 June 2-3 also appears to show more absorption in the lower part in both 171 Å and 195 Å than in 625 Å, as do the prominences on 1996 July 31, 1997 May 9, and 1999 March 20. The implication is that the increase in absorption in the lower part of the prominences is due to the inclusion of helium as an absorber of coronal radiation. As an example, the prominence on 1999 March 20 at 14:05 UT shows much more continuum absorption (and therefore mass) in the lower part of the prominence in 368 Å and 195 Å (Fig. 3.4), and the prominence observed on 1997 May 9
Table 3.2. Mass Calculations of Quiet Sun Prominences

<table>
<thead>
<tr>
<th>CDS Obs. Date</th>
<th>CDS Obs. Time</th>
<th>Solar Angle</th>
<th>625 Å Mass $(10^{13} \text{ g})^a$</th>
<th>368 Å Mass $(10^{13} \text{ g})^a$</th>
<th>171 Å Mass $(10^{13} \text{ g})^a$</th>
<th>195 Å Mass $(10^{13} \text{ g})^a$</th>
<th>He°/H° Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-07-31</td>
<td>10:58</td>
<td>317°</td>
<td>8.25 ± 1.28</td>
<td>8.31 ± 1.71</td>
<td>15.50 ± 2.48</td>
<td>21.41 ± 1.96</td>
<td>0.23</td>
</tr>
<tr>
<td>1997-05-09</td>
<td>22:18</td>
<td>228°</td>
<td>4.65 ± 0.62</td>
<td>5.99 ± 1.27</td>
<td>7.13 ± 2.03b</td>
<td>13.06 ± 2.21</td>
<td>0.27</td>
</tr>
<tr>
<td>1997-05-14</td>
<td>06:31</td>
<td>58°</td>
<td>1.04 ± 0.01</td>
<td>1.32 ± 0.21</td>
<td>...</td>
<td>...</td>
<td>0.23</td>
</tr>
<tr>
<td>1997-08-07</td>
<td>19:56</td>
<td>47°</td>
<td>1.29 ± 0.37</td>
<td>1.78 ± 0.60</td>
<td>...</td>
<td>...</td>
<td>0.34</td>
</tr>
<tr>
<td>1999-03-20</td>
<td>14:05</td>
<td>208°</td>
<td>3.54 ± 0.54</td>
<td>4.16 ± 0.68</td>
<td>7.29 ± 2.56b</td>
<td>11.04 ± 2.81</td>
<td>0.28</td>
</tr>
<tr>
<td>1999-03-23</td>
<td>11:56</td>
<td>210°</td>
<td>2.93 ± 0.59</td>
<td>5.46 ± 0.85</td>
<td>...</td>
<td>6.72 ± 1.87</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>13:03</td>
<td>210°</td>
<td>2.67 ± 0.40</td>
<td>3.38 ± 0.77</td>
<td>10.93 ± 3.37</td>
<td>10.15 ± 2.10</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>14:11</td>
<td>152°</td>
<td>3.35 ± 0.89</td>
<td>4.72 ± 0.12</td>
<td>...</td>
<td>7.79 ± 1.41</td>
<td>0.44</td>
</tr>
<tr>
<td>1999-06-02</td>
<td>18:14</td>
<td>152°</td>
<td>2.96 ± 0.77</td>
<td>...</td>
<td>8.02 ± 2.30</td>
<td>10.56 ± 2.49</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>19:21</td>
<td>152°</td>
<td>3.42 ± 0.74</td>
<td>...</td>
<td>13.45 ± 3.75</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1999-06-03</td>
<td>06:30</td>
<td>210°</td>
<td>2.70 ± 0.86</td>
<td>...</td>
<td>5.38 ± 1.65</td>
<td>11.83 ± 3.25</td>
<td>...</td>
</tr>
<tr>
<td>1999-10-12</td>
<td>14:32</td>
<td>310°</td>
<td>3.79 ± 1.14</td>
<td>5.34 ± 1.35</td>
<td>...</td>
<td>...</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>15:37</td>
<td>310°</td>
<td>3.52 ± 0.83</td>
<td>4.23 ± 1.14</td>
<td>...</td>
<td>...</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>16:41</td>
<td>310°</td>
<td>2.86 ± 0.57</td>
<td>3.90 ± 1.01</td>
<td>8.73 ± 3.08</td>
<td>10.85 ± 4.35</td>
<td>0.42</td>
</tr>
<tr>
<td>2005-05-18</td>
<td>10:05-22:30</td>
<td>295°</td>
<td>4.83 ± 1.74</td>
<td>...</td>
<td>14.16 ± 4.21</td>
<td>13.07 ± 3.52</td>
<td>...</td>
</tr>
</tbody>
</table>

Averages among the prominences:

<table>
<thead>
<tr>
<th>CDS Obs. Date</th>
<th>CDS Obs. Time</th>
<th>Solar Angle</th>
<th>625 Å Mass $(10^{13} \text{ g})^a$</th>
<th>368 Å Mass $(10^{13} \text{ g})^a$</th>
<th>171 Å Mass $(10^{13} \text{ g})^a$</th>
<th>195 Å Mass $(10^{13} \text{ g})^a$</th>
<th>He°/H° Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.64</td>
<td>4.29</td>
<td>10.02</td>
<td>13.01</td>
<td>0.32</td>
</tr>
</tbody>
</table>

^a Total mass is based on continuum absorption at each wavelength and an assumed composition, and the noted statistical error is estimated from the results of ten analyses.

^b Averaged over two EIT observations for 1997-05-09, and a TRACE and EIT observation for 1999-03-20.

^c Masses for 2005-05-18 averaged over eighteen 625 Å, three 171 Å, and twelve 195 Å observations.
also displays well the trend of more absorption and mass in 368 Å and 195 Å than in 625 Å (Fig. 3.5). Two of the prominences show approximately the same distribution of continuum absorption in both CDS lines (1997 May 14 and 1999 March 23); both are short and very small, but one is thin and mostly transparent, while the other exhibits an abundance of continuum absorption.

The many consecutive observations of an active prominence on 2005 May 18 provide a contrasting example. This prominence shows activity throughout the day, including two instances when a small volume of mass appears to rise up the northern leg and is deposited in the spine; the second occurrence is displayed in Fig. 3.6. Moreover, the spatial distribution of the continuum absorption (and the mass) is very similar for 625 Å and 195 Å, aside from the higher opacity in 625 Å making the prominence appear more extended. This result implies that the neutral hydrogen and helium are causing continuum absorption at the same locations, and thus neutral hydrogen and helium have comparable spatial distributions in this active prominence.

3.5 Discussion of Mass Values Obtained

The measurements of the continuum absorption in these EUV lines provide some information about the column densities and total mass, but more clearly, they illuminate similarities and differences in the spatial distributions of the absorption when due to neutral hydrogen alone, compared to when helium is also contributing to the absorption. Recall that an assumed composition of 45% $H^0$, 45% $H^+$, 9% $He^0$, and
Figure 3.4: The original observations, interpolated coronal radiation, and mass maps of a small quiet Sun prominence on 1999 March 20. In the mass maps, a brighter pixel corresponds to greater mass, and the scaling for 195 Å is three times greater. The solar grid is included for easier comparison of features. All times are UT.
Figure 3.5: The original observations, interpolated coronal radiation, and mass maps of a small quiet Sun prominence on 1997 May 9. In the mass maps, a brighter pixel corresponds to greater mass, and the scaling for 195 Å is three times greater. The solar grid is included for easier comparison of features. All times are UT.
Figure 3.6: The original observations and mass maps of an active medium-sized quiet Sun prominence on 2005 May 18. In the mass maps, a brighter pixel corresponds to greater mass, and the scaling for 195 \AA{} is four times greater than in 625 \AA{}. The solar grid is included for easier comparison of features. All times are UT.
1% \( \text{He}^+ \) has been used to calculate the prominence masses. The mass values can change significantly if this composition were modified – for example, the 625 Å mass would double if hydrogen were 75% ionized, and the 195 Å mass would be halved if the helium abundance were 30% (instead of 11%). This remains a possibility to explain the different mass measurements depending on the wavelength, but seems unlikely due to the findings of NLTE models of different opacities in the EUV lines.

