



Propagating disturbances in the lower solar corona
by Meredith Jennings Wills-Davey

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of
Philosophy in Physics
Montana State University
© Copyright by Meredith Jennings Wills-Davey (2003)

Abstract:

TRACE observations allow us to see propagating coronal waves in multiple narrowband filters and with high spatiotemporal resolution. I analyze four wave-front propagations observed in TRACE, in particular an event from 13 June 1998. Studying morphology and dynamics, I conclude observationally that three of the four fronts are fast-mode MHD waves.

Having developed new mapping algorithms, I automate the tracking of waves with bright fronts by finding reproducible fronts, natural trajectories, and fast-mode velocities in large regions of the quiet corona. I use this automated method to examine the 13 June 1998 event in detail, and determine density and flux changes along several propagation tracks. Various properties of the front - density, amplitude, flux - are found to increase through much of its lifetime, and when these properties stabilize, it experiences almost no dispersion. This suggests that the wave is traveling through a dispersionless medium.

Through comparison of EUV passbands, I am able to place altitude and temperature constraints on the 13 June 1998 event, and show that the front moves only through the lowest part of the corona, trapped in a wave guide. This analysis is reinforced analytically, by considering a propagating MHD wave in a hydrostatic atmosphere, and through existing theories.

Conclusions offer explanations for the dearth of soft x-ray observations of propagating waves, as well as the seeming uniformity of EUV events. In light of the above-mentioned propagation constraints, I address the usefulness of such waves in coronal seismology. Finally, I discuss how seemingly contradictory theories are merely disparate descriptions of the same kind of event.

PROPAGATING DISTURBANCES IN THE
LOWER SOLAR CORONA

by

Meredith Jennings Wills-Davey

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Physics

MONTANA STATE UNIVERSITY — BOZEMAN
Bozeman, Montana

May 2003

APPROVAL

of a dissertation submitted by

Meredith Jennings Wills-Davey

D378
W6854

This dissertation has been read by each member of the dissertation 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.

Loren W. Acton, Ph. D.

Loren W. Acton
(Signature)5/13/03
Date

Approved for the Department of Physics

John C. Hermanson, Ph. D.

John C. Hermanson
(Signature)5-16-03
Date

Approved for the College of Graduate Studies

Bruce R. McLeod, Ph. D.

Bruce R. McLeod
(Signature)5-29-03
Date

STATEMENT OF PERMISSION TO USE

In presenting this dissertation in partial fulfillment of the requirements for a doctoral degree at Montana State University — Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library. I further agree that copying of this thesis is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U. S. Copyright Law. Requests for extensive copying or reproduction of this thesis should be referred to University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan, 48106, to whom I have granted "the exclusive right to reproduce and distribute my dissertation in and from microform along with the non-exclusive right to reproduce and distribute my abstract in any format in whole or in part."

Signature



Date 5-16-03

WITH APOLOGIES TO ROBERT LOUIS STEVENSON:

Dang it, Jim, I'm an astronomer, not a doctor! I mean, I am a doctor, but I'm not *that* kind of doctor. I have a doctorate; it's not the same thing. You can't *help* people with a doctorate! You just sit there and you're *useless*!

- DISNEY'S *Treasure Planet*

ACKNOWLEDGEMENTS

Over the years, this work has become a passion for me. In this body of research, a lot of my best ideas are coming to fruition. I'm sure I will leave important people out here, but please know that, even in my forgetfulness, you are appreciated.

My thanks to my advisor, Loren Acton, for letting me do my project instead of his (and my thanks to Dick Canfield for convincing him). I think all of the scientists in the MSU solar group have contributed to this work in some way; I've marked up the white boards of Piet Martens, Dana Longcope, Charles Kankelborg, and Dave McKenzie in particular. Thanks also to every post-doc, grad student, and undergrad who patiently listened as I rattled off my latest finding.

My thanks to Alan Title, Karel Schrijver and Markus Aschwanden, for the myriad waves they found in the *TRACE* data, and to Vic Pizzo for giving me a first crack at *GOES-SXI*. Thank you to Barbara Thompson for all of her help and collaboration, and to Craig DeForest, for providing an exciting next step.

Finally, special thanks go out to Leon Golub and Ed DeLuca, who, whether they meant to or not, drew me into this field in the first place. And of course, this wouldn't have happened without the love, support, home-cooked meals, and good scientific debate of my husband, Alisdair Davey.

TABLE OF CONTENTS

1. INTRODUCTION	1
“So What are Waves, Really?”	1
The Basic Mathematics of Waves	4
Compressive Propagations in Three Dimensions	5
Previous Studies of Propagating Solar Disturbances	7
Waves in the Chromosphere	8
Waves in the Corona	14
Connecting Chromospheric and Coronal Waves	17
Discrepancies in the Data	18
Our Contribution to the Understanding of Coronal Propagations	22
2. PROPAGATING WAVES IN THE <i>TRACE</i> DATA	25
The <i>TRACE</i> Instrument	25
The 13 June 1998 Wave Event	27
Description of the Data	27
Dynamics in the Original Data	28
Dynamics in the Manipulated Data	32
Effect of the Event on Fine-Scale Structures	35
Observations by Other Instruments	39
Additional Wave Events	44
The 20 October 1999 Event	44
The 30 August 1998 Event	48
The 14 July 1998 Event	52
Overview of these <i>TRACE</i> Wave Observations	57
Constraints of <i>SOHO</i> -EIT and the Effect on EIT Waves	60
3. THE PHYSICS OF MHD WAVES	63

MHD Waves in the Solar Corona	63
The Nature of MHD Waves in the <i>TRACE</i> Data	67
Analysis of the 13 June 1998 Event	71
Creating Meaningful Wave Profiles	74
Calculating Energy Flux	77
The Dispersion of the Wave	84
Loop Oscillations Instigated by MHD Waves	85
Coronal Seismology	92
4. SPATIAL CONSTRAINTS ON WAVE PROPAGATION	98
The Appearance of a Fast-mode Propagation in the Corona	98
Using the 13 June 1998 Event to Constrain Theory	102
Modeling an Unshocked MHD Wave in a Simplified Corona	106
5. CONCLUSION	111
Implications of a Coronal Wave Guide	112
EIT Observations	112
Coronal Seismology	113
The Wave Guide and the 14 July 1998 Event	114
Theories on Fast-Mode MHD Propagation in a Real World Context	115
APPENDICIES	118
Appendix A: Development of Automated Mapping Protocols	119
Appendix B: Magnetohydrodynamics and the Solar Corona	132
BIBLIOGRAPHY	136

LIST OF TABLES

Table	Page
2.1 Times and exposures from the 13 June 1998 event.	29
2.2 Times (in UT) and exposures (in seconds) from the 20 October 1999 event.	46
2.3 Times and exposures from the 30 August 1998 event.	50
2.4 Times and exposures from the 14 July 1998 event.	54

LIST OF FIGURES

Figure		Page
1.1	Hydrogen- α observation from the McMath-Hulbert Observatory, May 10, 1949	9
1.2	Example of a "Moreton wave"	10
1.3	Representation of a fast-mode MHD disturbance in Uchida (1968) .	12
1.4	Example of an "SXT wave"	15
1.5	Example of an "EIT wave"	17
1.6	EUV wavefront cospatial with a Moreton wave	19
1.7	<i>GOES</i> - <i>SXI</i> observation of an EIT wave	21
2.1	13 June 1998: <i>TRACE</i> 195 Å and 171 Å data (This figure is also available as a movie.)	31
2.2	13 June 1998: <i>TRACE</i> emission measure data (This figure is also available as a movie.)	33
2.3	13 June 1998: Automated mapping of the propagation front	34
2.4	13 June 1998: Positions of fine-scale structures	36
2.5	13 June 1998: Average motion of fine-scale structures	38
2.6	13 June 1998: Fine-scale structures and their correspondence to temperature data (This figure is also available as a movie.)	40

2.7	13 June 1998: <i>SOHO</i> -EIT data (This figure is also available as a movie.)	42
2.8	13 June 1998: Movie of <i>SOHO</i> -LASCO data	43
2.9	20 October 1999: <i>TRACE</i> 195 Å full field of view	45
2.10	20 October 1999: <i>TRACE</i> 195 Å subregion data (This figure is also available as a movie.)	46
2.11	20 October 1999: Automated mapping of the propagation front . .	47
2.12	30 August 1998: <i>TRACE</i> 171 Å full field of view	48
2.13	30 August 1998: Movie of <i>TRACE</i> 171 Å subregion data	49
2.14	30 August 1998: Interpretation of subregion data	51
2.15	30 August 1998: Possible “pre-wave” activity	52
2.16	14 July 1998: <i>TRACE</i> 195 Å and 171 Å data (This figure is also available as a movie.)	56
2.17	Properties of wave events considered in this research.	58
3.1	Cartoon showing wave propagation with respect to oscillating magnetic field structures	69
3.2	Response functions for the <i>TRACE</i> 171 Å and 195 Å passbands . .	72
3.3	Density profiles for three trajectories from 13 June 1998 event . . .	78
3.4	Integrated energy flux along each track as a function of time	82
3.5	Mapping of width measurement for dispersion tracking	86

3.6	Change in pulse width as the wave propagates	87
4.1	Temperature as a function of height in a model solar atmosphere . .	105
4.2	Altitudes of reflection for fast-mode waves	110
A.1	Stills showing the progress of an EIT wave	121
A.2	Comparison of front-finding techniques for the 13 June 1998 event .	123
A.3	Propagation fronts and trajectories determined through automated mapping	128

ABSTRACT

TRACE observations allow us to see propagating coronal waves in multiple narrowband filters and with high spatiotemporal resolution. I analyze four wave-front propagations observed in TRACE, in particular an event from 13 June 1998. Studying morphology and dynamics, I conclude observationally that three of the four fronts are fast-mode MHD waves.

Having developed new mapping algorithms, I automate the tracking of waves with bright fronts by finding reproducible fronts, natural trajectories, and fast-mode velocities in large regions of the quiet corona. I use this automated method to examine the 13 June 1998 event in detail, and determine density and flux changes along several propagation tracks. Various properties of the front – density, amplitude, flux – are found to increase through much of its lifetime, and when these properties stabilize, it experiences almost no dispersion. This suggests that the wave is traveling through a dispersionless medium.

Through comparison of EUV passbands, I am able to place altitude and temperature constraints on the 13 June 1998 event, and show that the front moves only through the lowest part of the corona, trapped in a wave guide. This analysis is reinforced analytically, by considering a propagating MHD wave in a hydrostatic atmosphere, and through existing theories.

Conclusions offer explanations for the dearth of soft x-ray observations of propagating waves, as well as the seeming uniformity of EUV events. In light of the above-mentioned propagation constraints, I address the usefulness of such waves in coronal seismology. Finally, I discuss how seemingly contradictory theories are merely disparate descriptions of the same kind of event.

CHAPTER 1

INTRODUCTION

Clear-colored stones
are vibrating in the brook-bed...
or the water is. – SOSEKI

“So What are Waves, Really?”

The word “wave” is an ambiguous term, and largely contextual, regardless of whether it is used in scientific studies or in day-to-day life. Most of our senses depend on waves. Electromagnetic waves enter our eyes and we see; acoustic waves reach our ears and we hear. We float on them on the ocean when we go to the seashore. We perform them with our hands to greet each other across distance. We participate in them at sporting events to cheer our team on.

Intrinsically, all of these waves are the same. Any wave is simply the motion of an object from one place to another and then back to its starting point. A standing wave encompasses only this oscillating behavior.¹ A vibrating guitar

¹In some cases, the word *oscillation* may be used to describe a wave. This is correct in cases

string, for example, moves back and forth in a regular, predictable way, but the string itself stays in roughly the same place; while the string oscillates about a central region, it doesn't really go anywhere.

A traveling wave, on the other hand, travels. It takes the behavior of a standing wave and incorporates it into a propagating motion. With a traveling wave, any given point through which the wave passes will oscillate once, but all points along the wave's path experience the same sort of oscillation. Imagine a string, with beads spaced at regular intervals, attached to a wall very far away at one end and held taut in your hand at the other. Give the end you are holding one firm shake, and you will initiate a traveling wave. If you watch the beads along the string, you will notice that, as the pulse travels along, each bead moves up and down once and then returns to normal. In a conceptual sense, you could think of a traveling wave as the opposite of a standing wave. With a vibrating guitar string, all points along the string move many times around a single equilibrium point. With a traveling wave on a beaded string, all points along the string move for a finite period of time as the wave passes, but the equilibrium point around which each bead's oscillation happens moves from bead to bead along the string.

The important thing to realize about any wave is that, in the end, everything

where a repeating, regular pattern exists. However, while an *oscillation* may always be considered a *wave*, a *wave* is not always an *oscillation*. An example of a non-oscillating wave might be a single traveling pulse on a string.

returns to its initial conditions. Even though the wave itself may travel away, it doesn't take any *stuff* with it. All the wave can take with it is its motion, and any related quantities like energy or momentum. However, it is this transfer of motion that makes the wave interesting. In a sense, the motion that reaches you is information that can be transferred without having to actually send you *stuff*.

In some cases, that information transfer is literal. If someone shouts at you across a great distance, the words you hear are information transfer in the form of waves. In other cases, wave information must be interpreted. If you feel the ground move under your feet, it might be an earthquake, or just a really big truck driving by. You may not be able to differentiate. (That's why they make seismometers.)

What should be most apparent is the simplicity of waves for transmitting information. It is so simple, in fact, that wave transmission appears in all sorts of contexts in the natural world. We may use waves in a deliberate manner (shouting, for instance), but all you really need is something to instigate the wave and the right conditions for it to propagate, and waves will form naturally. They often do, of course. Water waves are an often-cited example; almost anything breaking the surface of smooth water will start some sort of wave. Similarly, all noises are acoustic waves. Any time you become aware of something that happens at any distance from (meaning *not physically touching*) you, chances are you found out about that something because of a (electromagnetic, acoustic etc.) wave.

The Basic Mathematics of Waves

Since all waves can be described in similar ways (they oscillate; they move through things but don't take *stuff* with them; etc...), it should not be surprising that, for the most part, they follow the same mathematical constructs. Typically, waves are described using trigonometric functions,² such as

$$\psi(t) = A \cos(\omega t). \quad (1.1)$$

Here, A is the *amplitude* and the *frequency* of the oscillation is defined by ν where $\omega = 2\pi\nu$. Trigonometric functions essentially define oscillatory behavior. Their derivatives are self-similar (sines produce cosines and *vice versa*), and the inverted nature of sines and cosines produce the self-correction necessary for a particle to move around a central point. Therefore, as a particle moves away from the equilibrium, its velocity decreases, and it eventually turns around and moves back. Similarly, the since the second derivative of a function is its negative, any particle moving away from the center experiences negative acceleration.

Equation (1.1) can be generalized to many situations that involve *simple harmonic motion*. What is especially interesting about simple harmonic motion (and

²This equation is meant to demonstrate a basic trigonometric function, and as such, has been written without a spatial variable. To be more strictly correct, a cosine function describing oscillatory behavior should be written $\psi(x, t) = A \cos(kx - \omega t)$, where x is a position and k is the associated wave number.

subsequently, waves in general) is that the way such a system moves depends on only two things: how you start it moving (or the *initial conditions*) and properties of the system itself. This manifests itself differently depending on the sort of oscillation you are considering. In the case of something like a pendulum, the period is determined, not by the mass of the bob, but by gravity and the length of the string.

