Coupling the photospheric and coronal magnetic fields : observations and analysis
by Brian Neal Handy

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
The work presented in this thesis is composed of two complementary fields in solar physics. The first section is devoted to current issues in instrument hardware, in particular the Ultraviolet (UV) channel of the Transition Region and Coronal Explorer (TRACE) instrument. The chapter as presented is reproduced from Handy et al. (1998). The TRACE instrument carries UV optics to image solar plasmas in the Lyα &lamba; 1216 Å emission line, the C IV A 1550 Å resonance line doublet, the UV continuum at 1600 Å and a "white light" image centered at ≈ 5000 Å The C IV lines are particularly difficult to image properly as they are superimposed on a background UV continuum that increases six orders of magnitude over the wavelength range 1300-2100 Å Chapter 2 considers the problem of isolating the C IV resonance lines from the UV continuum, discusses the optics used to achieve this goal, presents a formalism for data analysis and finally shows a sample dataset from post-launch observations.

Chapter 3 considers observations from a high time-cadence joint observing cam-paign with the Extreme-ultraviolet Imaging Telescope (EIT, Delaboudiniere et al. 1995) and the Michelsen Doppler Imager (MDI, Scherrer et al. 1995) on the Solar and Heliospheric Observatory (SOHO, Domingo, Fleck, & Poland 1995), 10-14 Au-gust 1997. This coordinated observation makes it possible to observe the response of the (1 MK) solar corona to the evolution of the photospheric magnetic field. Qualita-tive observations show that coronal loops evolve continually on a discontinuous basis: small emerging loops spread, the magnetic footpoints coalesce (or cancel) with other flux concentrations, then the coronal loops reconnect to larger concentrations at a greater range of distances. We find that the quiet solar corona has a typical evolution time scale of nominally 15 hours, in very good agreement with the observations of Schrijver et al. (1997) who find that photospheric magnetic flux concentrations have a lifetime of less than 40 hours. Hence, pairs of flux concentrations must evolve on a timescale of less than 20 hours. We also evaluate two theories of coronal heating via magnetic reconnection and attempt to reconcile our observations against these theoretical predictions.

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APPROVAL

of a thesis submitted by

Brian Neal Handy

This thesis has been read by each member of the thesis committee, and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style and consistency, and is ready for submission to the College of Graduate Studies.

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John C. Hermanson, Ph. D. — J Herm (Signature) — 7-14-98 Date

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Date July 14, 1998

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ABSTRACT

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CHAPTER 1

INTRODUCTION

The work presented in this thesis is composed of two complementary fields in solar physics. Chapter 2 is devoted to current issues in instrument hardware, in particular the Ultraviolet (UV) channel of the *Transition Region and Coronal Explorer* (TRACE) instrument. The chapter as presented is reproduced from Handy et al. (1998). Chapter 3 considers observations and results from a high cadence joint observing campaign with the Extreme-ultraviolet Imaging Telescope (EIT, Delaboudinière et al. 1995) and the Michelsen Doppler Imager (MDI, Scherrer et al. 1995) on the Solar and Heliospheric Observatory (SOHO, Domingo et al. 1995), 10-14 August 1997. TRACE is similar in design and capability to the EIT instrument, with greater temporal and spatial resolution over a smaller field of view.

1.1 The Transition Region.

The solar transition region represents the layer between the relatively cool ($\simeq 10^4$ K), optically thick chromosphere and the hot ($\simeq 10^6$ K), tenuous, optically thin solar corona. This shift in temperature T (and hence density ρ, as the pressure P must be continuous across the boundary and $P \sim \rho T$) occurs so rapidly that the transition region more accurately represents a temperature regime instead of a geometric layer (Stix 1989). Observations (both filtergrams and spectral observations) of transition region emission lines show a very inhomogeneous environment with a great deal of structure (Reeves, Noyes, & Withbroe 1972; Brueckner 1981; Damè et al. 1996). Figure 1.1 represents an idealized (stratified, spherically symmetric) model of the solar atmosphere that demonstrates this sharp discontinuity in the physical parameters in that region.