The increased amount of measured mass in the lower part of the material when helium is also absorbing continuum radiation implies that the neutral helium is concentrated in the lower portion of the structure, as compared to neutral hydrogen, in five of the prominences analyzed (and partially so in another). In addition, the active prominence on 2005 May 18 shows apparent movement of pieces of material up its northern leg on two separate occasions, and both times the distribution of the continuum absorption and mass is approximately the same for both lines, meaning that the neutral hydrogen and helium distributions are very similar.

These results lead to conclusions parallel to those of the earlier study on the He/H absorption ratio in filaments (in Chapter 2). The concentration of neutral helium in the lower part of the prominences measured here is the same interpretation for the edge effects seen in quiescent filaments (§ 2.3.1), and the mixed distribution of helium and hydrogen in the active prominence undergoing apparent mass loading up one of the legs corresponds to the same physical process proposed for filaments increasing in absorption that have a near-constant absorption ratio (§ 2.3.2). The combination of
the results from these two studies, which used very different techniques, strengthen the results of both since the possible effects on the He/H absorption ratio in filaments due to changes in the temperature or velocity would not affect the EUV continuum absorption measurements, and different opacities (in the EUV lines observed by CDS) would not be a problem for the comparison between Hα and He I 10830 Å. Therefore the He/H absorption ratio is a good proxy for the composition, and the difference in continuum absorption seen in the lower part of the prominences in this study may truly be caused by more neutral helium being located there, instead of any effects from different opacities, heating, or instrumentation.

The 195 Å mass values obtained are comparable to those calculated by Gilbert et al. (2005, 2006), given that the prominences analyzed here were selected to be small. The pattern of the lowest mass calculated being from the 625 Å observation and the highest from 195 Å might indicate that the much higher opacity at 625 Å (compared to 195 Å; Anzer & Heinzel, 2005) may be responsible for a saturation of the continuum absorption and an underestimation of the mass from 625 Å (previously suggested by Heinzel et al., 2008). The opacities at 368 Å and 171 Å have not yet been modeled, but our observational results indicate that the 368 Å opacity would be slightly lower than for 625 Å, and the opacity at 171 Å would be similar to 195 Å, which would match well with the theoretical photoionization cross-sections at these wavelengths (Fig. 3.1). The smaller masses calculated from 171 Å may be due to emission at its cooler line temperature of $1.0 \, MK$ (compared to $1.5 \, MK$ for 195 Å;
Phillips et al., 2005), but the true cause cannot be determined without an NLTE model of prominence continuum absorption at 171 Å. The different opacities would also explain why the $\text{He}^0/\text{H}^0$ neutral ratios were measured to be much higher than the expected value. Overall, the mass calculations from the 195 Å images appear to give the most accurate values, which is supported by the results of the other studies. However, further work is necessary before all of the measured masses can be considered completely reliable.

Better NLTE spectral diagnostics need to be modeled for all of these EUV lines to determine the correct opacities that compare well to the observations. The findings of this observational study could be used to test the accuracy of NLTE models, which would, in turn, allow our observational analysis to better determine the composition of prominences. Additional observations using newer observatories, with their highly-improved spectral resolution and cadence, would also advance this line of work by expanding the sample and searching for shorter timescale variations; the Atmospheric Imaging Assembly (AIA) instrument on the Solar Dynamics Observatory (SDO) would be invaluable to such a study. A collaborative research effort following up on the results and suggestions in Heinzel et al. (2008), such as improved NLTE modeling and new multi-wavelength EUV observations by Hinode/EIS, would greatly improve the understanding of the observational results of this study, and could lead to accurate determinations of the helium abundance and the ionization fractions in prominence material – parameters that are critically important to modelers of promi-
nence support, waves and oscillations, and prominence formation.
Chapter 4

Study Using the High Resolution and Cadence of New Observatories

The improved capabilities of newer instruments make it possible to further the understanding of the physical processes occurring in prominences. In particular, higher spatial resolution shows more detail in the material’s distribution, and better cadence allows tracking of its dynamics over shorter timescales. Moreover, simultaneous observations over many wavelengths can cover a wide range of plasma temperatures, yielding information about heating and its possible causes in relation to prominence dynamics.

The study presented in this chapter was motivated by results from the analyses of the He/H absorption ratio (Chapter 2) and EUV continuum absorption (Chapter 3), which both included possible indications of cross-field diffusion in quiescent prominences and mass loading in active (including pre-eruption) prominences. Those previous findings, while enhancing our understanding of the physical processes important in prominences and the interactions between prominence mass and the behavior of its magnetic field, were insufficient in quality or quantity to reach definitive con-
clusions. In the newer research in this chapter, we utilized new data sets to expand upon the previous studies to overcome some of the instruments' limitations.

The ground-based observations from MLSO (i.e. Hα and He I 10830 Å) have relatively low spatial resolution and are affected by atmospheric distortion, limiting the scale of the perceivable features to 5 Mm or greater (see § 2.1); also, the limited daytime observing hours (~ 8 hours per day) reduces MLSO's ability to monitor dynamics with timescales between a few hours and a few days (e.g. cross-field diffusion). The existing EUV observations (described in § 3.2) also have limitations. Specifically, the cadence of SOHO/EIT is only one full-Sun image every twelve minutes in 195 Å (and less often in the other lines), and pixel binnings smaller than 5.25 arcsec have a low signal-to-noise ratio (or include too many cosmic ray hits, when a longer exposure time is used to compensate). This is problematic for the continuum absorption measurements, which require a strong signal uncorrupted by spurious artifacts in the data. TRACE EUV observations have a higher resolution and cadence than those of EIT, but because of its limited FOV, many prominences are missed by TRACE because other portions of the Sun were being targeted. SOHO/CDS has an even smaller FOV, and some of the available prominence observations did not include the wavelengths desired for our analysis of the prominence mass composition, since we desire Mg X 625 Å, which shows H0 absorption, and Mg IX 368 Å, which shows absorption due to H0 and He0. Furthermore, the CDS prominence observations seldom lasted longer than a few hours, inhibiting a large, statistical study of dynamical evolution.
in the mass composition.

To extend the science beyond our initial findings (from the analyses of the existing data), improved observations were required: higher spatial resolution to show more detail of small-scale structure, better cadence to study dynamics on shorter timescales, longer duration (for CDS, in particular) to study mass variation over extended periods, and greater wavelength coverage so that the different observations could be compared to yield information about the mass composition. Fortunately, instruments with such advanced capabilities were recently launched on the STEREO and Hinode spacecraft. Therefore, we augmented the MLSO, SOHO and TRACE observations with prominence observations from STEREO and Hinode. In order to achieve the best results when multi-wavelength observations from many different instruments are focused on the same object, all of the observatories must be coordinated to target the same prominence at the same time. The coordination of instruments is handled by a formal process for proposing and executing a targeted observing campaign (see below).