Because the properties of the wave derive from the system, in a case where the propagating medium is not well-known, the wave itself can be used as a diagnostic tool. By measuring properties of the wave – amplitude, period, velocity etc. – some specific attributes of the medium can be determined. Of course, the measurable properties may be limited. In the case of the pendulum, the period will tell us a combined factor of gravity and string length. We cannot, for instance, determine the mass of the bob.

Compressive Propagations in Three Dimensions

For the research encompassed in this dissertation, we need to understand waves traveling through compressible media, such as gas or plasma. The waves themselves are created by the interaction of forces that affect the gas, such as pressure, gravity, or electromagnetic forces. If the gas is inherently stable, a perturbation

will cause these forces to act to return the medium to its initial conditions. If the gas overshoots its initial state, it causes a secondary perturbation and recorreption. Over time, this can become an oscillation.

The general solutions in the case of ideal gases are in the form of *plane waves*, with solutions

$$\psi(\mathbf{x}, t) \sim \text{Re}[e^{i[(\mathbf{k} \cdot \mathbf{x}) - \omega t]}], \quad (1.2)$$

where ω is the *frequency* and $\mathbf{k}$ is the *wave number* vector. Various wave quantities can be derived from ω and $\mathbf{k}$, notably the *period* ($T = 2\pi/\omega$), the *wavelength* ($\lambda = 2\pi/k$) and the *direction of propagation* ($\hat{\mathbf{k}} \equiv \mathbf{k}/k$).

Properties of the gas (its pressure, density, velocity etc.) can be described with plane wave solutions. These properties are then related to each other through various conservation laws (conservation of mass, energy, momentum etc.). Manipulating the resulting conservation law equations, it is often possible to create a single equation which define ω and $\mathbf{k}$ in terms of each other. This relationship is called a *dispersion relation*. As an example, the dispersion relation for a sound wave is

$$\omega^2 = \frac{\gamma k_B T}{m} k^2 \quad (1.3)$$

where γ is the ratio of specific heats, k_B is Boltzmann's constant, T is the temperature, and m is the average mass of a particle.

The dispersion relation reveals an inherent relationship between the wave's frequency and its wave number, which can be taken one step further. The velocity of a propagation can be determined from these quantities. The *phase velocity* is the motion of a single constant position along the shape of the wave (the top of a given crest, for example). A phase velocity is defined as

$$v_{ph} = \frac{\omega}{k}. \quad (1.4)$$

The *group velocity*, on the other hand, is the speed at which the energy of the wave packet propagates, and comes from

$$v_{gr} = \frac{\partial \omega}{\partial k}. \quad (1.5)$$

In the case of the sound wave in Equation (1.3), or any dispersion relation where ω and k scale linearly, v_{ph} and v_{gr} are identical. They are also dependent only on properties of the medium, so something like the sound speed is a known quantity, and is independent of the exciter. For the work encompassed in the next few chapters, it is reasonable to assume that any wave velocity is determined by the medium.

Previous Studies of Propagating Solar Disturbances

This research deals primarily with the solar corona. However, propagations across the solar disk were both theorized and observed long before space-based telescopes were able to see actual coronal dynamics.

Waves in the Chromosphere

Evidence of solar wave fronts was first seen in ground-based chromospheric data in the Hydrogen α line. An observation from May, 1949 may be the earliest documented wave event. As part of the study of flaring region, Dodson (1949) notices "a bright 'ejection' appear[ing] in the central region of the flare and spread[ing] southward. [This 'ejection' is] of *plage*-, not flare-intensity..."³ [Dodson's italics]. Chromospheric data from this time show an expansion that might be interpreted as a front (see Figure 1.1).

Studies of sympathetic flaring – instances where one flare appears to instigate another some distance away – by Richardson (1951) and Becker (1958) also postulated waves as a trigger mechanism. Richardson (1951) found that flares occurred nearly simultaneously at disparate points on the disk far more often than random chance would allow. Becker (1958) examined many series of eruptions and filament activations, and concluded that a pair might relate to a single propagating event

³Dodson, H. W., p. 382.

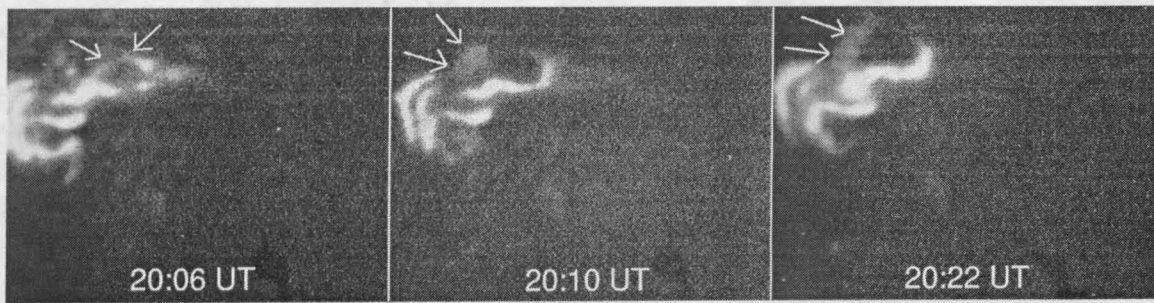


Figure 1.1: Hydrogen- α observation from the McMath-Hulbert Observatory, May 10, 1949. The stills shown above are from Dodson (1949). In her paper, Dodson discusses an “ejection” of “plage-intensity” that originates near the center of the flare. The arrows [inserted by this author] point out what may be the “ejection” Dodson speaks of.

traveling across the disk at speeds of order 2000 km/sec.

Direct observations of the waves themselves was not accomplished until Moreton & Ramsey (1960). While the original straight-line velocities of ~ 1000 km/s were inferred from the relative timing of sympathetic flaring events, eventually observational improvements allowed for direct observation of Doppler shifts, with new measurements showing velocities of $\sim 500 - 2500$ km/s. Subsequent studies (i.e. Athay & Moreton [1961]; Smith & Harvey [1971]) used Doppler imaging to reveal propagations moving away from some flaring regions. Over time, these high-speed chromospheric fronts came to be called “Moreton waves.” An example of a typical Moreton wave observation is shown in Figure 1.2. The data in Figure 1.2 are from an event observed with the Flare Monitoring Telescope at the Hida Observatory on 3 November 1997. Since the event is quite dim, these data are displayed as *running difference* images. Each still is created by taking a piece of normalized

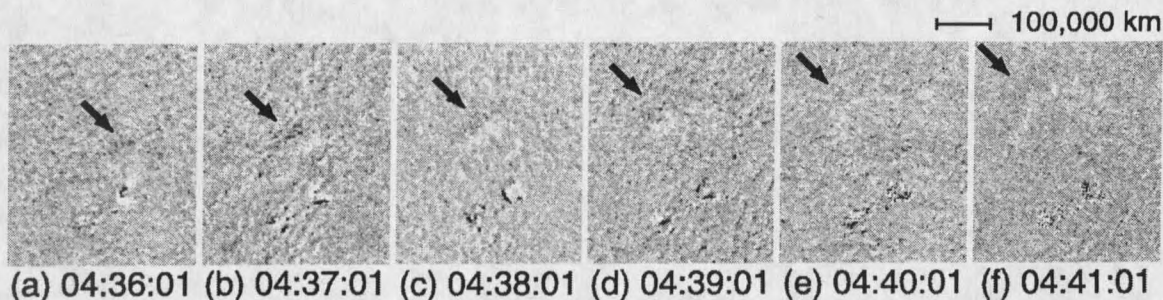


Figure 1.2: Example of a “Moreton wave.” This figure is from Narukage et al. (2002), and shows a typical “Moreton wave” in a series of images. These stills are running difference images; the leading and following bright and dark fronts are an artifact of that process.

data and subtracting the preceding image. Bright areas represent increases in intensity from the previous image; dark areas are decreases. Since subtractions only refer to the previous image, and not some baseline for the entire dataset, running difference images are most useful for following dynamic changes. The adjacent dark and bright fronts in Figure 1.2 signify a propagating dip in intensity.

Moreton waves are by no means common events. In looking at over 4000 flares, Moreton & Ramsey (1960) detected only seven wave events – a rate of less than 0.2%. Smith & Harvey (1971) produced the canonical survey of propagating chromospheric disturbances; their catalogue, spanning 1960 to 1967, contained 60 events. Of these, only fifteen showed detectable fronts; the rest were determined by associating flares and filament oscillations. The visible events appeared more constrained in velocity and structure. Their velocities ranged from 350 to 1125 km/s, with a mean of ~ 600 km/s. This was a smaller spread and lower

mean than the invisible propagations, which varied from 400 to 2000 km/s and averaged 880 km/s. Most of the visible events were also highly directional, usually having an angular width of less than 90° . However, beyond these factors, many fronts displayed individual or unique characteristics. The data set was split evenly between bright and dark propagations. The cohesiveness of fronts varied; some seemed to expand as they traveled, while others maintained their structure. One event from 25 June 1960 showed two different components – one visible and one not – traveling at markedly different speeds. Smith & Harvey saw a great deal of variety in their data set, so much so that they felt “[no] single interpretation or model yet published adequately accounts for all of the observed effects.”⁴

Some of the original wave studies (Moreton & Ramsey [1960]; Moreton [1960]; Smith & Harvey [1971]) found associations between Moreton waves and other large-scale energetic solar phenomena, in particular Type-II radio bursts and geomagnetic storms.⁵ It was this relation with Type-II radio bursts that led to what became the dominant theory for explaining Moreton waves.

Uchida (1968) considered the question of Moreton waves from a coronal, rather than a chromospheric, perspective. Uchida reasoned that waves with a characteristic velocity of ~ 1000 km/s must propagate primarily through the corona. In

⁴Smith, S. F. and Harvey, K. L., p. 159

⁵Dodson (1949) also associated her event with a geomagnetic storm, but she only considered the wave peripherally in her study.

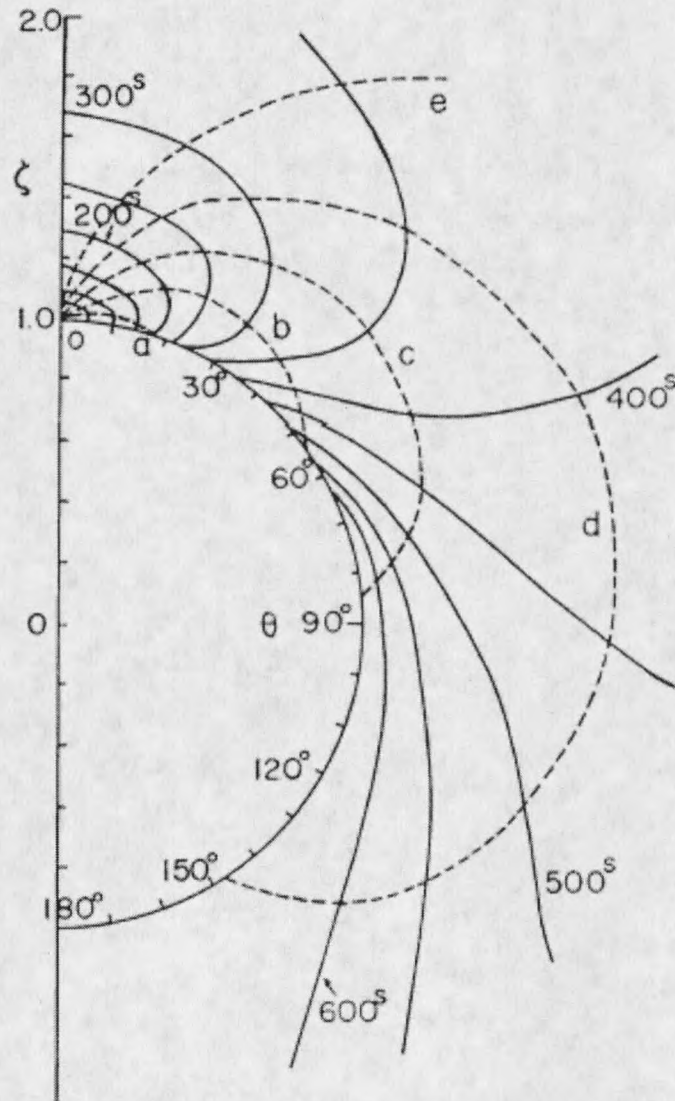


Figure 1.3: Representation of a fast-mode MHD disturbance in Uchida (1968). This figure is the original representation in Uchida (1968) of a coronal shock front propagation. The solid lines show the position of the wavefront over time. Notice that the base of the front reaches down to the solar surface, simulating the “drag” in the chromosphere. The dashed lines are representative paths of wave packets. If the front expands in the manner of a spherical wave, these describe how the front would spread; if the packets are considered more individually, the dashed lines are propagation trajectories.

the chromosphere, the sound speed is of order 10 km/s; anything traveling as fast as a Moreton wave would be unrealistically shocked and would dissipate before traveling a typical Moreton wave propagation distance. On the other hand, such speeds are consistent with the fast-mode magnetohydrodynamic (MHD) velocity in the corona.

Modeling a spherically symmetric corona and an isothermal atmosphere, Uchida found that a fast-mode MHD shock front in the corona would “drag” through the chromosphere. The original figure from Uchida (1968) is shown in Figure 1.3. Such a model could account for the $H\alpha$ and the “action-at-a-distance” observations. The “drag” would also reasonably produce the propagating intensity decrease seen in running difference images. Additionally, a shock front such as the one in Figure 1.3 would also create the related Type-II radio bursts.

Uchida refined his model in subsequent papers (Uchida [1970]; Uchida, Altschuler, & Newkirk [1973]), showing that variations in coronal density and magnetic field strength could lead to the directionality seen by Smith & Harvey (1971). However, until continuous coronal observations were available, his model was only testable in the context of Moreton waves.

Waves in the Corona

The launch of *Yohkoh* (Ogawara et al. [1992]) in 1991 – with its soft x-ray telescope (SXT) – offered the first opportunity to observe large-scale coronal wavefronts directly. *Yohkoh*-SXT had a broadband detector sensitive to coronal emissions with temperatures > 2 MK. Surprisingly, MHD propagations in *Yohkoh*-SXT were not readily apparent. Extensive study of the 10-year database has revealed, to date, three “SXT wave” events, all cospatial with – and showing velocities similar to – Moreton waves (Thompson et al. [2000]; Khan & Aurass [2002]; Narukage et al. [2002]). An example of the SXT wave seen by Khan & Aurass (2002) can be seen in Figure 1.4⁶. Unfortunately, a dropoff in high-cadence continuous chromospheric data resulted in a dearth of Moreton wave observations during *Yohkoh*’s tenure. In this time, though, there is no evidence of a chromospheric Moreton wave having no SXT component, lending some credence to the Uchida (1968) theory.

Such results might suggest that coronal propagations are a rare occurrence; after all, Moreton & Ramsey (1960) found that Moreton waves happened in only a tiny fraction of flares. However, the first images from the Extreme Ultraviolet Imaging Telescope (EIT) – launched aboard the Solar and Heliospheric Observatory (SOHO) in 1997 – revealed a different sort of activity. Rather than a

⁶The events discussed by Khan & Aurass (2002) and Narukage et al. (2002) occurred on the same day and initiated from the same active region. However, they are separated in time by over four hours, and thus have been studied as two different episodes.