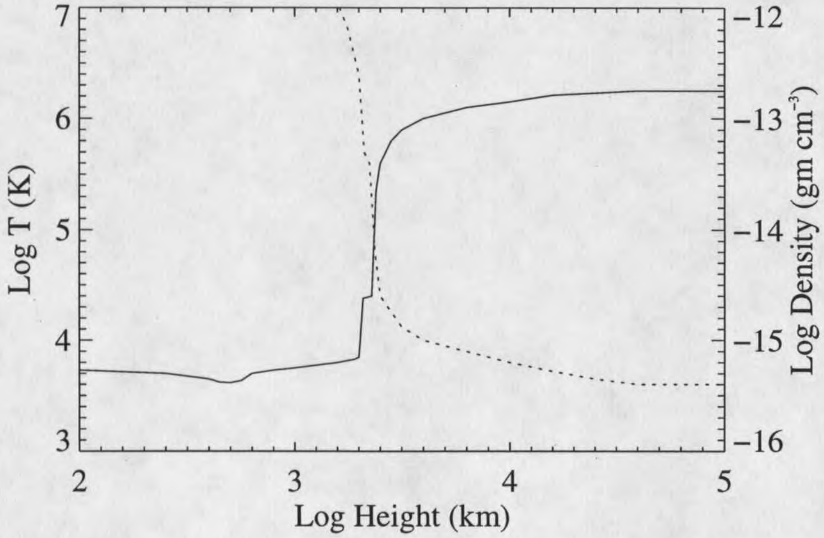

Figure 1.1: Average temperature and density gradients in the solar atmosphere. This model represents a spherically symmetric, stratified atmosphere. The solid line is temperature and the dotted line is density. (From Vernazza, Avrett, & Loeser (1981)).

The transition region also reflects a change in the morphological structure of the solar atmosphere: images of the sun taken in chromospheric emission lines (e.g. Hα, Ca II and other lines at 5–10,000 K) show a mottled chromospheric network that blurs with increasing height and temperature. This blurring effect is due to the topology of the magnetic network at those heights: at low levels near the photosphere the magnetic concentrations remain tightly bundled but expand to fill the available space with increasing height as the magnetic pressure begins to exceed the gas pressure (Kopp & Kuperus 1968; Feldman, Doschek, & Mariska 1979). Hence, the ability to observe line and continuum emission in the chromospheric and transition regions would provide an additional datapoint in understanding the evolution of emerging magnetic bipoles, which are already well-observed in the photosphere through any number of ground-based solar observatories and also in the corona from instruments such as the Soft X-ray Telescope on *Yohkoh* (Tsuneta et al. 1991).

Skylab and UV images from sounding rocket flights of the chromosphere and transition region show a clear correspondence to the structure of the photospheric magnetic field. The next phase of understanding the solar transition region is a better understanding of the geometry of this region. It has been argued that only a fraction of the transition region connects to the hotter corona, and it has been speculated that much of this region lies in small, closed loops that do not rise to coronal heights. (c.f. Dowdy, Rabin, & Moore 1986 and Mariska 1992; also see figure 2.12 in section 2.7). This observation puts constraints on the pathways providing heat to the transition region, as heat tranfer from the corona preferentially occurs along magnetic lines of force. This implies that closed loop structures in the transition region require some alternative heating mechanism.

The TRACE mission is the next step in this process of understanding the solar chromosphere, transition region and corona. TRACE is a 30 cm aperture Cassegrain telescope with four channels to image solar plasmas in three extra-ultraviolet (EUV) wavelengths and a number of UV wavelengths, covering a spectrum of emission lines over a temperature range from 10,000K–1MK. TRACE will collect images with a spatial resolution of 1.0 arcsec (0.5 arcsec pixels) at a maximum temporal resolution of $\approx$ 5 sec. TRACE was launched April 1, 1998 into a sun-synchronous polar orbit, allowing for continuous uninterrupted observing for eight months, followed by a three month eclipse season, then a second observing period of nominally three months. The baseline mission is for one year.