STEREO consists of two nearly identical spacecraft (Ahead and Behind) that were launched into specific orbits that result in STEREO-A and STEREO-B drifting ahead and behind the Earth, respectively. They both separate from the Earth-Sun line-of-sight by approximately 22° per year, providing two additional viewpoints of the Sun and a basis for 3-D stereoscopic reconstructions of the solar corona (Kaiser et al., 2008). Each STEREO spacecraft has two instrument packages that combine to make
in-situ measurements of the interplanetary plasma and magnetic field (IMPACT and PLASTIC), an instrument observing radio bursts from the Sun (SWAVES), and the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) package, which contains a heliospheric imager, two white-light coronagraphs, and the Extreme Ultraviolet Imager (EUVI). EUVI-A and EUVI-B image the full solar disk in the same four EUV wavelengths as EIT, but with much better resolution, cadence, and signal-to-noise (see Table 4.1 below; Howard et al., 2008). After an initial commissioning phase, STEREO began normal operations in early 2007.

The Japanese satellite Hinode started its operations in fall 2006, and consists of the X-ray Telescope (XRT), the EUV Imaging Spectrometer (EIS), and the Solar Optical Telescope (SOT; Kosugi et al., 2007). SOT has a 0.5 m primary mirror and an advanced correlation tracking system that yields optical images with extremely high spatial resolution and image stabilization (due to an advanced correlation tracking system; Tsuneta et al., 2008). Three instruments compose SOT: the Spectropolarimeter (SP) measures photospheric vector magnetograms; the Broadband Filter Imager (BFI) has very high spatial resolution, a wide spectral bandwidth, and a small FOV (218 × 109 arcsec) that can completely contain a small-sized prominence (or medium-sized prominences that are inclined); the Narrowband Filter Imager (NFI) has a much narrower bandpass with slightly coarser spatial resolution and a larger FOV (328 × 164 arcsec).

The striking initial results from high resolution SOT observations were particularly
promising for prominence research. In quiescent prominences observed in chromospheric spectral lines (Hα and Ca II H), Berger et al. (2008) observed dark apparent upflows of heated material (which are dark because the material is heated enough so that it is emitting much less at chromospheric temperatures) that appears to be rising buoyantly, and bright downflows of material that may be emitting more because hot material is cooling as it falls (Fig. 4.1(a)). These small-scale flows are very rarely seen in the wealth of ground-based optical observations, yet SOT found seven examples within a year. In relation to the work in this thesis, such vertical flows would increase the theoretical timescales for cross-field diffusion of neutrals (as observed; § 2.3.1). Contrastingly, in an active region prominence, Okamoto et al. (2007) observed a very high level of activity with a predominance of horizontal flows, and previously unseen vertical oscillations by threads of material (Fig. 4.1(b)). The waves that are causing the oscillations yield information about the plasma parameters and the magnetic field structure, although the exact conclusions are still being debated.

The organization and direction of observations such as these, especially when multiple instruments are involved, are carried out by running prescribed observing programs. Coordinated observations require resources to be allocated in advance, and Joint Observing Programs (JOPs) are used by NASA and ESA as a formal way to coordinate instruments on SOHO with other observatories, and more recently this process has been adopted for coordination with STEREO instruments. Observational studies using Hinode are likewise coordinated via Hinode Operation Plans (HOPs),
Figure 4.1: Observations by Hinode/SOT in Ca II H 3969 Å from (a) Berger et al. (2008) of a quiescent prominence on 2006 Nov 30, with labels denoting dark upflows (U), bright downflows (D), and voids that are not upflows (V), and from (b) Okamoto et al. (2007) of an active region prominence on 2006 Nov 9 with strong horizontal flows and vertical oscillations in fine threads.
which are required to include plans for observations by all three Hinode instruments, since they all must point at the same location on the Sun. Note that any observational study using SOHO or STEREO in conjunction with Hinode must include both a JOP and a HOP.

The remaining sections of this chapter contain descriptions of the observing programs used to obtain the improved prominence observations (§ 4.1), the analyses of these prominences, the results, and discussions of the implications (§ 4.2), and an overview of future observational research that would follow up on these results by further profiting from the capabilities of these and future solar observatories (§ 4.3).

4.1 JOP and HOP Observations

The expected scientific results of the study, method for target selection, and operating sequences for Hinode/SOT, STEREO/EUVI, TRACE, SOHO/CDS, SOHO/EIT, and MLSO were submitted as a combined observing program, under my leadership. The plan was proposed to the science planners for SOHO, TRACE, STEREO, and Hinode, and was accepted for immediate operation in the summer of 2007 and denoted as JOP 188 and HOP 24. The program was a “target of opportunity” study to be used mainly on prominences or filaments near the limb, and the primary observing window was chosen to be 18:00-24:00 UT daily (to overlap with MLSO’s observing hours), with extended hours to be requested whenever a highly active prominence showed indications of a possible eruption. The program ran from July 3 to August 5, 2007, and three prominences were targeted during that time for a total of 134 observ-
Table 4.1. Instruments Used in JOP 188 and HOP 24

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Instrument</th>
<th>Wavelength (or range)</th>
<th>Resolution (arcsec/pixel)</th>
<th>Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOHO</td>
<td>CDS</td>
<td>319-629 Å</td>
<td>4.06 x 1.68</td>
<td>68 mins</td>
</tr>
<tr>
<td></td>
<td>EIT</td>
<td>195 Å</td>
<td>2.63</td>
<td>12 mins</td>
</tr>
<tr>
<td></td>
<td></td>
<td>171-304 Å</td>
<td>2.63</td>
<td>6 hours</td>
</tr>
<tr>
<td>TRACE</td>
<td>TRACe</td>
<td>195 Å</td>
<td>0.5</td>
<td>155 s</td>
</tr>
<tr>
<td>STEREO</td>
<td>SECCHI/EUVI</td>
<td>171 Å</td>
<td>1.6</td>
<td>2.5 mins a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>195, 304 Å</td>
<td>1.6</td>
<td>10 mins a</td>
</tr>
<tr>
<td>Hinode</td>
<td>SOT/BFI</td>
<td>3969 Å</td>
<td>0.109</td>
<td>20 s</td>
</tr>
<tr>
<td></td>
<td>SOT/NFI</td>
<td>6563 Å, DG b</td>
<td>0.16</td>
<td>20 s</td>
</tr>
<tr>
<td>MLSO c</td>
<td>ACOS/PICS</td>
<td>6563 Å</td>
<td>2.9</td>
<td>3 mins</td>
</tr>
<tr>
<td></td>
<td>ACOS/CHIP</td>
<td>10830 Å</td>
<td>2.29</td>
<td>3 mins</td>
</tr>
</tbody>
</table>

a STEREO includes both the Ahead and Behind spacecraft. Aside from the cadences tabulated, the standard SECCHI/EUVI observing sequence included four hours per day of high-cadence observations, with 171 Å every 75 s, 304 Å every 2.5 mins, and 195 Å every 5 mins.

b Hα Dopplergrams were only taken on Aug 4-5. Also, in 2007 there were “bubbles” in the NFI instrument that reduced image clarity.

c MLSO was the only ground-based observatory used and had daytime hours of 17:00-02:00 UT.

My responsibilities as the JOP/HOP Leader were to identify prominence targets, notify the instrument operators of these targets and the time windows when the coordinated observations would occur, and make any adjustments to improve the observing sequences.