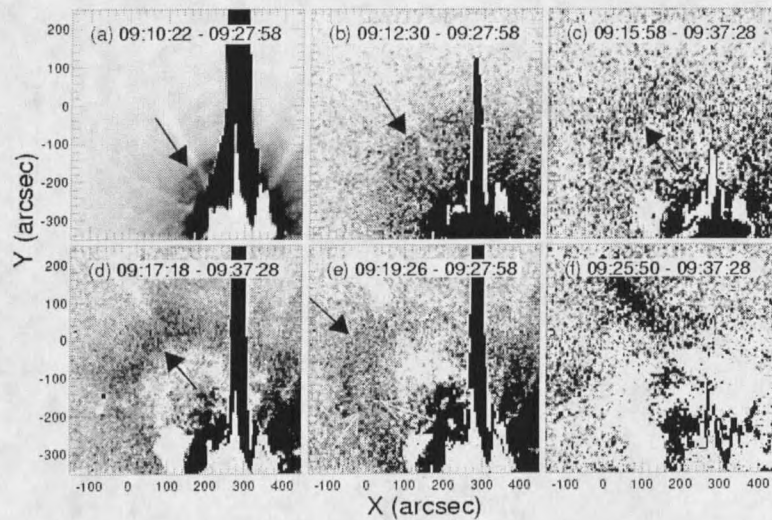


Figure 1.4: Example of an “SXT wave.” This figure is a reproduction from Khan & Aurass (2002). This SXT wave was observed on 3 November 1997 by Yohkoh-SXT, and is associated with a Moreton wave. Like Figure 1.2, these data are shown as running difference images. The spike in the center of each image is saturation of the detector due to the flare.

lack of events, wave fronts are observed quite often by the EUV telescope currently in operation. *SOHO*-EIT, with its full-disk field of view and 15-minute cadence, is characterized by a phenomenon called “EIT waves.” They are typically seen in Fe XII, in the 195 Å passband, with a peak temperature of ~ 1.5 MK. Since their first reporting by Thompson et al. (1998), hundreds of these events have been observed.

EIT waves show an extremely uniform morphology. A typical event can be seen in Figure 1.5. They are large, basically circular propagations, traveling at about 300 km s^{-1} and originating primarily from flaring active regions⁷. Unlike

⁷There is some evidence that EIT waves can result from filament eruptions as well. This is

the narrow, well-defined fronts of Moreton waves, EIT waves always initiate as broad structures⁸, and, being initially dim anyway, fade quickly as they propagate and decrease in amplitude. They are inherently dim structures, and are best observed using difference imaging techniques. The EIT waves seen by *SOHO* are long-lived and seem constrained to travel through regions of low activity. As a result, the number of EIT wave observations appears to vary inversely with the solar cycle.

EIT waves are associated with many of the same energetic phenomena as Moreton waves. Biesecker et al. (2002) has published the most comprehensive study to date looking at waves in *SOHO*-EIT data. They considered 173 events observed from March 1997 through June 1998. Since EIT waves are inherently tenuous, a “quality” rating was applied to each event. These Q-factors described the level of confidence the researchers had that an observation was in fact a propagation – Q0 being a < 10% confidence level, up to Q5 at ~ 100% confidence. Each EIT wave was then correlated with a possible flare, CME, and/or Type-II radio burst. Surprisingly, only 66% of total events were associated with flares, comparable to the total CME association of 58%. However, as the level of confidence in the event went up, the likelihood of an EIT wave correlating with all three phenomena in-

discussed in Chapter 2.

⁸This excludes a single EUV observation from 24 September 1997, studied in Thompson et al. (2000), of a sharp, bow-shaped wavefront.

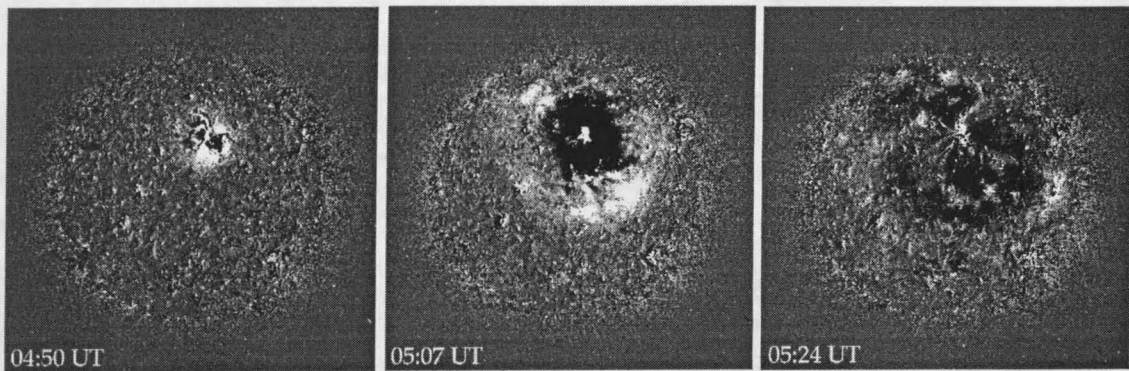


Figure 1.5: Example of an “EIT wave.” This figure shows stills of an EIT wave from 12 May 1997. Because they are dim phenomena, running difference images are used to show morphology. This event is typical in that it is global, roughly circular, and long-lived.

creased; all events with a Q5 rating had related flares, CMEs, *and* Type-II radio bursts. Klassen et al. (2000) also looked at correlations between EIT waves and Type-II radio bursts. Looking at 21 radio events, they found that EIT waves corresponded to 90% of their sample. EIT waves have also become associated with the “coronal dimming” commonly seen with CMEs (Harra & Sterling [2001], [2003]). In fact, EIT waves seem to occur in circumstances so similar to Moreton waves that one wonders about the connection.

Connecting Chromospheric and Coronal Waves

The primary differentiating factor between EIT- and Moreton waves appears to be frequency – Moreton waves are rare, EIT waves are common. In the few cases where data are available, Moreton waves always have associated EIT waves

(Pohjolainen et al. [2001]; Warmuth et al. [2001]; Eto et al. [2002]; Vršnak et al. [2002] etc.). It might even seem that EIT waves are the likely candidate for a spatial transition between Moreton waves in the chromosphere and SXT waves in the x-ray corona. Unfortunately, the observations themselves may be harder to reconcile. Khan & Aurass (2002) and Narukage et al. (2002) show good spatiotemporal correlation between soft x-ray and $H\alpha$ wave fronts when comparing high-cadence (~ 1 minute) data. However, since *SOHO*-EIT typically takes data in ~ 15 minute intervals, EUV observations have insufficient temporal resolution for direct comparison. Moreton and SXT waves have lifetimes shorter than the cadence offered by *SOHO*-EIT, allowing no dynamic overlap. At present, only two observations have been published where a *SOHO*-EIT exposure time correlates well with the lifetime of a Moreton wave (Thompson et al. [2000]; Pohjolainen et al. [2001]). Both observations coincide well spatially with the Moreton wave, and, in the case of Thompson et al. (2000), a bow-shaped front is visible in the normalized 195 Å data. This particular front is different from other EUV wave observations; it is sharp and narrow, and it is visible in a still frame without the aid of differencing. The $H\alpha$ data are unusual as well, in that the Moreton wavefront is visible even without difference imaging. Figure 1.6 shows the Thompson et al. (2000) event.

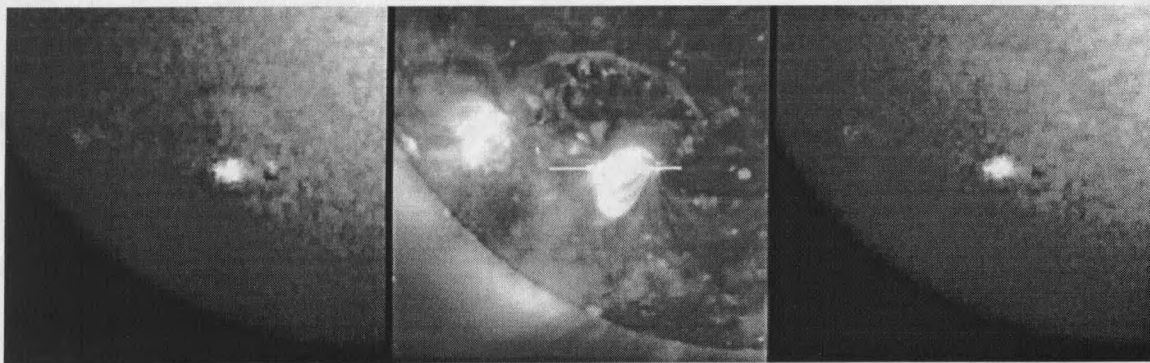


Figure 1.6: EUV wavefront cospatial with a Moreton wave. This figure from Thompson et al. (2000) shows observations from 24 September 1997 in SOHO-EIT 195 Å and H α . Unlike a typical EIT wave, this event is visible in EUV as a bow-shaped front that is cospatial with the Moreton wave. Neither dataset requires differencing.

Discrepancies in the Data

Data such as those in Figure 1.6 suggests that Moreton waves have coronal components. However, the much higher rate of EIT wave events suggests that coronal waves rarely penetrate the chromosphere. And, outside of the Thompson et al. (2000) study, it is generally difficult to treat EIT- and Moreton waves as a single phenomenon.

There is also one major discrepancy in existing contemporaneous observations – The velocities of Moreton and EIT waves differ considerably. Moreton waves exhibit velocities of > 600 km/s, while their EIT wave counterparts move at ~ 300 km/s, often for the same event (i.e. Eto et al. [2002]; Khan & Aurass [2002]). In these cases, the faster wave will be seen in ~ 1 minute cadence data very close to a flare, while the more diffuse wave appears after a longer time and farther away, in

some part due to the ~ 15 minute cadence of the *SOHO*-EIT observations. Even in the next exposure after that shown in Figure 1.6, the front diffused considerably, and the subsequent propagation was much more representative of an EIT wave. (Figure A.1 in Appendix A shows the entire EIT wave for this event.)

All of the EIT wave studies to date are hampered by slow EUV cadence; the 15 minute separation between frames will not allow for a dynamic velocity measurement of > 600 km/s. It is perhaps not even reasonable to expect good velocity confirmations from current *SOHO*-EIT observations.

Since the two types of waves are otherwise related in so many ways, new theories have tried to account for the velocity discrepancy. Warmuth et al. (2001) propose that a constant deceleration can connect the early, fast Moreton wave observations to the later, slower EIT waves. The events they look at can all be fit with curves showing a similar deceleration. Vršnak et al. (2002) follow up this theory by showing that such decelerations can be produced by a shock whose front is weakly inclined to the solar surface. Following a different tack, Chen et al. (2002) model a piston shock event and find that a double wave front is created – a leading narrow shock front (the Moreton wave) followed by a diffuse density perturbation (the EIT wave). Present data seems to support both models equally well. Until higher cadence EUV observations see a Moreton wave event, we will be hampered in our understanding of the relationship between Moreton- and EIT waves.

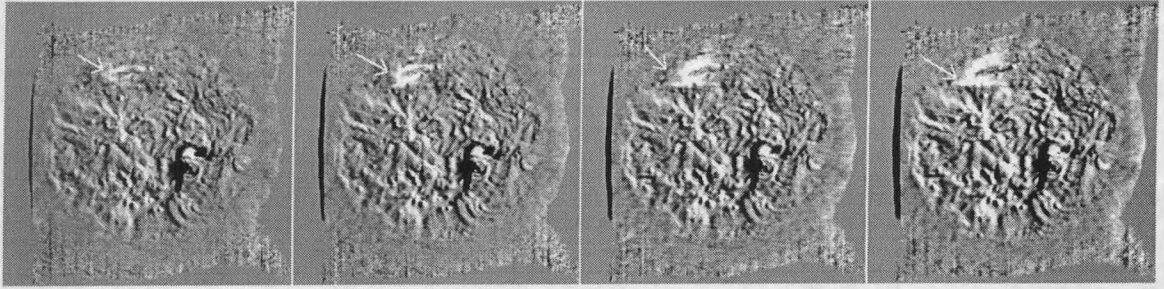


Figure 1.7: *GOES-SXI* observation of an EIT wave. These stills show a wave event seen by the Solar X-ray Imager aboard *GOES-12*. Allowing for differences due to the broadband nature of the detector, the morphology of the wave is similar to those seen by *SOHO-EIT*. *This figure was produced courtesy of V. Pizzo.*

Unfortunately, neither of the hypotheses address the overabundance of EUV waves⁹, or the lack of wave observations in soft x-rays. It is possible the difference might lie in the detectors themselves. *SOHO-EIT* uses multi-layer, narrow-band filter technology, constraining observations to limited temperature ranges – in the case of the 195 Å passband, around 1.5 MK. On the other hand, *Yohkoh-SXT* was a broadband, multi-temperature instrument, with observations starting at around 2 MK. The differences between SXT and EUV observations suggested several possibilities: (a) EIT waves can only exist at temperatures < 2 MK; (b) The structure of the low to middle corona (where we observe in EUV) is more conducive to the initial wave formation than the higher temperature corona where SXT observed; and/or (c) EIT waves exist at a variety of temperatures, but the limited range

⁹There is some implication with the Chen et al. (2002) model that a shock front should precede all EIT waves, and that the problem is our observational techniques. Starting from this assumption may have led to rather artificial conclusions in recent papers, notably Shibata et al. (2002) and Harra & Sterling (2003).

of the EUV detector allows for easier observation (implying that perhaps the dim events are “washed out” in a broadband detector).

New light has been shed on this last idea – that EIT waves are easily observed by narrow-band filters, but may be “washed out” when observed with a broadband instrument – by recent observations from *GOES*-12 Solar X-ray Imager (SXI) (Hill & Pizzo 2002). SXI is a broadband instrument operating with spatial resolution comparable to SXT and EIT, but with a 1-minute cadence. The 0.6-6.0 nm band-pass allows for observations down to lower temperatures (~ 1 MK) than those seen in SXT. Despite its limited viewing time, SXI has already observed several propagation events comparable to those seen by *SOHO*-EIT. Figure 1.7 shows an example of one such event. The morphology of the event is by no means identical to those seen in *SOHO*-EIT, but characteristics such as the velocity and the diffuse nature of the front suggest an EIT wave. This observation was also obtained during a short calibration run of a few days, suggesting the event was likely quite common. While future analysis needs to be done, these early results suggest that broadband instruments are capable of seeing EIT waves, meaning the differences in observations are temperature- or formation-, rather than instrument-related.

Our Contribution to the Understanding of Coronal Propagations

Up to now, the studies of coronal wavefronts have focused primarily on data from the *SOHO*-EIT and *Yohkoh*-SXT instruments. The work has been largely subjective – relying on visual inspection to find wavefronts – and physical parameters, such as changes in plasma properties due to the wave, have not been considered. Additionally, the current theoretical research primarily addresses the connection between EIT- and Moreton waves, not acknowledging the radical difference in occurrence rate between the two phenomena. There are as yet no theories postulating the existence of EIT waves by themselves.

In this work, the question of EIT waves is addressed using a new and largely unused source of data – the Transition Region and Coronal Explorer (*TRACE*). The *TRACE* telescope is the same sort of detector as *SOHO*-EIT, but benefits from faster cadence, allowing us to circumvent the slow cadence issue plaguing typical EIT wave observations. Additionally, higher cadence has allowed us to see evidence of waves in ways that would be invisible to *SOHO*. In Chapter 2, we examine four wave events seen in the *TRACE* telescope, and discuss how these observations contribute to the existing body of knowledge on coronal waves.

The quality of the *TRACE* data also allows us to finally derive meaningful physical parameters from the observations. In Chapter 3, we focus on one exceptional *TRACE* event and use its morphology and dynamics to better understand

the physics of the wave and the surrounding corona. This particular event offers us the rare opportunity to justify physical assumptions using data dynamics. We also discuss how such a wave event can be used as a diagnostic tool in the growing field of "coronal seismology."