Chapter 2 of this thesis is a description of the UV channel of TRACE. A brief introduction to the capabilities of the instrument and optics is presented. The TRACE instrument is able to image solar plasmas in the H I Lyα λ1216 Å line, the C IV resonance doublet at 1548 and 1550 Å, the UV continuum centered at 1600 Å and a wide-band white-light image centered at 5000 Å. The method for reducing the UV data to produce photometrically accurate C IV images is discussed in some detail. The C IV resonance doublet is superimposed on a UV continuum that increases six orders of magnitude over 1000 Å, making it quite difficult to observe the C IV emission lines with current multilayer technology. Chapter 2 addresses this problem and suggests a method to filter out the contaminating emission from nearby lines and the underlying UV continuum. The capability to make time-lapse observations of the

C IV emission line pair has not been possible since the *Ultraviolet Spectrometer and Polarimeter* (UVSP, Tandberg-Hanssen et al. 1981) on the *Solar Maximum Mission* (SMM). TRACE will provide higher spatial and temporal resolution over a larger field of view. The combination of high spatial resolution and time-lapse imaging makes TRACE a very provocative mission.

1.2 The Magnetic Field: Connecting the Photosphere and Corona.

Several studies of the evolution of the photospheric magnetic field in quiet sun regions have shown the magnetic structures to be evolving on very rapid timeframes: for magnetic features with fluxes exceeding $\approx 2 \times 10^{18}$ Mx as much flux is cancelled as is present in the quiet-Sun network with in 1.5 to 3 days (Schrijver et al. 1997). Hagenaar, Schrijver, & Title (1997) studied the cellular pattern of the supergranular network from Ca II K filtergrams and found supergranule cell diameters of $L =$ 13–18 Mm. Surprisingly, there is little to be found in the literature discussing the corresponding size and timescales of coronal brightenings in the quiet sun to compare to these findings. Numerous references exist that describe active regions that appear to live for multiple solar rotations, and there are similarly numerous references describing time and length scales associated with X-ray Bright Points (XBPs) (Golub, Krieger, & Vaiana 1976a; Golub, Krieger, & Vaiana 1976b; Strong et al. 1992; Harvey-Angle 1993; Harvey 1997), but a systemmatic comparison of evolution in both the photospheric magnetic field and the quiet solar corona does not appear to exist. In chapter 3 the response of the corona visible in the Fe XII 195Å emission line is compared to the evolution of the underlying photospheric magnetic field and also to the results discussed above. It is found that the quiet corona evolves on timescales of 10–15 hours, in favorable comparison to the lifetime of features in the photospheric magnetic field, and it is also found that small-scale coronal brightenings on average are 18–26 Mm in size, slightly larger than the size of a typical supergranule. Emerging flux tends to evolve and grow continuously on a discontinuous basis: the largest-scale structures in the quiet corona are the product of merging and growing flux concentrations in the photosphere, resulting in coronal reconnection to correspondingly larger opposite polarity concentrations. This amounts to a continuous process of small-scale reconnection in the corona, giving rise to an isotropic distribution of coronal brightenings interacting with opposite polarities from nearest-neighbors to stronger concentrations at significantly larger distances.

CHAPTER 2

UV OBSERVATIONS WITH TRACE

2.1 Abstract

The *Transition Region and Coronal Explorer* is a space-borne solar telescope featuring high spatial and temporal resolution. TRACE images emission from solar plasmas in three extreme-ultraviolet (EUV) wavelengths and several ultraviolet (UV) wavelengths, covering selected ion temperatures from 6000 K to 1 MK. The TRACE UV channel employs special optics to collect high resolution solar images of the H I Lyα line at 1216 Å, the C IV resonance doublet at 1548 and 1550 Å, the UV continuum near 1550 Å and also a white light image covering the spectrum from 2000–8000 Å.