The operating specifications used for all of the instruments are provided in Table 4.1. EIT, SECCHI/EUVI, and MLSO were all instructed to continue their stan-
dard observing schedules, only with the request to avoid any maintenance programs whenever a prominence was targeted. In the summer of 2007 the default plan for TRACE was to observe the same targets as Hinode, and the wider FOV of TRACE (compared to SOT) meant that its pointing would not need to be separately specified. TRACE observed predominantly in the Fe XII 195 Å bandpass since that wavelength gave the best EUV mass measurements in the previous study (§ 3.4), and the long exposure time (see Table 4.1) was set to yield good signal-to-noise. The CDS planners had more than a decade of experience in targeting its small FOV, and the CDS observing sequence needed for this JOP had already been written and used on several prominences before (POBS1.2/v46, by T. Kucera). This sequence used CDS to observe twenty transition region lines simultaneously (including Mg X 625 Å and Mg IX 368 Å) and raster 30 successive 4 arcsec slit observations to create a 122 × 240 arcsec image approximately every hour. SOT was a critical part of the observing program due to its capabilities and its observation of chromospheric lines at optical wavelengths. Although images from EIS would be redundant and prominence material cannot be seen in XRT, Hinode's common pointing (combined with the importance of SOT) forced the inclusion of those instruments as well, so the EIS and XRT observers used pre-existing routines for targeting the quiet Sun.

Since the observing sequences for the other instruments were well established, the main focus of my role as the JOP/HOP Leader was to write and coordinate the observations done by Hinode/SOT. The spacecraft is operated by a multinational
team based at the Japanese Aerospace Exploration Agency’s Institute of Space and Aeronautical Science (JAXA/ISAS) in Sagamihara, Japan, and the data is processed at the Hinode Science Center at the National Astronomical Observatory of Japan (NAOJ) near Tokyo. I was awarded a graduate student research fellowship (East Asia and Pacific Summer Institutes: EAPSI) supported jointly by the NSF and the Japan Society for the Promotion of Science (JSPS) to fund my travel and expenses for a two month stay at NAOJ. To augment the organization of HOP 24, I also served as one of the SOT Chief Observers (COs) for the week of July 5-12. As such, I was directly involved in the targeting and planning of SOT for the first prominence observed in the JOP/HOP.

The SOT observing routines initially used for the HOP were already available (from J. Okamoto and T. Berger), and included Hα line center (6563 Å) and Ca II H (3969 Å) at 20 s cadence. Later, HOP 24 conducted the first observations of the Hα Doppler wings by SOT on Aug 4-5. Dopplergrams (DGs) were constructed pixel-by-pixel by subtracting the intensity in the red wing (+312 mÅ) from the intensity in the co-aligned blue wing (-428 mÅ) observation, and then dividing by the sum. As discussed below (§ 4.2.3), DGs provide information about the line-of-sight velocities, which is important when determining the 3-D motion of dynamic prominence material and the possible magnetic field topologies the material illuminates (note that only the 2-D projected velocities can be determined for the prominences in Fig. 4.1). A caveat for all of the SOT Hα observations is that for the duration of the HOP, there were
Table 4.2. Prominences Observed by JOP 188 and HOP 24

<table>
<thead>
<tr>
<th>Observing Dates</th>
<th>Total Obs. Time</th>
<th>Latitude on Disk</th>
<th>Solar Angle</th>
<th>Prom. Size</th>
<th>Level of Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 Jul 9-12</td>
<td>22 hours</td>
<td>50° N</td>
<td>321°</td>
<td>Small</td>
<td>Quiescent</td>
</tr>
<tr>
<td>2007 Jul 21-24</td>
<td>21 hours</td>
<td>45° N</td>
<td>315°</td>
<td>Small</td>
<td>Quiescent</td>
</tr>
<tr>
<td>2007 Aug 1-5</td>
<td>91 hours</td>
<td>25° S</td>
<td>244°</td>
<td>Medium</td>
<td>Active</td>
</tr>
</tbody>
</table>

“bubbles” (of gas) in the SOT/NFI detector that effectively limited the Hα FOV to only the right half of the detector. In addition, if the NFI wavelength was changed, the bubbles would move, sometimes covering the entire FOV, so the observing sequence could not also include any measurements of the chromospheric magnetic field (from Mg Ib 5172 Å) that would have provided valuable context information. However, since the bubbles were relatively static, the effects on the pixel intensities (due to image distortion from the bubbles) were able to mitigated effectively by frequent flat-fields created by the SOT operations team.

Over the five-week duration of the JOP/HOP, only three prominences were available as targets (Table 4.2). The first two were small and quiescent, while the third was larger, with one central barb, and had a high level of activity. Fig. 4.2 shows the raw TRACE 195 Å observations of all three prominences, and Fig. 4.3 contains observations on Aug 4 from a majority of the important instruments and wavelengths used in the JOP/HOP (EUVI He II 304 Å and MLSO limb observations are not included in the figure; the different observing times in the figure are due to competition for CDS
Figure 4.2: Raw observations by TRACE in Fe XII 195 Å of the three prominences observed by JOP 188 and HOP 24 in 2007: (a) July 11 at 18:19, (b) July 24 at 02:30, and (c) Aug 5 at 04:41. The raw (Level-0) data is still vignetted (caused by the circular telescope aperture), and has not yet been flat-fielded nor despiked, which corrects for cosmic ray hits. All times are UT.

observing time late that day and a short data gap for EIT). The SOT observations turned out well for the first and third prominences, but for the second, the Hinode pointing was too far south and the prominence was entirely out of the small FOV of SOT. The only ineffective EUV observations were on Aug 4, when the prominence was far too large to fit within the CDS FOV, and the overlapping rasters, intended to cover the prominence over multiple observations, were mistakenly pointed too far east and missed the prominence on the limb (Figs. 4.3(e) and 4.3(f)).

4.2 Results from New Prominence Observations

The large number of instruments involved in the JOP/HOP allowed several studies to be carried out on the same prominences. All three analyses found promising initial results that require further observations of more prominences before definitive
Figure 4.3: Multi-wavelength observations from JOP 188 and HOP 24 of a medium-sized, active prominence targeted on 2007 Aug 4: (a) EUVI-B Fe XII 195 Å, (b) TRACE 195 Å, (c) EUVI-A 195 Å, (d) EIT 195 Å, (e) CDS Mg IX 368 Å, (f) CDS Mg X 625 Å, (g) SOT Ca II H 3969 Å, (h) SOT Hα blue Doppler wing (6563 Å -428 mÅ), and (i) SOT Hα red wing (6563 Å +312 mÅ). Images (g)-(i) are zoomed-in, compared to (a)-(f), and are centered on the central barb. The CDS images are a mosaic of three successive rasters, observed from 15:44-19:10. STEREO-A and STEREO-B were separated from the Earth by 13.4° and 9.6°, respectively. All times are UT.
conclusions can be made. In the first, the continuum absorption seen in EUV observations was used to calculate the prominence column densities and mass (§ 4.2.1). The higher spatial resolutions of TRACE and EUVI permitted the analysis of much smaller portions of the prominence plasma (marking an improvement over the data used in Chapter 3), making it possible to probe small-scale mass variations and compare those results to the predictions of cross-field diffusion or mass loading in prominences. In the second analysis, the scale heights of the emission in optical lines were compared to determine if any variations in the compositional distribution due to gravitational settling were visible (§ 4.2.2). This line of work follows up on the results of our previous studies on quiescent prominences, which found observational evidence that neutral helium was located lower in the structure than neutral hydrogen (§ 2.3.1 and § 3.4), which could be due either to cross-field diffusion or gravitational settling. Finally, SOT Hα Dopplergrams were constructed to search for trends in the 3-D dynamics of prominence material on small, previously-inaccessible length scales (§ 4.2.3). There were initial indications of flows on very small scales (Okamoto et al., 2007; Berger et al., 2008, see above), but the lack of 3-D velocity information limited the knowledge and understanding that could be gained from the high resolution SOT observations.