In Chapter 4, we consider the existence of EIT waves as phenomena independent of a faster shock front. By examining *TRACE* observations and placing them in their coronal context, we find theoretical constraints on the propagation of unshocked coronal waves. Using these constraints to formulate a hypothesis, we create and test a simple model in which EIT waves are trapped in a wave guide in the lowest layers of the corona. We show how this model is consistent with myriad aspects of the observed data.

We conclude with a discussion of the *TRACE* data and the next steps that are required to further our observational understanding. We also consider the implications of our wave guide theory.

CHAPTER 2

PROPAGATING WAVES IN THE *TRACE* DATAThe *TRACE* Instrument

TRACE – the Transition Region And Coronal Explorer (Handy et al. [1999]) – is a normal-incidence telescope used in conjunction with *SOHO*. It encompasses a field of view of $511'' \times 511''$, or approximately 350 Mm. At maximum resolution, *TRACE* images 1024×1024 pixels of $0.499''$ each; however, summed 2×2 observations, resulting in $0.998''$ pixels, are also common. The propagations considered here are seen only in the EUV. Channels correspond to Fe IX/X ($171 \text{ \AA}$) and Fe XII ($195 \text{ \AA}$), with peak sensitivity at 1 and 1.5 MK, respectively. For the 13 June 1998 event, UV data ($1216 \text{ \AA}$) was also examined for evidence of a corresponding chromospheric counterpart (Moreton wave). Evidence of large-scale propagations has not yet been seen in lower temperature channels, and data are insufficient in the higher temperature *TRACE* passbands.

Although the EUV channels of the *TRACE* instrument are comparable to those seen by *SOHO*-EIT, there are marked differences in spatial and temporal resolu-

tion. At its highest resolution, EIT pixels are $2.59''$ across; when the field of view encompasses the entire solar disk, EIT uses 2×2 binning, resulting in pixels of $5.18''$. Most observations of EIT waves take place during the instrument's "CME Watch" – a program which takes full-disk $195 \text{ \AA}$ data continuously at 15-17 minute ($\sim 10^3$ second) intervals. Conversely, the *TRACE* data discussed in the following sections have a spatial resolution of $< 1''$, with cadences that vary from 12 to 120 seconds.

Such spatiotemporal resolution differences mean that a single event can result in complementary observations (as is discussed in the following section). It also means that it is possible for *TRACE* to see wave events that are invisible to *SOHO*-EIT. Three of the four events discussed in the following section are of this type.¹ At present, only a handful of wave events observed by *TRACE* have been reported. Most of these are small and short-lived, and are not seen by *SOHO*-EIT. However, little examination has been done of the *TRACE* database specifically looking for propagation fronts. A more systematic study has been compiled by D. C. Myers of the *SOHO*-EIT database (Myers & Thompson [2002]). Unfortunately, it only includes events through June 1998, after which time EIT waves were deemed too difficult to catalogue due to increased solar activity. This is only two months into

¹The 14 July 1998 event was actually a rather large event, but it took place during the *SOHO* loss period. Presumably, if the data had been available, it would have been observable by *SOHO*-EIT.

the *TRACE* observation period, so cross-correlation with the Myers database has resulted in a only single overlap. Unfortunately, it is likely that discovery of further *TRACE* events will have to be done independently from *SOHO*-EIT.

The 13 June 1998 Wave Event

This event is one of the best current *TRACE* observations of a propagation front. Many aspects of this wave front have already been considered by Wills-Davey & Thompson (1999) .

Description of the Data

These data were initially obtained as part of Joint Observing Program (JOP) 082 coordinated by K. Harvey, which looked for canceling flux in magnetic bipoles. JOP082 contains observations from *TRACE*; *SOHO*-EIT, -MDI, and -CDS; *Yohkoh*-SXT; and various ground-based observatories. Study of this event is drawn mainly from the *TRACE* data, with *SOHO*-EIT used in a supplementary capacity. For this JOP, *TRACE* took contemporaneous data in several wavelengths, and pointing focused on a Quiet Sun region at disk center.

We examine 42 images, taken 15:24:58 – 15:45:11 UT; the frames cycle through the *TRACE* 1216, 171, and 195 Å passbands. The wave event is only visible in 28 of

the 42 images; no evidence of the wave can be seen in the chromospheric (1216 Å) data. The lack of a chromospheric component (both cospatially or preceding the wavefront) leads us to question theories that require a Moreton (or any shock) wave to precede an EIT wave.² The 171 Å images were taken at full-resolution, while the 195 Å data have summed 2×2 pixels. Table 2.1 provides the time and exposure of each image. The dataset covers a total of 20 min 13 s, after which the *TRACE* satellite entered the South Atlantic Anomaly. At this time, the instrument experienced a ten-minute data gap, and images immediately subsequent are degraded for several minutes due to excessive cosmic ray hits. As a result, all meaningful evidence of the propagation front is lost. This confines our analysis to the data shown in Table 2.1. Fortunately, this interval does contain the entire motion of the front as it passes through the field of view, so we are only constrained in our study of residual motions, such as coronal loop oscillations.

Dynamics in the Original Data

A movie of this event is shown in Movie 2.1. This and all the movies discussed in this research are available on the accompanying CD-ROM, or can be found at <http://solar.physics.montana.edu/meredith/Thesis/>. Whenever possible, it

²It is possible that even the high temporal resolution of *TRACE* is insufficient to see the shock waves required in these models. If this is the case, the shock front must either be super-Alfvénic ($v > 2500$ km/s) or have a lifetime of under a minute.

Table 2.1: Times and exposures from the 13 June 1998 event. These observations are available contemporaneously in both the 171 Å and 195 Å passbands.

<i>TRACE</i> 171 Å		<i>TRACE</i> 195 Å	
Time (UT)	Exposure (s)	Time (UT)	Exposure (s)
15:25:24	16.384	15:25:52	23.172
15:26:27	16.384	15:27:11	38.968
15:27:44	16.384	15:28:54	65.536
15:29:28	27.556	15:29:56	23.172
15:30:42	27.556	15:31:26	38.968
15:32:10	27.556	15:33:20	65.536
15:34:05	27.556	15:34:32	23.172
15:35:17	27.556	15:36:01	38.968
15:36:45	27.556	15:37:55	65.536
15:38:39	27.556	15:39:07	23.172
15:39:52	27.556	15:40:35	38.968
15:41:20	27.556	15:42:30	65.536
15:43:15	27.556	15:43:43	23.172
15:44:28	27.556	15:45:11	38.968

is best to refer to the dynamic representation of these data, either alone or in conjunction with still figures. Movie 2.1(a) and (c) show the 195 and 171 Å data, while (b) and (d) present corresponding *base difference* images. These are images where the same pre-event image has been subtracted from each subsequent image. Base difference images are useful for revealing changes in intensity due to the event. They also help reveal subtle structures, such as the otherwise dim propagating intensity increase in the 195 Å data. Figure 2.1 shows the same data as still frames. For the purposes of this writing, Figure 2.1 and Movie 2.1 are essentially interchangeable. In the figure captions, references to the movies specifically will be presented in SMALL CAPS. Hereafter, whenever we refer to Figure 2.1, please

consider it a reference to Movie 2.1 as well. A similar convention may be also be used with subsequent data sets.

This propagation event was initiated by a *GOES*-class C2.9 flare in AR 8237. A coherent front passes across the entire *TRACE* field of view in less than 20 minutes. It affects the surrounding plasma both through the front's localized brightening and by instigating fine-scale disturbances such as coronal loop oscillations. While over-arching structures react to the propagation, it has no noticeable effect on compact structures, such as x-ray bright points.

The 195 Å data [shown in Figure 2.1(a) and (b)] show an event which is comparable to an EIT wave. The 195 Å base difference data in Figure 2.1(b) shows what appears to be a "bright front" originating below the south center of the field of view and propagating north and northeast. This bright front is followed by spatially-contained, long-lived "dimming region."

However, the 171 Å data are less typical of EIT observations. While a propagation is apparent in Movie 2.1(c) and (d), the front is not bright and distinct. Instead, it is defined primarily through the motion of fine-scale coronal structures. In early frames, it might even be characterized as a "propagating dimming." It is the fine-scale motion that really stands out in the 171 Å images. In particular, two structures – in the southwest corner and across the northern region of the field of view – are comparable to previously studied oscillating loops (i.e. Aschwanden

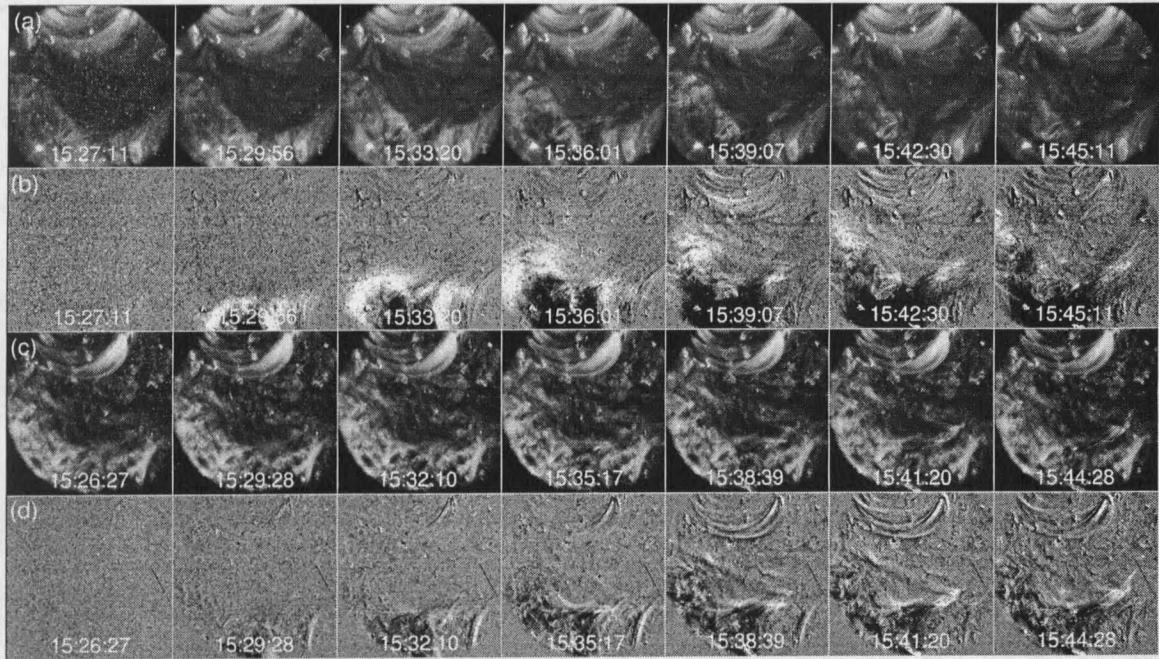


Figure 2.1: 13 June 1998: *TRACE* 195 Å and 171 Å data. (This figure is also available as a movie.) Each row shows a series of still frames, excerpts from a complete dataset of 14 images taken 15:25:24 - 15:45:11 UT. The time of each image is given at the bottom of the frame. The data in each row are as follows: (a) 195 Å normalized data, (b) 195 Å base difference images, (c) 171 Å normalized data, (d) 171 Å base difference images. Data taken at 15:25:52 UT has been subtracted from each of the 195 Å base difference images; the 171 Å data are differenced with data taken at 15:25:24 UT. Because the same image has been subtracted to form each base difference image, any positive (white) or negative (black) regions correspond to genuine changes in intensity. Region (b) shows the propagation of a strong “bright” front; such a propagation represents either a region of increased density or an area moving into the peak 195 Å passband temperature. A propagation is also visible in Region (d), but the front is less well-defined. These differences suggest that the effect of the front is somehow localized, either in space or temperature, since the 1 MK and the 1.5 MK passbands are affected differently. The labeling of the accompanying movie figure is identical. In that case, the datasets (a) – (d) are shown dynamically, and all images from each dataset are included. Although the images will all be shown simultaneously with an even cadence, each image will be labeled with its proper observation time.

et al. [1999] or Schrijver, Aschwanden & Title [2002]). Wills-Davey & Thompson (1999) have already used the 171 Å data to track visually the motion of these sets of loops.

Dynamics in the Manipulated Data

The noticeable differences between the two EUV datasets prompted us to find a way to combine the two so that the results would be more physical and less dependent on things like peak passband temperature. The results were three new datasets.

The first combined the 171 and 195 Å passbands simply by aligning the images and taking a ratio of 195 Å/171 Å. This served to enhance the bright propagating front and increase the contrast of otherwise dim fine-scale structures from the 171 Å data.

The other two datasets attempted to define the data in more meaningful physical quantities. Since the response functions for the 171 and 195 Å overlap, with certain simplifications it is possible to use these data to determine local temperature and emission measure. A routine (`trace_teem.pro`) to do this exists in the Solarsoft Library. By definition, the two-dimensional nature of the data will lead to a spatial ambiguity. However, our intention is to derive values only from base difference images. This is reasonable if we assume that any changes are due only

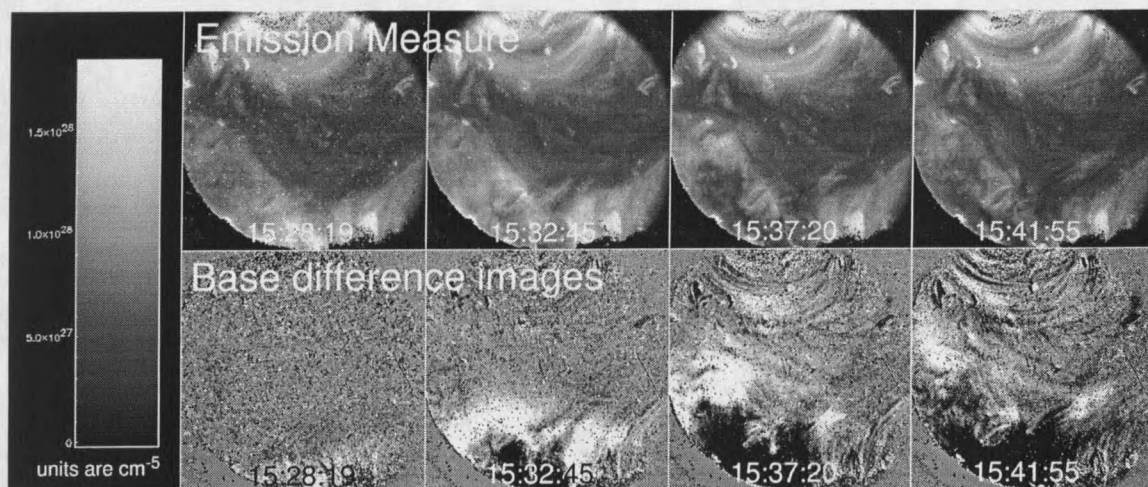


Figure 2.2: 13 June 1998: *TRACE* emission measure data. (This figure is also available as a movie.) This figure shows still frames of emission measure data derived from the 195 Å and 171 Å in Figure 2.1. The times given are the averages of the times of the data used to create each image. The first row is in units of emission measure, corresponding to the color bar on the side. The second row consists of images differenced from the 15:25:38 UT emission measure data. The color gradation of the base difference images is designed primarily to show morphology, and only positive (white) or negative (black) changes in emission measure should be considered. In the accompanying movie figure, the emission measure data is shown on the left, and units correspond to the color bar. The base difference images are shown on the right.

to the wave, that the wave is spatially localized, and that its temperature does not extend out of the range of *TRACE* observation limits. The extremely quiet sun through which the wave passes satisfies the first criterion; the second two are accounted for in the physical constraints on the wave (discussed in Chapter 4).