We present an analytical technique for creating photometrically accurate images of the C IV resonance lines from the data products collected by the TRACE UV channel. We use solar spectra from several space-borne instruments to represent a variety of solar conditions ranging from quiet sun to active regions to derive a method, using a linear combination of filtered UV images, to generate an image of solar C IV 1550 Å emission. Systematic and statistical error estimates are also presented. This

work indicates that C IV measurements will be reliable for intensities greater than 10^{14} photons $s^{-1}cm^{-2}sr^{-1}$. This suggests that C IV 1550 Å images will be feasible with statistical error below 20% in the magnetic network, bright points, active regions, flares and other features bright in C IV. Below this intensity the derived image is dominated by systematic error and read noise from the CCD.

2.2 Introduction

The UV spectrum provides a wealth of diagnostics for plasmas in the solar transition region and chromosphere. H I Lyα λ 1216 Å and the C IV resonance doublet at λ 1548 and 1550 Å (hereafter shortened to C IV) in particular are interesting lines for observing plasmas with temperatures from 10–100,000 K. Lyα also provides stunning prominence images at the solar limb. Essentially all transition region models (see Fontenla et al. (1990) and references therein) have Lyα as the main energy loss mechanism below 10^5 K. C IV is an interesting diagnostic in a variety of ways. It has also been suggested (Bruner & McWhirter 1988; Doyle 1996) that the total radiated power of an emitting plasma may be deduced from the intensity of C IV. Hawley & Fisher (1994) suggest that the C IV fluxes serve as a pressure diagnostic under appropriate conditions. Brekke et al. (1996) have observed C IV flare intensities to vary by a factor of $\sim$ 15,000 over pre-flare levels.

However, C IV is a difficult line to observe. At 1550 Å, C IV sits atop a UV continuum background that raises five orders of magnitude in intensity over 1200–3500 Å. Various methods have been attempted to generate a "clean" C IV image. The *Ultraviolet Spectrometer and Polarimeter* on the *Solar Maximum Mission* collected images by rastering a grating over a 256×256 pixel image with 3 arcsecond pixels (Woodgate *et al.* 1980). The spectrometer produced relatively clean images with a temporal resolution of about 3 minutes. The *High Resolution Telescope and Spectrograph* (HRTS) sounding rocket experiment employed a tandem Wadsworth Spectrograph with spatial resolution of 1 arcsecond along a 1000 arcsecond slit. HRTS was able to step the slit to cover a 10×800 arcsecond region in 20 seconds. Consequently HRTS was able to map a portion of the solar atmosphere as a function of time (Dere et al. 1984). HRTS used a spectrograph to establish spectral purity. The *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER) experiment on the *Solar and Heliospheric Observatory* is a spectrograph capable of stepping across the solar disk to generate full-sun images with pixel sizes of $\sim$ 1 arcsec px^{-1} and 20-40 mÅ px^{-1}, again at the expense of temporal resolution (Wilhelm et al. 1995). The *Solar Physics Plasma Diagnostics* (SPDE) rocket payload (Damè et al. 1996) observed in C IV and neighboring wavelengths using multilayer optics in the *Transition Region Camera.* The design approach for this instrument was the catalyst for the TRACE UV channel.

The UV channel of TRACE has been designed from the beginning with the intent of estimating C IV emission on a strong UV background. The UV filters in TRACE were chosen to satisfy this requirement, and an analysis with sample solar spectra has been performed to illustrate this approach.

2.3 The TRACE Instrument

2.3.1 Overall Description

The TRACE instrument is a 30 cm aperture Cassegrain telescope intended to observe solar plasmas from 6000 to 1 MK with 1 arcsecond spatial resolution and with high temporal resolution and continuity (Tarbell et al. 1994). The optical path of the

Table 2.1: Telescope Characteristics.

Primary Mirror Diameter	30 cm
Effective Focal Length	8.66 m
Pixel Size	21×21 μm
	0.5×0.5 arcsec
CCD Size	1024×1024 pixels
Field of View	8.5×8.5 arcmin
Wavelength Channels:	Fe IX λ171 Å
	Fe XII λ195 Å
	Fe XV λ284 Å
	H I Lyα λ1216 Å
	C IV λ1550 Å
	White Light λ5000 Å
Image Stabilization	$\pm$ 0.1 arcsec

telescope is illustrated in figure 2.2 and the principal characteristics are given in Table 2.1.