4.2.1 EUV Mass Calculations

The JOP 188 observations conducted by CDS, TRACE, and EUVI had good signal-to-noise (with a ratio of 10 or better, after flat-fielding), which is important
when calculating the column mass in each data pixel, and the prominences were observed for a long enough duration that the dynamics in their activity could be analyzed in the data, marking a vast improvement over the previous set of prominence observations from the archived data (§ 3.2). In addition, the three prominences in the JOP had differing levels of activity, so the contrasting trends in the spatial distribution of the composition for quiescent and active prominences found previously (§ 3.4) could both be tested via the improved observations.

The EUV continuum absorption was analyzed with the same general method described in § 3.3. In this method, the background radiation of the corona is interpolated between points on either each side of the prominence material, and the foreground radiation and amount of continuum absorption are calculated by comparing pixels on the disk and limb that have the same column density of prominence material. Unfortunately, when stringently applying this method, all three prominences presented difficulties either in accurately evaluating the amount of foreground radiation, or in interpolating the line-of-sight background coronal radiation at the site of the prominence material. Such problems were not unexpected, given that less than half of the prominence candidates from the SOHO data archive could be successfully analyzed in the previous study (nine out of twenty; see § 3.2). However, by relaxing the restrictions (i.e. by making assumptions about or allowing modifications to the coronal radiation), the JOP 188 EUV observations were able to provide reasonable estimates of the prominence masses and their distributions, on par (in the degree of accuracy)
with other current techniques (e.g. Heinzel et al., 2008).

The first two prominences (from July 11 and July 24) were very thin (i.e. caused little continuum absorption, due to a low column density; Figs. 4.2(a) and 4.2(b)), which often creates a problem when trying to compare the intensity between pixels on the disk and limb. The portions of the prominence being compared must have the same column density of material, but when the prominence is thin, the sensitive measurements are easily corrupted by small fluctuations in the corona in front or behind the prominence material. To analyze thin prominences like these, the method must be modified basically by overestimating the amount of background coronal radiation. This increases the amount of “measured” continuum absorption so that it is much greater relative to fluctuations in the coronal intensity – effectively, the ratio of signal (continuum absorption) to noise (coronal fluctuations) is artificially increased – and with this assumption, our basic method works as designed. The effect of this assumption was measured by overestimating the coronal background for prominences previously analyzed (those in Table 3.2), which found that the spatial distribution of the material is essentially unmodified, and the total prominence mass calculated approximately doubles, on average (and is always less than half an order-of-magnitude too high), so the actual prominence mass can be estimated as half the measured value. For these two prominences, this modification to the method only worked for the CDS Mg IX 368 Å and Mg X 625 Å observations (and not Fe XII 195 Å). The prominences appear far darker in these two lines because the opacity is much higher
than at 195 Å (Anzer & Heinzel, 2005; Heinzel et al., 2008), and indeed in the 195 Å observations these small, thin prominences are barely discernible from other features in the corona.

The July 11 prominence was calculated to have a total mass of $2.1 \times 10^{13}$ g from 368 Å and $1.6 \times 10^{13}$ g from 625 Å, both observed at 22:46 UT. The actual mass would be closer to $1 \times 10^{13}$ g, given the errors introduced by our assumptions. This value compares favorably to our previous measurements (§ 3.4), bearing in mind the small size of this prominence. The measured mass is almost entirely in the footpoints, although there is some spurious mass found that resulted from emissivity blocking due to the filament channel (between the legs; Fig. 4.4). The distribution of the mass is similar for both wavelengths, and implicitly for both neutral hydrogen and helium; this is in agreement with our previous studies, which only saw differences in the $H^0$ and $He^0$ distributions in the spine or at the tops of the legs. High-resolution SOT observations of this prominence are provided in Figs. 4.4(g) and 4.4(h) to provide context information about the location of the prominence material. For this prominence, the SOT observations do not much expand our knowledge of prominences, but they at least indicate that at smaller scales, there is no significant amount of mass that was missed in the EUV observations.

The prominence observed on July 24 presented an additional difficulty for the mass calculation, aside from being thin. It consisted of two sections of material, and the FOV of the CDS observations abutted the southwestern edge of the prominence.
Figure 4.4: The original observations, overestimated background coronal radiation, and mass maps of a small quiet Sun prominence observed by SOHO/CDS on 2007 July 11 at 22:46. In the mass maps, a brighter pixel corresponds to greater mass. Hinode/SOT observations are provided in (g) Ca II H 3969 Å and (h) Hα 6563 Å for context information about the location of the prominence material. The solar grid is included for easier comparison of features. All times are UT.
Figure 4.5: The original observations, overestimated background coronal radiation, and mass maps of a small quiet Sun prominence observed by SOHO/CDS on 2007 July 24 (a)-(c) at 21:03 in Mg IX 368 Å and (d)-(f) at 18:45 in Mg X 625 Å. In the mass maps, a brighter pixel corresponds to greater mass, and the color scaling is two times greater for 368 Å. The solar grid is included for easier comparison of features. All times are UT.

(Fig. 4.5), so the background coronal radiation could not be interpolated between the corona on either side of this prominence. In addition, on the disk, the filament channel, a small active region, and a coronal hole further complicate the coronal interpolation for the southern section of the prominence. The approach adopted in this case was to calculate the mass of just the northern section, via the assumption of an overestimated coronal background. The mass of the northern half was calculated
to be $2.7 \times 10^{12}$ g from 368 Å and $2.2 \times 10^{12}$ g from 625 Å, so the actual mass is estimated to be $1 - 2 \times 10^{12}$ g. The mass of the entire prominence is difficult to deduce from the limited amount of information, but can be approximated as $1 - 8 \times 10^{12}$ g. This mass value is quite low for a prominence, although still reasonable given its small size. Again, the mass is predominantly in the legs of this section of the prominence. Approximately the same amount of mass is measured in the western leg from both lines, but the 368 Å mass map registers more continuum absorption in its eastern leg than 625 Å, possibly indicating the presence of excess $H^0$ there. This finding is uncertain due to the caveats associated with this prominence, yet it does raise questions about why more $H^0$ would be located in one leg, and not the other. The mass composition in that leg might be affected by the southern section of the prominence, but it is still unclear how or why such an asymmetry (across the northern section) would be present.

The final prominence, observed by the JOP on Aug 4, had a much higher column density, but there were complications regarding the interpolation of the background coronal radiation. There was an active region just northwest of the footpoint far to the north (of the central barb and southern footpoint), so that footpoint could not be included in the total mass calculation (Fig. 4.3(b)). In addition, the extra emission from that active region to the northwest and another to the southwest made it impossible to establish the background coronal radiation over the entire prominence by using interpolation points off to each side. Instead, the interpolation was done
Figure 4.6: The original observation, overestimated background coronal radiation, and mass map of a small quiet Sun prominence observed by TRACE in Fe XII 195 Å on 2007 Aug 4 at 21:03 UT. In the mass map, a brighter pixel corresponds to greater mass. The solar grid is included for easier comparison of features.

between a radial scan that slightly overlapped the material just north of the central barb, and another that went through the thin part of the spine in the southern section of the prominence. The analysis corrected for the continuum absorption by the material, and it yielded an acceptable version of the background coronal radiation (Fig. 4.6(b)). A further problem surfaced because this prominence did not have enough material left on the disk to be used for the calculation of the foreground radiation. Therefore, since the longitude of the prominence was known to be 85° W, the foreground radiation was set to be 45% of the interpolated coronal radiation. This additional assumption eliminated one of the unknown variables (eliminating the need for a comparison between pixels on the disk and limb that have the same column density of prominence material), and allowed the calculation of a prominence mass of $9.7 \times 10^{13} \text{ g}$, which would increase roughly $\sim 30\%$ if the material in the northern
footprint were included. The total mass compares well with prominences of similar size that were measured before. An important result from this calculation is the level of detail in the mass map that resulted from the high-resolution EUV observations from TRACE. Small threads of the prominence material can be identified, and the full application of this method (without any assumptions) could lead to significant new findings on small-scale mass variations in prominences.