After using the ratio data as an internal check for consistency (see Appendix A), the motion of the bright front is derived from the emission measure data. (Examples of the emission measure data can be seen in Figure 2.2 and Movie 2.2. To the

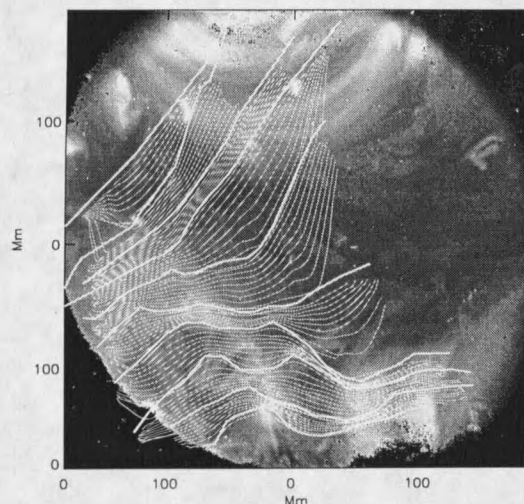


Figure 2.3: 13 June 1998: Automated mapping of the propagation front. This figure shows the position of the bright front in the emission measure data (see Figure 2.2) in ten of the fourteen frames. To give a sense of propagation speeds at points in space, “mini-fronts” have been interpolated between the measured fronts in ten-second intervals. Some of the interpolations may display spurious effects (especially at the edges), but the basic areas of speeding up, slowing down, and turning are apparent.

casual observer, it appears similar to the 195 Å data in Figure 2.1.) Using automated mapping methods, we were able to determine the position of peak intensity along the bright front for ten of the fourteen images.³ To understand better how the wavefront moved from one position to the next between frames, we also interpolated “mini-fronts” between the peak intensity ridges at ten-second intervals. A tracing of the propagation fronts can be seen in Figure 2.3.

Our automated results show that the front originates outside of the field of view

³The automated methods used to determine these fronts are discussed in Appendix A.

on the southern edge (presumably at the site of the flare) and propagates north and northeast through the field of view. The eastern edge of front moves relatively uniformly towards the northeast, while the western edge starts by propagating northward and then turns toward the northeast.⁴ The mean propagation velocity is ~ 300 km/s, although the velocities vary between 100-600 km/s at different points in space and time.

The velocity variations are due primarily to the turn. Looking at Figure 2.1 (a) and (c), the region in which the front appears to turn (the center of the field of view) is noticeably dimmer than other areas through which the front passes. This dim area may correspond to a region of lower density, presenting two possible explanations for the observed turn. If the front is an MHD wave (discussed in more detail in Chapter 3), it could be a genuine refraction. Uchida, Altschuler, & Newkirk (1973) show that fast-mode MHD waves will refract away from regions of lower density. However, in a region that is so dim, it can be difficult to find and map a propagating intensity increase. It is also possible that Figure 2.3 is inaccurate, and the front does not turn at all, or at least not as significantly. This possibility is discussed in more detail in Appendix A.

⁴When cardinal directions are used to in the context of the solar disk, it is assumed that one is looking up from the Earth towards the Sun and referring to the cardinal directions of their position. Therefore, while North and South are the same, East and West are mirrored.

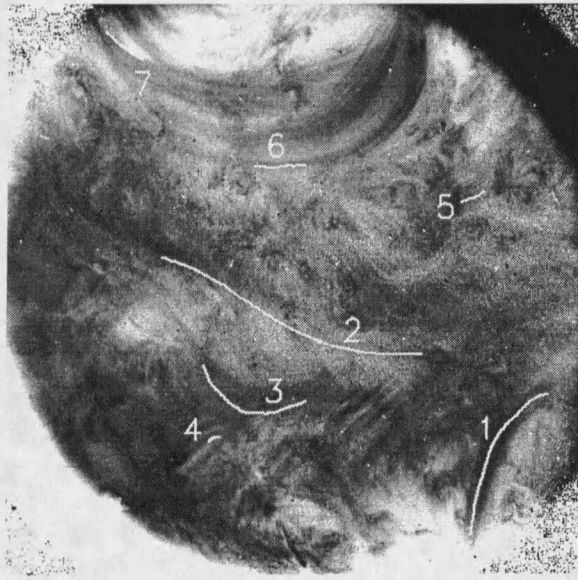


Figure 2.4: 13 June 1998: Positions of fine-scale structures. The data shown here is a still of the $195 \text{ \AA}/171 \text{ \AA}$ ratio data from 13 June 1998. Superimposed are the positions of seven fine-scale structures that exhibit substantial motion due to the wave. The tracings shown are considered the initial conditions for the data in Figure 2.5, which show the average motion of each structure. The numbers correspond to the labeling of the plots.

Effect of the Event on Fine-Scale Structures

Previous work by Wills-Davey & Thompson (1999) used only the $171 \text{ \AA}$ data to determine fine-scale structure motions (in particular, coronal loop oscillations). By using the ratio data mentioned in the previous section, we can take advantage of higher contrast in the combined data and study a larger number of structures (some of them less coherent).

Figure 2.4 shows seven structures in which we measured coherent motion due to the propagation front. Wills-Davey & Thompson (1999) focused on the regions

now labeled 1, 6 and 7. That study – done using observer-chosen points as opposed to the current automated technique – determined that the loop in the southwest corner experienced one entire oscillation and then started a second before the data dropout. Because the onset time was later, the loop spanning the north of the image only had time to oscillate once during the observing time. The limits of the available data make it impossible to determine if these structures (with the possible exception of 1 and 4) experienced real oscillation or merely relaxed back to their initial conditions.

In Figure 2.5, there are graphs of the average motion of each structure around its initial conditions as a function of time. These seven regions were chosen primarily to show examples of the effect a propagating disturbance can have on surrounding plasma. Particular structures (or parts of structures) were chosen because they displayed motion equivalent to first-order oscillation modes, and would thus produce meaningful values when averaged.

Not all of the structures are well-defined individual loops. Loop 2 appears to move coherently, but may be a collection of large, diffuse loops. Loops 6 and 7 are both part of the same large loop network, but their spatial separation causes them to react differently to the wavefront. The location of loop 5 is interesting in light of Figure 2.3. While it shows oscillatory motion, loop 5 is located *outside* of the measured path of the wavefront. This suggests that the wave probably does travel

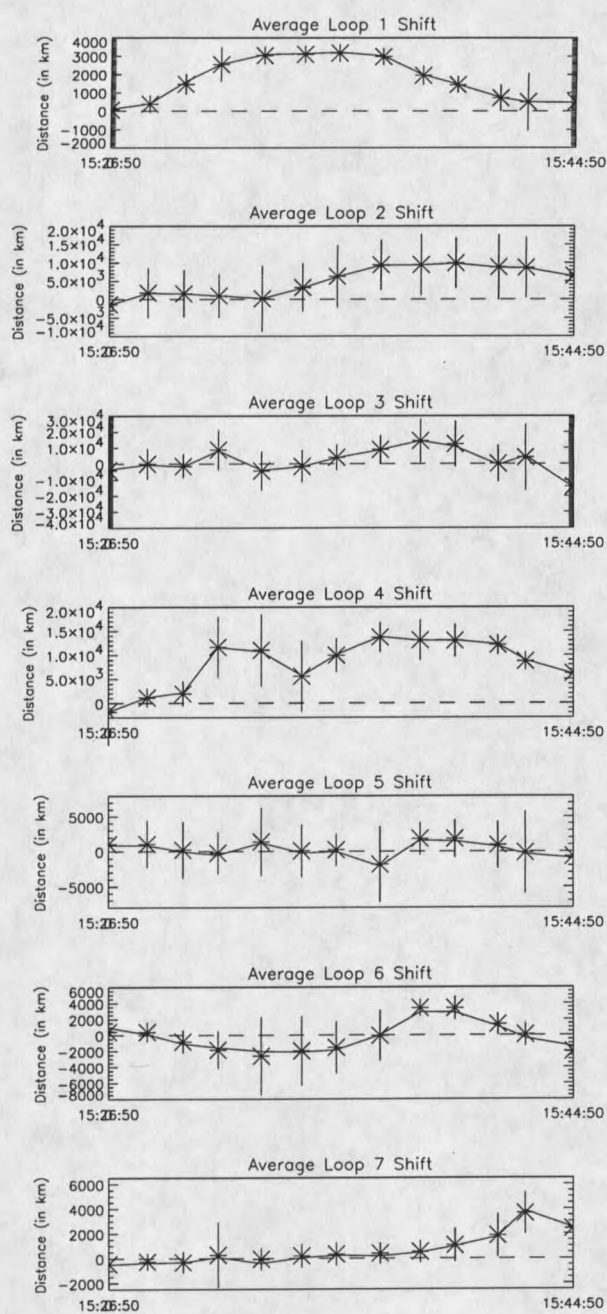


Figure 2.5: 13 June 1998: Average motion of fine-scale structures. Average motion of the fine-scale structures shown in Figure 2.4; the labeling of the plots corresponds to the numbering of the structures.

through the northwest corner of the field of view, and is simply immeasurable using intensity profiles.

The temperature of the fine-scale structures is also interesting. Figure 2.6 shows a temperature image with the seven loop structures superimposed. The accompanying color bar gives the range of temperatures. While these data do suffer from a two-dimensional/three-dimensional ambiguity, there is a noticeable dichotomy between cooler fine structures (~ 1.2 MK) and hotter diffuse material (~ 1.5 MK). When the wave passes through the region, the ambient diffuse material appears to be heated to even higher temperatures. However, each of structures showing quasi-oscillatory motion is a region of *cooler* material. A movie of the temperature data (Movie 2.6) reinforces a dichotomy between fine-scale cooler structures and hotter surrounding diffuse material. While it is important to consider these temperature calculations skeptically, the fact that there *is* a dichotomy should not be dismissed.

Observations by Other Instruments

While the *TRACE* observations of this event offer high spatiotemporal resolution in multiple wavelengths, they suffer from limited time span and limited field of view. Fortunately, this propagation occurred during a well-observed JOP, so complementary data are available.

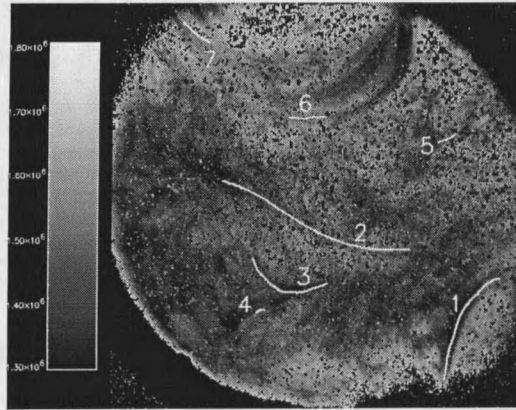


Figure 2.6: 13 June 1998: Fine-scale structures and their correspondence to temperature data. (This figure is also available as a movie.) This image is a still of temperature data from 13 June 1998. The color gradation corresponds to the color bar at the left. Superimposed on this image are the fine-scale structures shown in Figure 2.4. Each of the areas where we observe fine-scale motion is cooler than the surrounding material. The accompanying movie shows all of the temperature data instead of a single image. This better demonstrates that it is the cooler structures that seem to exhibit fine-scale motion.

SOHO-EIT offers the most relevant contemporaneous data. Because of its cadence, EIT has only one observation – taken at 15:40:08 UT – that directly overlaps the *TRACE* dataset.⁵ However, their data are full-disk and are available for some time after the *TRACE* data drops out. Movie 2.7 shows running difference⁶ and base difference images of the event and for an hour subsequent. The movie starts several frames before the event, at 14:50:43 UT. The start of the flare in AR 8237 can be seen in the third frame, at 15:23:33 UT. Evidence of the bright front is

⁵There is some evidence that the previous image, taken at 15:23:33 UT, observes the earliest stages of the flare in AR 8237, but this is technically outside of the *TRACE* field of view.

⁶In *running difference* images, data are differenced with the images taken immediately before. These are good for following dynamics, but should not be used quantitatively, since this type of differencing can introduce artifacts.

most visible in the fourth frame [also shown in Figure 2.7(a)]. Watching subsequent frames of the base difference movie, there may be evidence of the front continuing to propagate northeast for several frames. However, this is only barely visibly discernable, and could most likely not be measured using our automated methods.⁷

TRACE's field of view is limited, and the event initiates outside of it. Comparison with the *SOHO*-EIT data can help determine the entire trajectory of the front. The disturbance in Figure 2.7(a) shows that the front was only directed north of the active region. Additionally, it appears to be constrained to travel in a narrow wedge. There is no evidence that the wavefront travels outside of a set of transequatorial loops that connect the southern and northern active regions. In fact, the loops appear to start oscillating after the bright front disappears, suggesting that these transequatorial loops may have absorbed the wave energy [see Figure 2.7(b)]. Motion continues in the transequatorial field lines until 70 minutes after the initial disturbance.

This limited propagation trajectory is similar to those found by Smith & Harvey (1971) pertaining to chromospheric Moreton wave trajectories. Serendipitously, the *TRACE* field of view – between the north and south active regions and bounded west and east by transequatorial loops – seems to have encompassed the majority

⁷The difficulties of reproducibly finding EIT waves in the *SOHO*-EIT data are discussed in Appendix A on page 120.

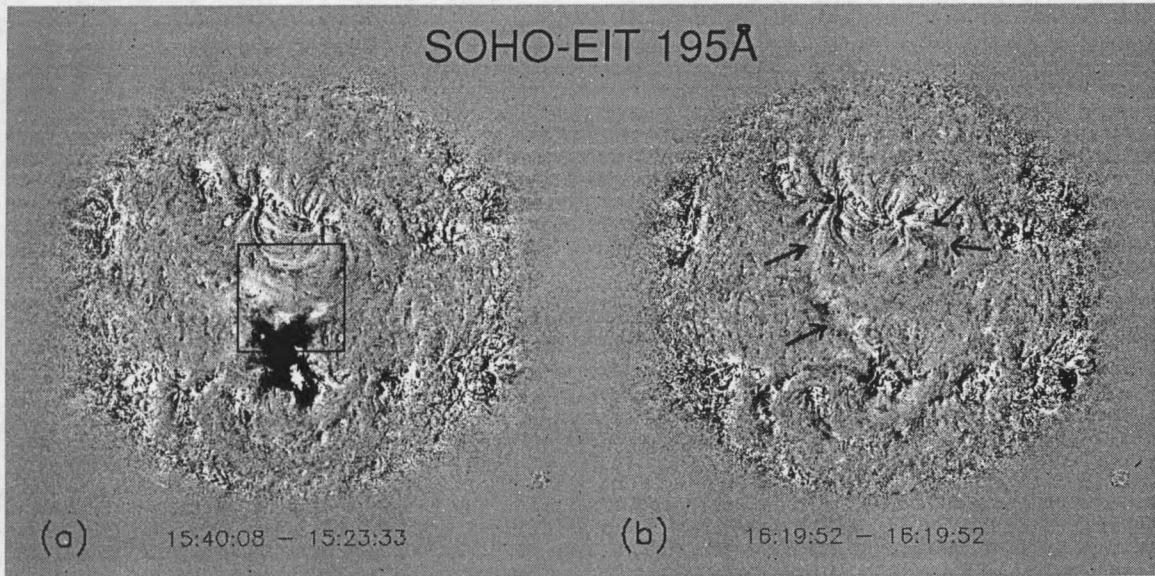


Figure 2.7: 13 June 1998: *SOHO*-EIT data. (This figure is also available as a movie.) The two frames in this figure show effects of the 13 June 1998 event observed by *SOHO*-EIT. Both stills are running difference images; the times at the bottom correspond to the two images involved in each subtraction. (a) is a difference image of the 13 June 1998 wave event as observed by EIT's "CME Watch," coinciding with the *TRACE* observation times. The *TRACE* field of view has been superimposed on this image. (b) shows motion in the transequatorial loops surrounding the region in which the event took place. The movie shows nine frames of difference images, spanning 14:50:43 - 16:50:33 UT. Images on the left are running difference images; those on the right are base difference images. The first frame of the running difference images, and all of the base difference images, have data from 14:35:42 UT subtracted from them. Frames (a) and (b) from the paper figure are labeled as such in the running difference movie, but watching the event dynamically provides better evidence of motion in the transequatorial field lines. In the base difference movie, it may be possible to see the northeast front propagate beyond the *TRACE* field of view for several frames. This visual observation is, however, subjective.