To provide wavelength discrimination the telescope is divided into four quadrants, each of which is sensitive to a different wavelength range. Three of these quadrants are sensitive in the extreme ultraviolet (EUV) and the fourth in the far UV through the visible wavelengths. The EUV quadrant bandpass selections are determined by multilayer coatings on the primary and secondary mirrors. The UV quadrant employs a narrowband all-dielectric primary mirror coated for wavelength selection and a MgF_2/Al overcoated secondary mirror. Further wavelength discrimination is accomplished via a selection of broadband and narrowband filters. Visible light is excluded from the EUV quadrants by thin aluminum entrance filters mounted on a nickel mesh in front of each EUV quadrant. The UV quadrant is shielded by a broadband UV filter. A quadrant selector located directly behind the entrance filters selects which of

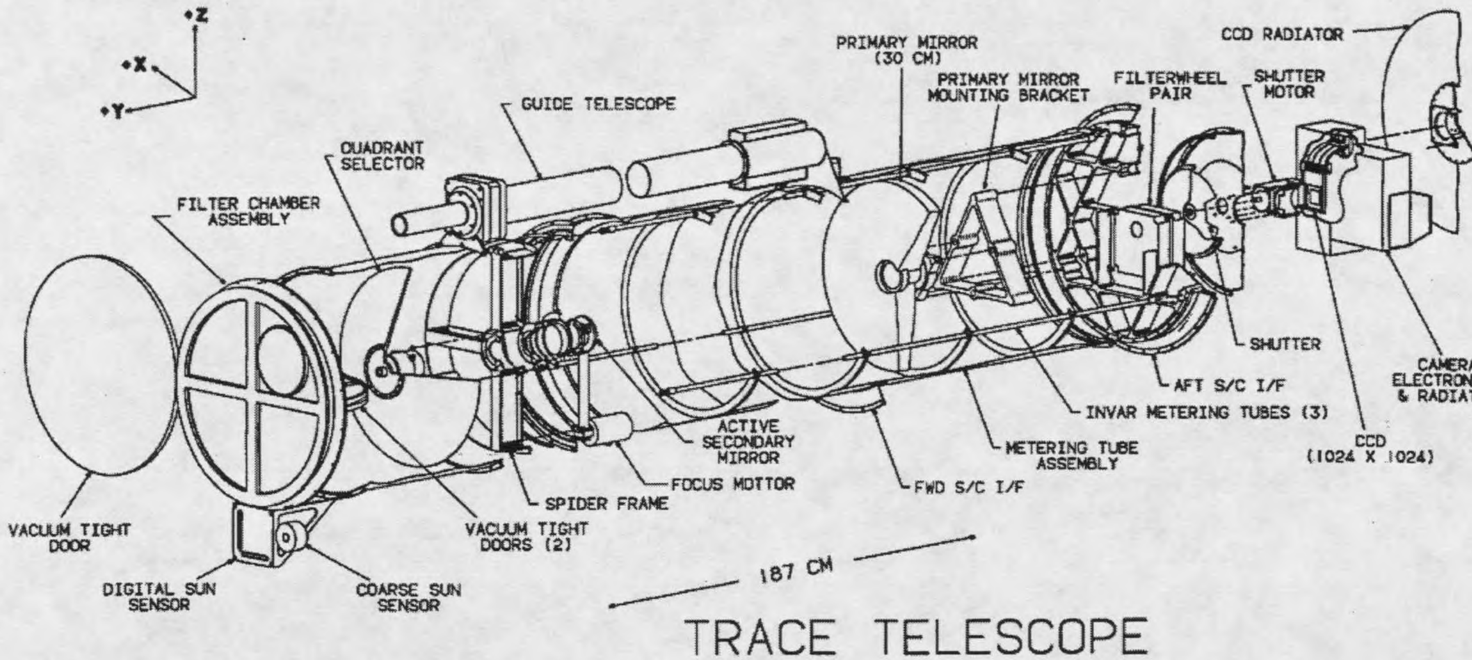

Figure 2.1: The TRACE Instrument.