The three prominences observed by the JOP/HOP were not ideal for our analytical method, but after utilizing some reasonable assumptions, estimates were made that yielded total masses that compare well to previous mass measurements. Looking to the future, the technique used here was designed to fully utilize the high resolution EUV observations by calculating the column mass at each data pixel, which represent very small portions of a prominence, leading to unprecedentedly detailed spatial maps of the prominence mass. In addition, our method has streamlined the analysis of a single observation from a process taking several hours and significant user input to one that is largely automated and takes only a few minutes (when not modified to accommodate complications in some prominence observations). This efficiency permits many more EUV observations to be analyzed with our technique, which is especially important now that the cadence of EUV instruments is increasing to very high levels; otherwise, only a fraction of the available observations could be analyzed, effectively reducing the cadence or the duration and limiting the physical timescales that would be probed.
The analysis of the continuum absorption in EUV observations using a method that preserves both the high spatial resolution and cadence is a crucial first step in advancing the understanding of prominence mass on small scales. New observations from the full-disk EUV imagers on STEREO and SDO will provide a significantly larger sample of prominences for analysis, and our method is well-equipped to analyze the torrent of data from them, to yield the most detailed picture yet of the small-scale spatial distributions of prominence mass and its dynamics over a wide range of timescales.

4.2.2 Comparing Emission Heights in Hα and Ca II H

Unlike cross-field diffusion, gravitational settling requires the heavier ions (in addition to the heavier neutral atoms) to be concentrated in the lowest part of the prominence structure to produce the “edge effects” observed in quiescent filaments in previous studies (§ 2.3.1). The scale-height of gravitational settling depends directly on the mass of the ions, so the scale-height of emission from Ca$^+$ ions (in Ca II H 3969 Å) would be forty times shorter than for hydrogen (in Hα; recall that H° is tightly bound to H$^+$ and will have the same distribution as free protons; § 1.6). A follow-up project to the He/H absorption ratio studies was to compare the spatial extent of emission in prominences in order to find conclusive evidence favoring either cross-field diffusion or gravitational settling as the cause of the edge effects (§ 2.5), and the very high spatial resolution of SOT makes such a determination possible.
Table 4.3. Emission Scale Heights for Prominence Observed on 2007 Aug 5

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Instrument</th>
<th>Scale height at 242.4°</th>
<th>Scale height at 245.3°</th>
<th>Scale height at 246.3°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca II H 3969 Å</td>
<td>SOT/BFI</td>
<td>81 arcsec</td>
<td>89 arcsec</td>
<td>71 arcsec</td>
</tr>
<tr>
<td>Hα 6563 Å, -428 mA</td>
<td>SOT/NFI</td>
<td>50 arcsec</td>
<td>34 arcsec</td>
<td>23 arcsec</td>
</tr>
<tr>
<td>Hα 6563 Å, +312 mA</td>
<td>SOT/NFI</td>
<td>92 arcsec</td>
<td>44 arcsec</td>
<td>37 arcsec</td>
</tr>
</tbody>
</table>

Only one of the three prominences observed by HOP 24 could be used for this study: the Aug 4-5 prominence. The July 11 prominence had an insignificant amount of material in the spine, and the one targeted on July 23 was not captured within the FOV of SOT. The prominence on Aug 4-5 was observed at the limb in Ca II H and the two Doppler wings of Hα, which were offset from line center by -428 mA and +312 mA. NLTE models of these lines calculate that prominences will show slightly less emission higher in the prominence, since that material is farther from the surface (i.e. less incident radiation) and additionally some of that radiation was already absorbed by material lower in the prominence (Heasley et al., 1977; Zhang & Fang, 1987), but the scale height of the emission in either spectral line is still a good relative measure of the density scale height of H^0 or Ca^+.

The highest altitude of the emission in the NFI Hα Doppler wings and BFI Ca II H are quite similar in all of the observations: ~ 40 arcsec (see Fig. 4.7). Exponential fits to radial scans at solar angles of 242.4°, 245.3°, and 246.3° (counterclockwise from north pole) were used to calculate the scale height of the emission from the prominence.
Figure 4.7: Hinode/SOT observations on 2007 Aug 5 of a medium-sized active prominence at the limb by (a) BFI Ca II H 3969 Å at 19:20:18, (b) NFI Ha blue Doppler wing (6563 Å -428 mA) at 19:20:26, and (c) NFI Ha red Doppler wing (6563 Å +312 mA) at 19:20:30. The three radial scans indicated in (a)-(c) are denoted by the solar angle (ordered south to north), and the semi-log plots are displayed in (c) through (h). Note that the greater dispersion of emission in (a) is due to the much broader wavelength filter of SOT/BFI than for the SOT/NFI observations in (b) and (c). All times are UT.
material (see dashed lines in Figs. 4.7(d)-(l)). These scale heights are all larger than the prominence's spine, and Ca II H scale heights are generally larger than for the Hα Doppler wings (Table 4.3). This is probably due to a combination of the smaller subset of the prominence plasma emission that is detected in the Doppler wings and the difference in filter bandpass widths. The larger bandpass is evident from the greater dispersion of the emission in Ca II H than in Hα, caused by the much broader wavelength filter of SOT/BFI than for SOT/NFI. Theoretically, gravitational settling would cause the Hα scale heights to be 40 times larger than in Ca II H; even accounting for the differences in the filters and the Doppler wing offsets, it is improbable that the ratio between the scale heights would change by over 1.5 orders of magnitude. Therefore this prominence is unlikely to be affected by any gravitational settling of its Ca⁺ ions. However, in the previous study, filaments that were highly active did not show edge effects (§ 2.3.2), so gravitational settling may not be expected to cause visible differences in the vertical extent of emission in this active prominence.

Quiescent prominences have been observed a few times by SOT via observing programs other than HOP 24 (e.g. Berger et al., 2008), but not all of these prominences were observed in both Ca II H and Hα. Additionally, MLSO limb observations in Hα and He I of the prominence should also be used to determine whether He/H edge effects should be expected, but since MLSO was not a part of these other observing programs, the observations were not specifically coordinated to include MLSO. An example of a prominence simultaneously observed in all four spectral lines is from
Figure 4.8: Observations on 2007 Aug 16 at 17:35 UT of a small quiescent prominence by (a) *Hinode/SOT/NFI* in Hα 6563 Å, (b) *Hinode/SOT/BFI* in Ca II H 3969 Å, (c) MLSO in Hα (disk occulted), and (d) MLSO in He I 10830 Å (disk occulted). Note that (a) and (b) have different spatial scalings, and artifacts in (a) are due to the “bubbles” in SOT/NFI.
2007 Aug 16. This prominence is mostly quiescent, primarily showing slow, vertical movement of material and no discernible flows along the spine; it also has enough of a spine to possibly exhibit edge effects, despite the large magnetic arch below one section of the spine (side note: the physics and implications of this arch are still under debate). This prominence also shows no notable difference in the spatial distribution of emission between Hα (Fig. 4.8(a)) and Ca II H (Fig. 4.8(b)). However, since the emission in Hα (Fig. 4.8(c)) and He I (Fig. 4.8(d)) limb observations from MLSO show similar heights in their emission, this proxy comparison for the He/H absorption ratio suggests that the presence of edge effects cannot be expected. Therefore, despite the low level of activity in this prominence, gravitational settling again may not be expected to reduce the scale height of emission in Ca II H, compared to Hα.