Figure 2.8: 13 June 1998: Movie of *SOHO*-LASCO data. This figure shows a still from the movie. The movie shows running difference images of LASCO C2 data. A partial halo CME is visible off the south limb.

of the wave event. Unfortunately, due to the data dropout, we are unable to watch the entire lifetime in detail.

Movie 2.7 shows the same persistent dimming observed in the *TRACE* data. Harra & Sterling (2001) have found that dimming regions associated with large-scale coronal propagations can be the result of coronal mass ejections (CMEs). This event does appear to be a CME, as is evidenced in the *SOHO*-LASCO data. At 16:06:05 UT, LASCO C2 observed a partial halo CME south of disk center which was observable until 23:06:05 UT. A movie of this CME can be seen in Movie 2.8.

The partial halo implies the CME could be earth-directed. On 18 June 1998,

WIND data show an interaction with a small solar wind disturbance. The coincident *LASCO* and *WIND* observations provide evidence that the event observed in *TRACE* may be associated with a CME. This fits with findings compiled by Biesecker et al. (2002), who find that 58% of EIT waves are CME-related phenomena.

Additional Wave Events

The 20 October 1999 Event

This propagation event differs from typical observations. Its instigator is not a flare, but a filament eruption. While such an initiation is unusual, this is not the only evidence of an eruption-driven front; Foley et al. (2003) describe another such event from 10 April 2001.

Observations of the event exist only in the 195 Å channel, and these data were taken over a 3/4 *TRACE* field of view – $384'' \times 384''$ images with 0.499'' pixels. We are interested in only a portion of the field of view near the northeast corner. Figure 2.9 shows the sub-region with respect to the entire *TRACE* field of view. Our data set contains 52 images, taken 05:51:49 - 06:07:49 UT. Table 2.2 lists the times and exposures of each image. We observe a period spanning 21 min 39 s. The exposure times and cadence during this event are significantly faster than

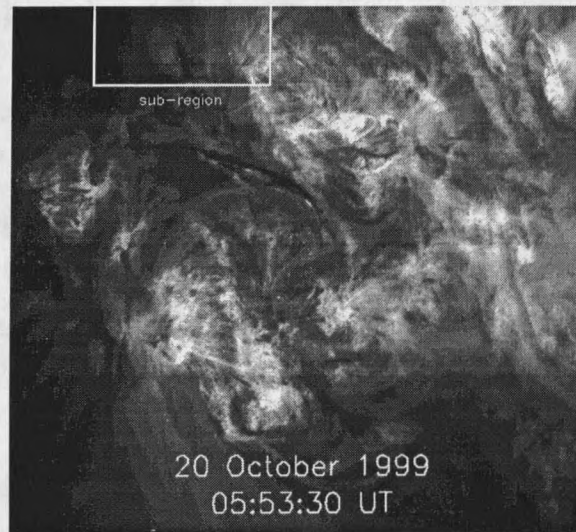


Figure 2.9: 20 October 1999: *TRACE* 195 Å full field of view. This image is a still from the time of the event, showing the entire *TRACE* field of view and the sub-region being considered in our study of the 20 October 1999 event.

those of the 13 June 1998 observations.

A movie of the dynamics of the sub-region can be seen in Movie 2.10, and example stills are shown in Figure 2.10. Since the event is quite simple, we only show base difference images. While a bright moving front is visible, there are no observable mass motions or loop oscillations.

An automated mapping of the motion of the bright front is shown in figure 2.11. These fronts are much closer together than those of the 13 June 1998 data, and may even suffer from overlap due to noise. What makes the 20 October 1999 wave unique is its velocity – it appears to move at ~ 50 km/s. In any region of the corona, such motion is subsonic. Current thinking holds that EIT waves are

Table 2.2: Times (in UT) and exposures (in seconds) from the 20 October 1999 event.

<i>TRACE</i> 195 Å							
Time	Exp	Time	Exp	Time	Exp	Time	Exp
05:51:49	13.776	05:56:52	13.776	06:00:36	13.776	06:04:21	13.776
05:52:20	13.776	05:57:09	13.776	06:00:54	13.776	06:04:39	13.776
05:52:50	13.776	05:57:26	13.776	06:01:11	13.776	06:04:56	13.776
05:53:20	13.776	05:57:43	13.776	06:01:28	13.776	06:05:13	13.776
05:53:50	13.776	05:58:01	13.776	06:01:46	13.776	06:05:31	13.776
05:54:20	13.776	05:58:18	13.776	06:02:03	13.776	06:05:48	13.776
05:54:50	13.776	05:58:35	13.776	06:02:20	13.776	06:06:05	13.776
05:55:19	13.776	05:58:53	13.776	06:02:38	13.776	06:06:22	13.776
05:55:40	2.896	05:59:10	13.776	06:02:55	13.776	06:06:40	13.776
05:55:48	4.872	05:59:27	13.776	06:03:12	13.776	06:06:57	13.776
05:56:00	8.192	05:59:45	13.776	06:03:29	13.776	06:07:14	13.776
05:56:17	13.776	06:00:02	13.776	06:03:47	13.776	06:07:32	13.776
05:56:34	13.776	06:00:19	13.776	06:04:04	13.776	06:07:49	13.776

20 October 1999 Base Difference Images



Figure 2.10: 20 October 1999: *TRACE* 195 Å subregion data. (This figure is also available as a movie.) These data are shown only as base difference images, with the 05:48:19 UT data subtracted from each image. The series of stills shows excerpts of the data; corresponding times are at the bottom of each frame. THE MOVIE IS LABELED JUST LIKE THE STILL FIGURE, BUT INCLUDES THE ENTIRE DATASET.

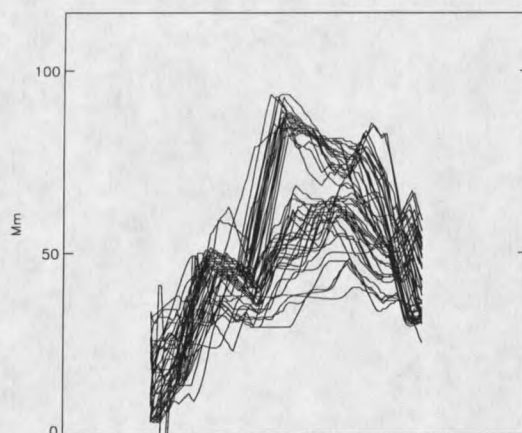


Figure 2.11: 20 October 1999: Automated mapping of the propagation front. This figure tracks the motion of bright front observed in the $195 \text{ \AA}$ data in Figure 2.10. All fronts shown are derived from original data; no interpolation was necessary.

fast-mode MHD propagations; we consider this postulation in greater detail in the next chapter. If we agree with these theories, then no EIT wave can be sub-sonic, and this observation must be a different phenomenon.

The question arises: what is it that is propagating? There is measureable motion in the weak bright front in Figure 2.10, and following the front is a dimming region. One possibility is the “bald patch flare” model proposed by Delannée & Aulanier (1999). Here, a propagating reconnection front creates opening field lines and allows material to escape in the form of a CME. It is possible the large-scale structural changes caused by the filament eruption could trigger such a front. This would account for the bright front and following dimming region, as well as why the front does not appear to instigate mass motions.

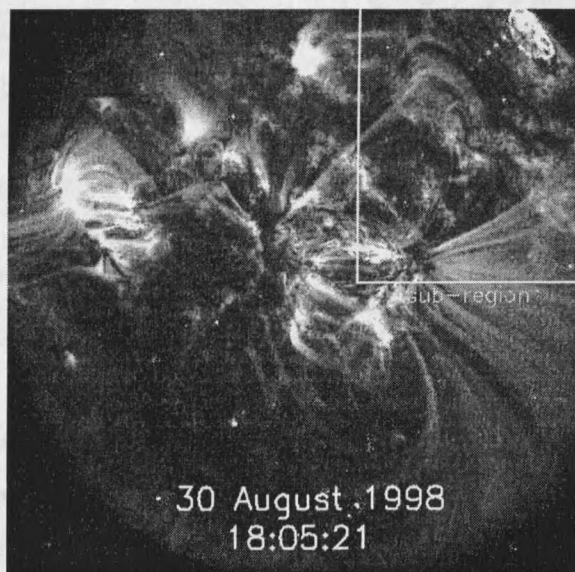


Figure 2.12: 30 August 1998: *TRACE* 171 Å full field of view. This image shows the entire *TRACE* field of view, pointing out the position of the subregion to be examined in this section.

The 30 August 1998 Event

This observation is a prime example of an event that is invisible to *SOHO*-EIT. This event is initiated by a M1.3 *GOES*-class flare in AR 8397, but in this case no discernable front is visible. We are aware of the event because of the resulting loop oscillations. We presume something has propagated from the flare to the nearby magnetic field because it is the most logical way to explain the onset of loop motions.

At the time of this event, *TRACE* was observing in the 171 Å passband and taking 2×2 summed images. The instigating flare occurs at the extreme northwest edge of the *TRACE* field of view, and evidence of the wave propagates about 3'

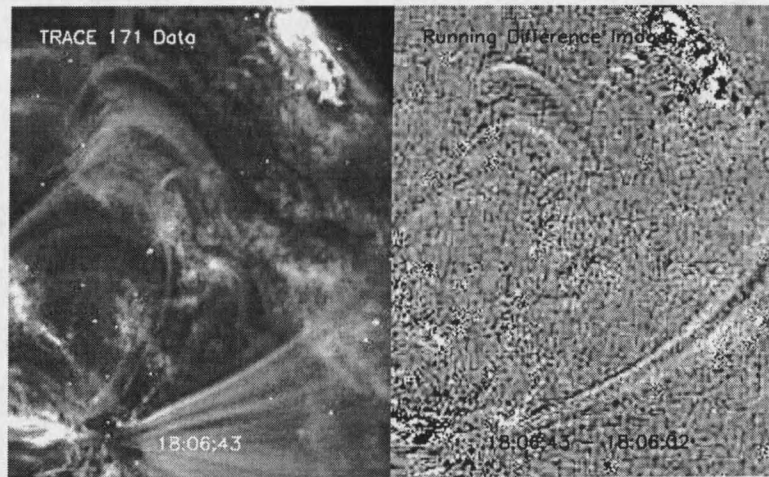


Figure 2.13: 30 August 1998: Movie of *TRACE* 171 Å subregion data. This figure shows a still from the movie. The frames on the left show the 171 Å normalized data, and the frames on the right are running difference images of these data. Times at the bottom correspond to the time of observation or the data involved in the subtraction.

into view. Subsequent figures refer to the subsection of the field of view shown in Figure 2.12. Movie 2.13 shows the event dynamically, both in the *TRACE* 171 Å data and as a series of running difference images.

The data set consists of 17 images, taken 18:01:26 - 18:12:04 UT, with the total observation covering 10 min 38 s. The times and exposures of each image are shown in Table 2.3.

Figure 2.14 traces out the positions of the two oscillating loops in the subregion – one to the southwest and one to the southeast of the flaring region. A possible extension has been added to the southwestern loop. Movie 2.13 shows that the southwest structure starts oscillating earlier, despite its apparent position

Table 2.3: Times and exposures from the 30 August 1998 event.

<i>TRACE</i> 195 Å			
Time (UT)	Exposure (s)	Time (UT)	Exposure (s)
18:01:26	5.792	18:07:26	5.792
18:02:02	2.048	18:08:02	2.048
18:02:43	3.444	18:08:43	3.444
18:03:23	5.792	18:09:26	5.792
18:04:02	2.048	18:10:02	2.048
18:04:43	3.444	18:10:43	3.444
18:05:21	1.216	18:11:23	3.444
18:06:02	2.048	18:12:04	3.444
18:06:43	3.444		

farther away than the eastern loop formation. This suggests that, outside of the field of view, the southwestern structure might pass close to the flaring region. Figure 2.14 gives a possible projection of the southwestern loop that could account for the oscillation timing.

Incorporating this extension, we can obtain rough velocity calculations (assuming straight line trajectories and neglecting projection effects) – 300-700 km/s for the southwestern loop and 200-400 km/s for the southeastern loop. These results suggest a mean speed of ~ 300 km/s.

The lack of a discernable front in the 30 August 1998 event is unexpected. However, we might expect some differences from typical EIT wave observations, given that these data are 171 Å versus *SOHO*-EIT's usual 195 Å. Since the velocities appear similar, it might not be unreasonable to compare this wave to the 171 Å from the 13 June 1998 event. In that case, we also see no bright propagation front.

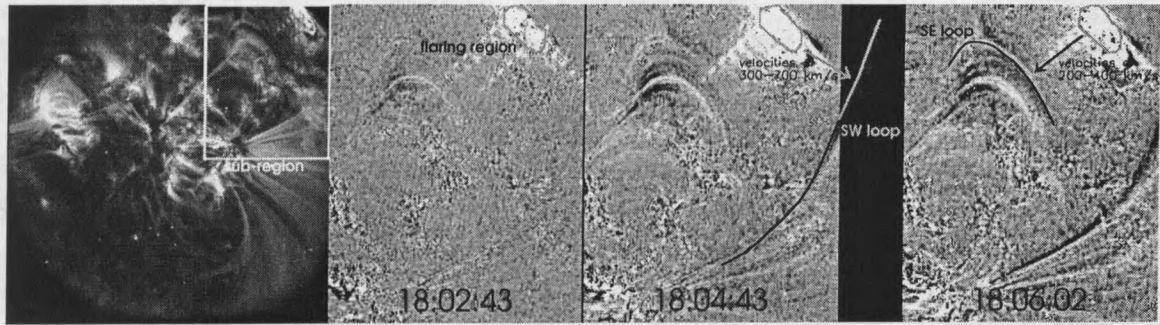


Figure 2.14: 30 August 1998: Interpretation of subregion data. Successive running difference images show the time of the flare and the loop oscillation onset times. A continuation of the southwest loop is drawn in, to demonstrate one possible geometry. Straight line velocity ranges associated with each loop onset time are included.

Unfortunately, there are no available $195 \text{ \AA}$ data, so we cannot see if this event has a corresponding bright front. When we consider the propagation speed, however, as well as the similarity to the 13 June 1998 $171 \text{ \AA}$ data, one might surmise that, given suitable $195 \text{ \AA}$ an EIT wave might have been observable.

In spite of the sparseness of the data, there may be additional information about the nature of the propagation. The first frame of Movie 2.13 shows evidence of a possible “pre-wave” event. The eastern loop brightens slightly several minutes before the oscillations start. A still of this brightening is also shown in Figure 2.15 (although the brightening is more visible when viewed as part of the movie). Any transmission from the flare to this loop brightening is $\geq 1300 \text{ km/s}$, of the order of the maximum fast-mode MHD velocity.