The results from comparing the emission in these two prominences were inconclusive in determining the importance of gravitational settling in prominences. The number of prominences observed by SOT simultaneously in Ca II H and Hα (at line center) must be increased to properly search for examples of differing emission scale-heights that would clearly contradict any correlation between the observed edge effects and the possibility of gravitational settling. A much larger sample of prominence observations by SOT would be needed to conduct a statistical study on the degree to which cross-field diffusion and gravitational settling are affecting the distribution of material in quiescent prominences, which would enhance our understanding of mass variation in prominences and provide a conclusive determination of the causes of the
edge effects we observe.

4.2.3 Dynamics in SOT Hα Dopplergrams

Initial results from SOT showed dynamic, small-scale vertical flows in quiescent prominences that could not be fully understood because only the 2-D position of features could be determined (Berger et al., 2008). Additional information on how the material moved along the line-of-sight was needed to better illustrate the path of these flows, and possibly indicate the magnetic structure of the prominence along which the material is moving. Conducting Doppler observations of prominences in Hα using SOT became a secondary goal of HOP 24, and the results, though the caveats are complex, support previous findings on counter-streaming flows along the spine in active prominences.

Aside from an initial test of the observing routine, the first observations by SOT of the Hα Doppler wings were done by HOP 24 on Aug 4-5. However, for this observation, the Doppler wing offsets were not modified for the location of the targeted prominence. The SOT Chief Observers inadvertently left the Doppler wings centered around an Hα line-center (-58 mÅ) better suited for the blue-shifted east limb instead of the red-shifted west limb. For this prominence at 25° S latitude and an altitude of 0.04 $R_\odot$, the rotation speed is 1.86 km/s, corresponding to a Doppler shift on the west limb of +40.7 mÅ. The Doppler wings actually used for the SOT observations were offset to -428 mÅ for blue and +312 mÅ for red, which corresponds to velocities of
21.4 \text{ km/s} eastward and 12.4 \text{ km/s} westward, respectively, relative to the co-rotating solar surface. The Dopplergrams (DGs) were constructed by subtracting the intensity in the co-aligned red-wing pixel from the intensity in the blue-wing pixel and dividing by the sum.

All of the DGs for this prominence average much more emission in the blue Doppler wing, and the fast-moving spicules in the chromosphere are especially blue (see Fig. 4.9). There is also a high level of small-scale activity and vertical motion in the central barb and southern footpoint, along with frequent flows a few arcseconds wide in threads along the spine. Note that the northern footpoint is out of the FOV. Flow speeds were estimated by tracking moving features and using the angle at which the spine was oriented when on the disk: \( \sim 55^\circ \) clockwise, relative to a north-south meridian. Sustained flows have speeds ranging 15 – 35 \text{ km/s}, and some small surges around the barb or footpoint approached 50 – 60 \text{ km/s}. There are also many fluctuations in the intensities in and around the barb that suggest fast, small-scale movements of the material, but no reliable velocity estimation could be made, in part because any semi-distinct feature had a lifetime of one minute or less. Note that since these observations were taken just after the end of \textit{Hinode}'s eclipse season (on Aug 3), there are still dimmings every hour and 38 minutes (i.e. the period of its low-Earth orbit) that last about 20 minutes early on Aug 4 and only around five minutes by the end of Aug 5; affected images are not included in the figure.

The incorrectly-centered Doppler wings have provided information about the promi-
Figure 4.9: *Hinode/SOT Hα Dopplergrams* of a medium-sized active prominence observed on 2007 Aug 4-5. All DGs are plotted on the same scale, with a brighter pixel corresponding to a higher intensity in the blue Doppler wing (-428 mÅ), a darker pixel to a higher intensity in the red wing (+312 mÅ). Note that the solar disk is slightly red. All times are UT.
nence material's dynamics in an unexpected way. The greater intensity observed in the blue wing is unlikely due to an excess of eastward motion (which would be manifested as apparent movement to the south, due to the orientation of the spine, that is not seen in the intensity observations), but rather seems to indicate that the flows are moving with an average velocity greater than 16.9 km/s. This is borne out by the estimations of the high speed flows of prominence material along the spine, and the high degree of small-scale motions in the legs. These SOT Hα DG observations of an active prominence contrast well to later DGs from HOP 73 of a quiescent prominence. T. Berger found that quiescent prominences only show a significant signal in DGs when the Doppler wings are closer to line center (±208 mA ≈ 9.5 km/s), which is explained well by the smaller flows and velocities in quiescents. The Hα DGs of a quiescent prominence on 2008 Sept 29 show little movement along the spine, but numerous vertical motions in the material, which becomes separated into pockets of red-shifted and blue-shifted flows that continually form, fluctuate, and mix on the order of minutes (Fig. 4.10).

The combination of just these two SOT Hα Dopplergrams presents a meaningful comparison of the types of flows, their velocities, and the larger-scale dynamics of the material in prominences between differing levels of activity. In the quiescent prominence, there is relatively little activity in the legs and along the spine, but there are slow-moving, small-scale vertical flows in the spine. By contrast, the active prominence shows high activity and flows in the legs and along the spine, with higher
velocities, that could be superseding any of the small-scale, slow vertical flows seen in quiescents. The cause of the higher activity might be mass loading of chromospheric material up the legs and onto the spine, but it is still uncertain, and this comparison between DGs of prominences with different levels of activity would benefit greatly from further observations and an expansion of the number of prominences in the data set. Ongoing Hα DG observations of prominences are being conducted with SOT via HOP 73, and there is high potential for these observations to illuminate the dynamics of prominence material to a previously unattainable level of detail, which could alter our perception of prominences and force a serious reexamination of the finer points of numerous prominence models.

Figure 4.10: Hinode/SOT Hα Dopplergrams 6563 Å ±208 mÅ of a medium-sized quiescent prominence observed on 2008 Sept 29 by HOP 73. All DGs are plotted on the same color scale, with a darker shade of red or blue corresponding to larger amounts of Doppler shifting material moving westward (away from the observer) or eastward (toward the observer) on the Sun, respectively. These observations are courtesy of T. Berger. All times are UT.
4.3 Prospects of New Observatories

The new observatories of STEREO, *Hinode*, and SDO are equipped to supply the high quality observations necessary to continue developing the research on prominence mass and composition discussed throughout this chapter, in addition to the potential follow-up studies outlined in § 2.5, assuming that appropriate targeted observations can be performed. STEREO-A and STEREO-B, separating from the Earth’s line-of-sight, are providing two additional viewpoints of the solar limb, from which EUV mass calculations of prominences straddling the limb can be taken more frequently. *Hinode* no longer has the capability to observe with a high cadence over a long period of time, due to the hardware failure of its high-throughput transmitter, making it time-consuming to downlink a large amount of data. However, processes important in quiet Sun prominences, like cross-field diffusion, have timescales of a few to several hours, so lower cadence observations (while retaining SOT’s high spatial resolution) could still yield productive results. Hα Dopplergrams from SOT are, in particular, an excellent source for learning a great deal about small-scale mass dynamics and making inferences about the magnetic field structure. The duration of the DG observations would need to be partially sacrificed to maintain high cadence, but the variations to be analyzed occur over timescales of minutes – much shorter than the capable length of continuous observations (several hours).