Such “pre-wave” activity might be consistent with simulations performed by

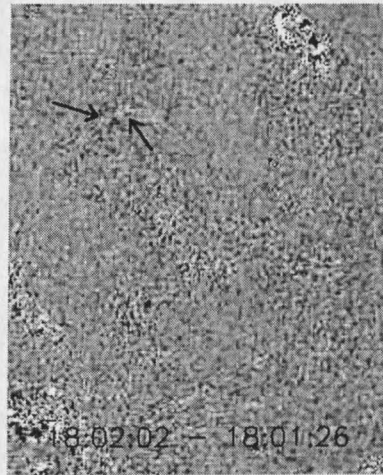


Figure 2.15: 30 August 1998: Possible “pre-wave” activity. This frame is a running difference image showing the first difference frame that includes the flare. The arrows point to the pre-wave brightening. Assuming the event begins just as the first exposure ends, information must travel from the flaring region at ≥ 1300 km/s.

Chen et al. (2002) and Uchida et al. (2001). Their results show that a piston-driven shock will produce a double wave front in the corona – a weak shock front (a Moreton wave) traveling at the maximum fast-mode velocity and a large-amplitude density deformation following at a fraction of that speed. The velocity observations from 30 August 1998 match these predictions. However, it is difficult to tell if the small brightening shown in Figure 2.15 is evidence of a shock front, or if loop oscillations imply a persistent enhancement.

The 14 July 1998 Event

This event (commonly referred to as “The Bastille Day Flare 1998”) is apparently responsible for more publications than any other one solar event. It has

been used to further the study of coronal seismology (DeMoortel, Hood, & Ireland 2002), coronal loop oscillations (Aschwanden et al. 1999), and flares (Aulanier et al. 2000). At present, the wave in this event has not been studied in as much detail as the other fronts mentioned above. Here, we will discuss the morphology of the wave front in the context of the other three. We will not, however, go into the same level of detail as in the 13 June 1998 event.

This wave is instigated as part of a flare in AR 8270. We examine 30 images, taken 12:52:46 - 13:29:53 UT. The times and exposures of each image are listed in Table 2.4. Our dataset covers a time of 37 min 7 s. This wave may be the only other that *TRACE* has seen in two wavelengths – 171 and 195 Å. Because the flare takes place at the center of the field of view, these data have shorter exposure times, making the wave less noticeable. In fact, while effects of the wavefront have been studied by Aschwanden et al. (1999), no previous research has made an attempt to find and study the propagation.

Movie 2.16 and Figure 2.16 show the event in both wavelengths. One difference from the 13 June 1998 data is immediately apparent. In the base difference images shown in Figure 2.1(b) and (d), a propagating bright front is apparent in *both* the 171 and the 195 Å data. The front does not appear to propagate uniformly, but rather emerges on the southeast side of the active region. Over a few frames, the front “swings around” the active region, resulting finally in a propagation that may

Table 2.4: Times and exposures from the 14 July 1998 event.

<i>TRACE</i> 171 Å		<i>TRACE</i> 195 Å	
Time (UT)	Exposure (s)	Time (UT)	Exposure (s)
12:52:46	16.384	12:53:41	13.776
12:54:01	16.384	12:54:56	13.776
12:55:16	16.384	12:56:11	13.776
12:56:32	16.384	12:57:22	9.740
12:57:38	11.584	12:58:37	6.888
12:58:50	8.192	12:59:47	4.872
12:59:57	5.792	13:01:01	3.444
13:01:09	4.096	13:02:17	4.096
13:02:26	4.872	13:03:32	4.872
13:03:43	5.792	13:04:49	5.792
13:05:00	6.888	13:06:02	4.096
13:06:15	8.192	13:07:18	4.872
13:07:32	9.740	13:08:34	5.792
13:08:50	11.584	13:09:50	6.888
13:10:06	11.584	13:11:03	4.872
13:11:21	13.776	13:12:22	5.792
13:12:36	9.740	13:13:35	6.888
13:13:51	11.584	13:14:48	4.872
13:15:01	8.192	13:16:04	5.792
13:16:19	9.740	13:17:21	6.888
13:17:32	6.888	13:18:34	4.872
13:18:46	8.192	13:19:50	5.792
13:20:04	9.740	13:21:06	6.888
13:21:22	11.584	13:22:22	4.872
13:22:35	8.192	13:23:35	5.792
13:23:49	9.740	13:24:51	6.888
13:25:07	11.584	13:26:11	8.192
13:26:29	13.776	13:27:24	9.740
13:27:38	9.740	13:28:41	11.584
13:28:57	11.584	13:29:53	8.192

be roughly circular. (It is difficult to be sure, since the front has already moved out of the eastern side of the field of view, and we have no access to corroborating data.) The active region at the center of the field of view is left in a region of persistent dimming, suggesting a typical "coronal dimming" event. Were there *SOHO*-EIT observations of this event, it is reasonable to assume it would appear as an EIT wave.

Since the wavefront initiates in the center of the image, we can only watch the propagation traverse half the field of view (unlike the 13 June 1998). However, the higher cadence compensates for the smaller distance, so we are able to observe the wave in roughly the same number of images.

Rather than moving at the ~ 300 km/s that seems to be common with EIT waves, initial results show that this front travels at up to ~ 500 km/s. This is currently the fastest observed velocity for an EIT wave. The implications of this faster velocity are still under consideration, and will be discussed in more detail in Chapter 4.

There is some evidence in this event of behavior predicted by Uchida, Altschuler, & Newkirk (1973). Their work finds that fast-mode MHD waves will refract away from regions of higher Alfvén speed. Here, as the front interacts with the small magnetic region in the northeast of the field of view, one can observe the front reflecting and causing a secondary wave. This reflection is visible in both wave-

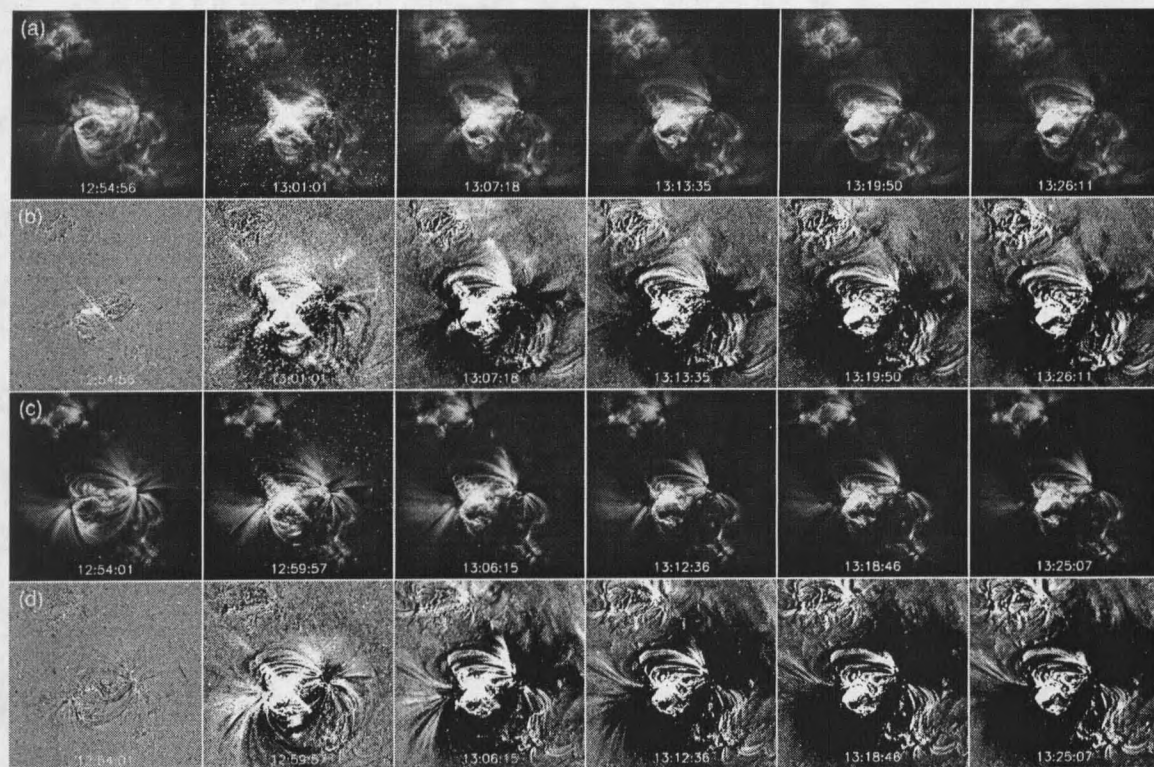


Figure 2.16: 14 July 1998: *TRACE* 195 Å and 171 Å data. (This figure is also available as a movie.) Each row shows excerpts from the thirty image dataset taken 12:52:46 - 13:29:53 UT. The data in each row are as follows: (a) 195 Å normalized data, (b) 195 Å base difference images, (c) 171 Å normalized data, (d) 171 Å base difference images. The time of each images is given at the bottom of the frame. 195 Å images have been differenced with 12:53:41 UT data; data from 12:52:46 UT has been subtracted from the 171 Å images. The wave observed in this event is the fastest of any yet seen in EUV, traveling at ~ 500 km/s. It is also the only event with bright fronts visible in both the 195 and 171 Å passbands. For the movie, labeling of data points is identical, but the entire dataset has been included. During later images, a reflection of the wave is visible in the northern region of the field of view, as the wavefront interacts with the magnetic region north of the active region. This appears to be the only evidence we have of wave reflection in the corona, although it is consistent with theories put forth by Uchida (1970).

lengths.

Both this and the 13 June 1998 observation appear to be the same type of event. Their similarities (bright fronts, coronal loop oscillations) can tell us about the nature of the propagations themselves, and we use these observations to constrain our physics in Chapter 3. Their differences (observed velocities, 171 Å fronts) may tell us how the waves are affected by the surrounding corona. This is dealt with in Chapter 4.

Overview of these *TRACE* Wave Observations

The four events considered in this chapter are all examples of coronal propagations. However, each is unique, and while in some ways, these events show similar characteristics, there are also massive differences. Some of these disparities are likely the constraints of limited data, but there is also the possibility that at least one propagation (from 20 October 1999) may be a different kind of wave entirely. Figure 2.17 offers a brief summary and comparison of the major characteristics of the four waves.

Unfortunately, only two of the four data sets contain dual-wavelength observations; the lack of a second passband for the 20 October 1999 and the 30 August 1998 data limits our analysis capabilities. However, even with single wavelength

	13 Jun 98	20 Oct 99	30 Aug 98	14 Jul 98
Front Observed in	171Å 195Å	195Å	171Å	171Å 195Å
Description in 195Å	Strong, bright front	Weak, bright front	—	Noisy, bright front
Description in 171Å	Weak, "dark" front	—	No front	Noisy, bright front
Instigator	Flare in AR 8237	Filament eruption	Flare in AR 8397	Flare in AR 8270
Velocities	100 ⇌ 600 km/s avg ~ 300 km/s	20 ⇌ 70 km/s avg ~ 50 km/s	200 ⇌ 700 km/s avg ~ 300 km/s	avg ~ 500 km/s
Loop Oscillations?	Yes	No	Yes	Yes
Unusual Characteristics	- Partial halo CME - "Dark" front in 171Å	- Extremely slow velocity	- No front observed - Possible "pre-wave" event	- Faster velocity - Bright front in 171Å - Reflection observed

Figure 2.17: Properties of wave events considered in this research. Four *TRACE* observations of propagating wave events are considered for this research. This figure offers a brief summary of the defining characteristics of the events discussed in the previous sections.

data sets, we may look for consistency or lack thereof.

As this chapter has shown, the 13 June 1998 event is by far the best example here of a “typical” EIT wave. In particular, it shows the bright front in 195 Å and propagates at about 300 km/s. None of the other data possess both of these characteristics. The 20 October 1999 front moves too slowly, the 14 July 1998 front too fast, and while the 30 August 1998 event has the expected velocity, it shows no visible front.

Even with these differences, however, the 30 August 1998 and the 14 July 1998 data are still suggestive of the coronal propagations seen by *SOHO*-EIT. For instance, both of these events (along with that of 13 June 1998) display coronal loop oscillations. Additionally, the lack of a bright front in the 30 August 1998 171 Å data is not too dissimilar from the “dark” front seen as part of the 13 June 1998 event. This suggests that a bright front might have been observed in 195 Å had data been taken. It is also reasonable that the fast velocity seen on 14 July 1998 might be the product of a slightly more energetic version of an EIT wave. Certainly Moreton and SXT waves travel faster than the 500 km/s observed here. Possibly the bright 171 Å front is also a result of this higher energy (this will be discussed in more detail in Chapter 5).

With its extremely slow velocity and lack of loop oscillations, though, it would seem that the data from 20 October 1999 show something other than an EIT wave.

Some sort of propagation is certainly measureable, but this seems more likely to be a slow-mode MHD wave or the propagating reconnection proposed by Delannée & Aulanier (1999).

Of course, neither the 20 October 1999 or the 30 August 1998 events would have been seen at all in *SOHO*-EIT. It is in the fine time and spatial scales that these data that really show their advantage. The “Unusual Characteristics” mentioned in Figure 2.17 give a few examples of the new and interesting findings that appear in these events. Two that bear mentioning in particular are the “pre-wave” propagation that appears as part of the 30 August 1998 event and the wave reflection in the Bastille Day 1998 data. The “pre-wave” – moving at ≥ 1300 km/s – may lend credence to postulations put forth by Chen et al. (2002). The reflection was predicted as early as Uchida (1970), but this appears to be the first such observation.

Hopefully, the events summarized in Figure 2.17 are only the first in a long line of interesting observations. Each of them – even the 13 June 1998 event – requires a good deal more analysis, and the wealth of new information is promising indeed.

Constraints of *SOHO*-EIT and the Effect on EIT Waves

The waves discussed in this research are not EIT waves as originally defined.

None of them is observable by *SOHO*-EIT, with the exception of the 13 June 1998 event, which appears briefly and would not be classified as an EIT wave event were it not for its *TRACE* counterpart.

The morphology of EIT waves has already been discussed in Chapter 1. What may not be apparent is the effect of *SOHO*-EIT instrument constraints on this accepted definition. A classic EIT wave observation consists of a large, bright, circular wavefront, propagating globally through regions of low activity at velocities of ~ 300 km/s. Most of these data are obtained during the *SOHO*-EIT "CME Watch," a program which has the advantage of full-disk observations but uses a much slower cadence than typical *TRACE* observing runs.

In studies to date, EIT waves show remarkable consistency in size, shape, and velocity. There are two possible reasons for this – either the physics of the corona constrains EIT wave events to be similar, or *SOHO*-EIT preferentially observes events of a particular size, shape, and velocity.

While not discounting the first possibility, let us look at the second. In order to meaningfully observe a dynamic event, an instrument must take three images; to observe an event using difference images, four images are required. For *SOHO*-EIT to collect data on an EIT wave during a "CME Watch," that event must be visible over at least four exposures, about 45-54 minutes.

Compared to the four events discussed in this chapter, observation by *SOHO*-

EIT would appear to require a long-lived event. Additionally, that same event would have to be visible through all four exposures. Since EIT waves are not localized and must propagate, there is a maximum speed at which a front can travel and remain on the solar disk for 45 minutes. Assuming maximum possible travel distance, a wavefront can travel no faster than ~ 480 km/s. This explains why no particularly fast waves have been observed by *SOHO*-EIT, as well as why there has been so much difficulty correlating Moreton and EIT wave observations.