After its launch (scheduled for fall 2009) and a commissioning phase, the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) instrument will
supply full-disk EUV images with high spatial resolution and cadence, which will yield numerous observations of continuum absorption by prominences. The SDO/AIA observations, along with those from EUVI-A and EUVI-B, will provide the large data set necessary to more fully utilize the technique of determining prominence mass from the continuum absorption, and the higher resolution and cadence will allow mass measurements of smaller and more dynamic portions of prominences.

The combination of these observations with numerous other spectral lines and magnetic field measurements – using instruments on STEREO, Hinode, and SDO – shows great potential to extend the understanding of the physics of prominences, due to the advanced instrumentation of these new observatories and their capability for probing smaller timescales and shorter spatial scales. These observations will help solve long-standing questions about the intricacies of the dynamics, support, and formation of prominences, while perhaps also detailing entirely new phenomena that will challenge the current paradigm.
Chapter 5

Conclusions

My doctoral research has focused on the composition and mass dynamics in quiet Sun prominences and filaments, and the four main studies conducted have found complimentary results that have significant implications on the physical processes important in prominences. This line of work is motivated in general by the consequences of prominence eruptions and their relation to coronal mass ejections, which substantially affect space weather near Earth and throughout the solar system. The specific motivation is that knowledge of the prominence mass, its composition, and the dynamics are critical in the understanding of various physical processes associated with prominences, including the relationship between the plasma and the magnetic field, the formation and evolution of the magnetic structure, the physics of mass draining and loading, the nature of MHD waves and oscillations, and the mechanisms that are important in initiating prominence eruptions and forming the related CMEs. The results of observational analyses of prominences, such as the doctoral research presented here, are necessary for comparisons to the physical models, and can help determine the underlying plasma physics important in prominences while augment-
ing space weather forecasting by advancing the predictive capacity for prominence eruptions and CMEs.

The methods for these studies vary, but all involve comparisons among observations at different wavelengths. The He/H absorption ratio was obtained by a comparison of absorption by neutral filament material between MLSO observations in He I 10830 Å and Hα 6563 Å; the $He^0/H^0$ neutral ratio was determined by comparing continuum absorption in SOHO/CDS Mg IX 368 Å to Mg X 625 Å; the Hinode/SOT Hα Dopplergrams were calculated by comparing the intensities in the blue wing (-428 mA) to the red wing (+312 mA); finally, direct comparisons between emission in SOT Hα to Ca II H 3969 Å were done to search for differences in the spatial distribution of the different elements in the prominence plasma. The results from these analyses in the four studies conducted can be summarized according to the amount of activity in the prominence:

- *Quiescent prominences.* The He/H absorption ratio frequently shows “edge effects,” with a helium deficit (when He I absorption is compared to Hα absorption) at the top of filaments and a helium surplus along the bottom (§ 2.3.1). For quiescent filaments decreasing in absorption, the absorption ratio sometimes shows increasing helium deficits as the material disappears (§ 2.3.2). In addition, the $He^0/H^0$ neutral ratio often shows more absorption in the lower part of prominences when $He^0$ is also an absorber of EUV continuum radiation (§ 3.4). In one prominence observed at high resolution, a simultaneous comparison of
SOT Hα to Ca II H and MLSO Hα to He I showed equivalent vertical extent of the emission in all four wavelengths (§ 4.2.2).

- **Active prominences.** Filaments observed by MLSO that were increasing in both Hα and He I absorption had an He/H absorption ratio distribution that is mostly constant (with no edge effects), and a similar average value of the absorption ratio among all of the varying filaments (§ 2.3.2). The one active prominence observed in the EUV also had comparable spatial distributions of the continuum absorption in both EUV lines (§ 3.4). In an active prominence observed by HOP 24, SOT Hα and Ca II H showed similar scale heights of the emission, with no evidence of any gravitational settling of the heavier ions (§ 4.2.2). Furthermore, SOT Hα Dopplergrams of the same prominence show many small-scale flows along the spine, all with higher speeds than is observed in quiescent prominences (§ 4.2.3).

- **Pre-eruption prominences.** An initial study of the He/H absorption ratio in a few filaments prior to their eruption found indications that the absorption ratio was becoming more homogenized and absorption was increasing during a 1-2 day period prior to eruption initiation (§ 2.3.3). A follow-up study utilizing higher cadence on a larger sample of pre-eruption filaments confirmed the earlier findings and quantified the combined, simultaneous trend, which all start 1-6 days prior to eruption: a high level of activity, near-homogenization of the absorption ratio, and increases in the Hα and He I absorption in the erupt-
ing filament sections (§ 2.4.1). Finally, MLSO observations of failed eruptions sometimes showed reformation of the erupting filament section afterward, and often the reformation of non-erupting sections (if they disappeared) in filaments that partially erupted (§ 2.4.3).

These results imply that certain physical processes are affecting the material in prominences, depending on the level of activity. The surplus of neutral helium concentrated in the lower part of quiescent prominences means that there is a vertical stratification of H and He, which is most likely caused by cross-field diffusion or gravitational settling. It seems unlikely that gravitational settling would be the primary cause, since ions would need to move across magnetic fields, but an initial attempt to prove its unimportance was inconclusive. For quiescent prominences that are decreasing in absorption, some are showing faster decreases in the amount of He compared to H, which is explained well by cross-field diffusion of neutrals.

In active prominences (including those that are newly forming), the increases in absorption and the presence of similar distributions for H and He suggest that material is being added with a standard composition, possibly via mass loading from the chromosphere, and that the active motions may help mix the material. The combined trend seen in pre-eruption prominences is similar to that for active prominences, with high levels of activity, increasing homogenization of the composition, and increases in Hα and He I absorption. The fact that this trend starts at least one day (and up to six days) prior to the eruption initiation implies that an extended period of mass loading
may be occurring prior to all eruptions, which seems contradictory since a heavier prominence would require a greater upward force to be expelled. Therefore a new explanation was formulated whereby extensive pre-eruption mass loading is simply a byproduct of a process in which the upward-directed forces (i.e. magnetic buoyancy of the flux-rope and decreasing downward magnetic tension from the overlying arcade) increase faster than the gravity due to the higher prominence mass (§ 2.4.2).

Future studies that follow-up on these results, to better determine the physical processes important in prominences, are already being prepared (see § 2.5 and § 4.3). Of particular importance to observers and data analysts are the greatly improved observations being obtained by the relatively new STEREO and Hinode spacecraft, and the potential findings from the coming launch and operation of the Solar Dynamics Observatory. Further missions are in development that will continue to advance the capabilities of observational research, which will better test the increasingly sophisticated computer models and simulations of the dynamic activity observed in prominences and other phenomena in the solar atmosphere.

There is a long history of prominence observations, in many wavelengths, which show intriguing dynamical behavior that is still poorly understood by solar physicists. Further motivated by the increasing importance of space weather and augmented by the highly improved capabilities of observing instruments that are now available, current research on prominences presents an exciting and timely opportunity to both expand the understanding of plasma physics in these magnetic structures in the solar
atmosphere, and improve the ability to forecast prominence eruptions and the related coronal mass ejections. Hazardous space weather already poses a significant danger to our technology-dependent society, and will continue to do so as we increase our strategic use of space and extend our manned spaceflight exploration to the far reaches of the solar system.
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