Even with a maximum speed established, the range of EIT wave speeds is still limited, and clusters around 300 km/s. If the first reason is also correct, and the physics of the corona constrains EIT waves to move at this speed, they would still have to travel a significant distance to achieve lifetimes observable by the *SOHO*-EIT "CME Watch." For a wavefront to remain coherent over a great distance, it must maintain a simple shape (circular) and experience little interference.

As a result, even if a range of EIT wave shapes and lifetimes were possible, *SOHO*-EIT would still only observe large, circular wavefronts. Given this conclusion, it does not seem unusual that most of the waves seen in *TRACE* are *not* observable by *SOHO*-EIT.

CHAPTER 3

THE PHYSICS OF MHD WAVES

As a highly ionized magnetic plasma, the solar corona is a *magnetohydrodynamic* (MHD) environment. A discussion of MHD and the nature of the corona is given in Appendix B. To understand the data discussed in Chapter 2, we need to consider the context in which the observations are created.

MHD Waves in the Solar Corona

As discussed in Appendix B, the corona, as a magnetically-dominated astrophysical plasma, obeys the “frozen-in flux” theorem – all ionized particles are constrained to move with, and only with, the magnetic field. The implication is that any gas dynamics are by definition also magnetic field dynamics. Therefore, a typical wave observable in the corona *must* have a magnetic component; it is difficult for simple acoustic waves to exist under these conditions.¹ Instead, all

¹The exception would be longitudinal compression waves parallel to the magnetic field. Since field lines cannot themselves compress, such a wave can be described as a sound wave. However, this condition requires very specific geometry, and we do not see evidence of such sound waves in the corona. Rather, compression waves parallel to the magnetic field are generally slow-mode magnetoacoustic waves, discussed in Equation (3.14).

possibilities are contained within the MHD equations.

When solving for waves in an atmosphere, it is often useful to simplify the conditions being considered. In this case, we treat the magnetic field as force-free, so that $4\pi\mathbf{j}/c = \nabla \times \mathbf{B}$ where j is current and $\mathbf{B}$ is the magnetic field. Additionally, we constrain the plasma to be affected only by gas pressure and magnetic forces, eliminating elements such as gravity. Using the equations of continuity (Equation [A.1]), motion (Equation [A.2]), and induction (Equation [A.6]) from Appendix B, we consider a small perturbation to the atmosphere, such that the density, pressure, velocity, and magnetic field are

$$\rho = \rho_0 + \rho_1(\mathbf{x}, t) \quad (3.1)$$

$$p = p_0 + p_1(\mathbf{x}, t) \quad (3.2)$$

$$\mathbf{v} = \mathbf{v}_1(\mathbf{x}, t) \quad (3.3)$$

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1(\mathbf{x}, t). \quad (3.4)$$

If we substitute these new perturbed variables into the MHD equations, keeping only the first-order terms, we are left with:

$$\frac{\partial \rho_1}{\partial t} + \rho_0 \nabla \cdot \mathbf{v}_1 = 0 \quad (3.5)$$

$$\frac{\partial \mathbf{v}_1}{\partial t} = \frac{1}{\rho_0} \left[-\nabla p_1 + \frac{(\nabla \times \mathbf{B}_1) \times \mathbf{B}_0}{4\pi} \right] \quad (3.6)$$

$$\frac{\partial \mathbf{B}_1}{\partial t} = \nabla \times (\mathbf{v}_1 \times \mathbf{B}_0). \quad (3.7)$$

We can make substitutions for ρ_0 , ρ_1 , p_1 , and $\mathbf{B}_0$ by using the sound speed

$$c_s^2 = \frac{\rho_1}{p_1} \quad (3.8)$$

and the *Alfvén velocity*

$$\mathbf{v}_A = \frac{\mathbf{B}_0}{\sqrt{4\pi\rho_0}}. \quad (3.9)$$

Differentiating Equation (3.6) and substituting in variables from (3.5) and (3.7), we can create a single equation dependent only on $\mathbf{v}_1$:

$$\frac{\partial^2 \mathbf{v}_1}{\partial t^2} = c_s^2 \nabla(\nabla \cdot \mathbf{v}_1) + \{ \nabla \times [\nabla \times (\mathbf{v}_1 \times \mathbf{v}_A)] \} \times \mathbf{v}_A. \quad (3.10)$$

For this system, it is reasonable to assume plane wave solutions of the form given in Equation (1.2) in the Introduction. The various derivatives of the exponential function leaves us with a simplified solution

$$\omega^2 \mathbf{v}_1 = (c_s^2 + v_A^2)(\mathbf{k} \cdot \mathbf{v}_1)\mathbf{k} + \mathbf{v}_A \cdot \mathbf{k} [(\mathbf{v}_A \cdot \mathbf{k})\mathbf{v}_1 - (\mathbf{v}_A \cdot \mathbf{v}_1)\mathbf{k} - (\mathbf{k} \cdot \mathbf{v}_1)\mathbf{v}_A] \quad (3.11)$$

which is the general *dispersion relation for MHD waves*.

If the angle between $\mathbf{k}$ and $\mathbf{B}_0$ (hence $\mathbf{v}_A$) is some angle θ_B , this dispersion relation can be reduced to the following two forms:

$$\omega = kv_A \cos \theta_B \quad (3.12)$$

and

$$\omega^4 - \omega^2 k^2 (c_s^2 + v_A^2) + c_s^2 v_A^2 k^4 \cos^2 \theta_B = 0. \quad (3.13)$$

Equations (3.12) and (3.13) are useful for discussing the propagation of a wave in an MHD environment, since they both can be simplified to a phase velocity ω/k . The velocity described by (3.12) is just the Alfvén velocity, constrained to travel parallel to the magnetic field. (3.13), however, offers two distinct solutions:

$$v = \left[\frac{1}{2} (c_s^2 + v_A^2) \pm \frac{1}{2} (c_s^4 + v_A^4 - 2c_s^2 v_A^2 \cos 2\theta_B)^{1/2} \right]^{1/2}. \quad (3.14)$$

These two solutions are known, respectively, as *fast-mode* and *slow-mode magnetoacoustic waves*.

The Nature of MHD Waves in the *TRACE* Data

The observations discussed in Chapter 2 are sufficiently detailed that, from morphology alone, we can draw conclusions about the nature of the propagations.² To see how morphology can act as a constraint, let us consider Equations (3.12) and (3.14).

Equation (3.12) is basically the Alfvén speed, which is a purely magnetic velocity. However, the $\cos \theta_B$ term means this velocity decreases with greater obliqueness to the magnetic field. In addition, it is not meaningful to compress a field line along its length, so any pure Alfvén wave must be a transverse wave.

Fast- and slow-mode magnetoacoustic waves are slightly more complex. With their combined Alfvén and sound speed components, they are roughly the magnetic equivalent of acoustic compression waves. It is the $\pm$ term in Equation (3.14) that differentiates these two modes.

Taken at its limits, a slow-mode wave traveling parallel to the magnetic field moves at the sound speed. However, as $\theta_B \rightarrow \pi/2$, the slow-mode speed goes to zero. In this way, a slow-mode wave can be thought of as a sound wave constrained to move along the magnetic field.

A fast-mode wave behaves differently. When moving along the magnetic field, it

²For the EUV observations considered, we work from the approximation that $\beta < 1$, where β is the ratio of gas to magnetic pressure. Under these circumstances, the Alfvén speed v_A should always exceed the sound speed c_s .

travels at the Alfvén speed, but its motion is compressional, rather than transverse as with a pure Alfvén wave. As $\theta_B \rightarrow \pi/2$, the velocity of the wave actually increases, reaching a maximum of $\sqrt{c_s^2 + v_A^2}$. Only a fast-mode MHD wave can propagate across field lines.

When we understand how each wave will interact with the magnetic field and the surrounding plasma, it becomes easy to use the *TRACE* observations to determine the sort of physics we are watching. In the case of the 13 June 1998 event discussed on pages 27 – 44, the data show a propagation that travels ubiquitously and coherently, regardless of the direction of surrounding large-scale magnetic structures. At the north of the field of view, the wave moves perpendicular to a single large magnetic loop complex. The motion across magnetic fields eliminates all but the possibility of a fast-mode magnetoacoustic wave.³ Figure 3.1 shows a cartoon overlay of the direction of wave propagation with respect to the magnetic field structures the wave interacts with. The loop oscillations observed in the 14 July and 30 August 1998 events also leave only a fast-mode wave as the cause of those disturbances.

In the past, Moreton waves have been theorized as a manifestation of fast-mode waves (Uchida [1968]), and numerical simulations of coronal propagations (Wang [2000]; Wu et al. [2001]; Chen et al. [2002]) have been created starting from

³The bright front observed in the data is indicative of a compression front (discussed in detail on page 73), further constraining the wave to be magnetoacoustic and not Alfvénic.

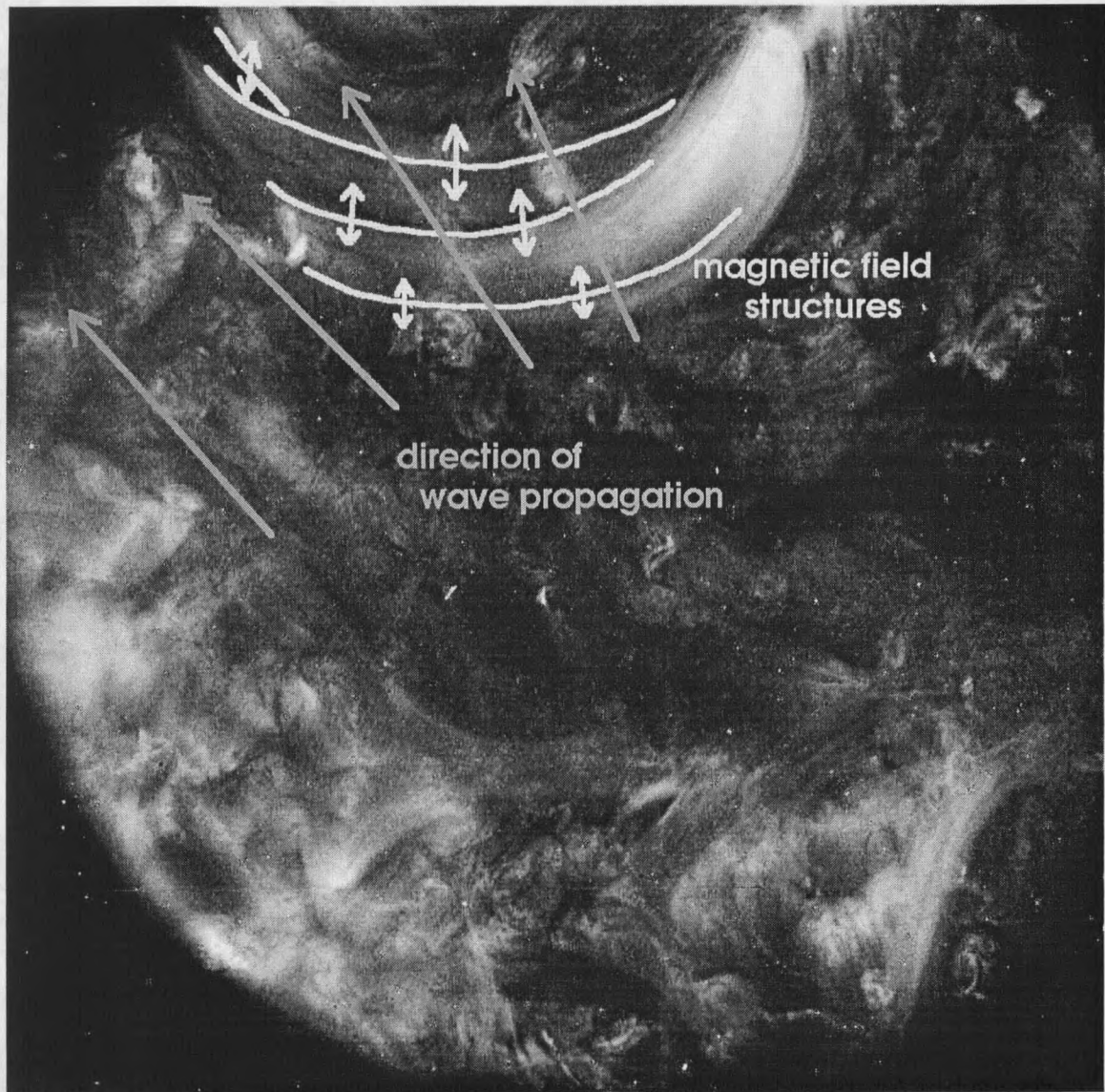


Figure 3.1: Cartoon showing wave propagation with respect to oscillating magnetic field structures. This cartoon overlay of the 13 June 1998 data demonstrates that the wave propagates across the magnetic field structures it excites to oscillate. The white lines outline the oscillating field lines, with the white double-pointed arrows demonstrating the direction of oscillation. The grey arrows roughly show the direction of wave propagation. Such excitation of perpendicular magnetic structures can only be effected by a fast-mode MHD wave.

this assumption. However, the solutions to these theoretical models generally start from reasonable, but unknown, values for local physical quantities in an attempt to recreate observed wave velocities. With the availability of sufficiently detailed data – such as that from *TRACE* – we can use the observations themselves to justify the existence of fast-mode waves, eliminating the need for modeling altogether.

The 20 October 1999 event (discussed on pages 44 – 47) is, unfortunately, not so easily classified. While some sort of propagation is certainly observable, there is no instigation of loop oscillations or similar motion of external magnetic structures. Additionally, the event moves at ~ 50 km/s. In an ideal gas, the sound speed shown in Equation (3.8) can also be defined as with Equation (1.3), so that

$$c_s = \left(\frac{\gamma k_B T}{m} \right)^{1/2}. \quad (3.15)$$

This means the sound speed is dependent on the local temperature. The 20 October 1999 event was observed in the *TRACE* 195 Å passband, which peaks at 1.5 MK. Even were the wave event to exist primarily at ~ 1 MK, the local sound speed would still be ~ 150 km/s. To have a local sound speed of ~ 50 km/s, the ambient medium would have to be $\sim 10^5$ K. Since, for the corona, $v_A > c_s$, this eliminates the possibility of a fast-mode or an Alfvén wave for the 20 October 1999 event. However, slow-mode waves are constrained to travel at $\leq c_s$. The weak, bright

front also suggests a compressional component. If this event can be classified as a wave at all⁴, it is likely a slow-mode magnetoacoustic wave interacting obliquely with the field.

Analysis of the 13 June 1998 Event

Figure 2.1 shows the 13 June 1998 event in two different passbands, *TRACE* 195 Å and 171 Å. The event is markedly different in the two data sets, with a strong bright front in the 1.5 MK images, but a dark propagation in 1.0 MK. If we consider the response functions of the two passbands (Figure 3.2), a comparison of these observations offers hints of the physics that might have occurred – the propagating compression front, so visible in the 195 Å data, may have heated 1.0 MK material out of the 171 Å passband (a temperature difference of only a few hundred thousand K), resulting in the observed under-density, and even a possible over-density in 195 Å. Not only is this a reasonable scenario, but it places some limits on our expectations of temperature dynamics – it is likely the plasma in the wave is heated away from the peak 171 Å temperature, but not too far from the 195 Å temperature.

If there is a change in temperature being observed, the question naturally arises

⁴The propagating reconnection event suggested by the Delannée & Aulanier (1999) “bald patch flare” model might not technically be considered a wave.

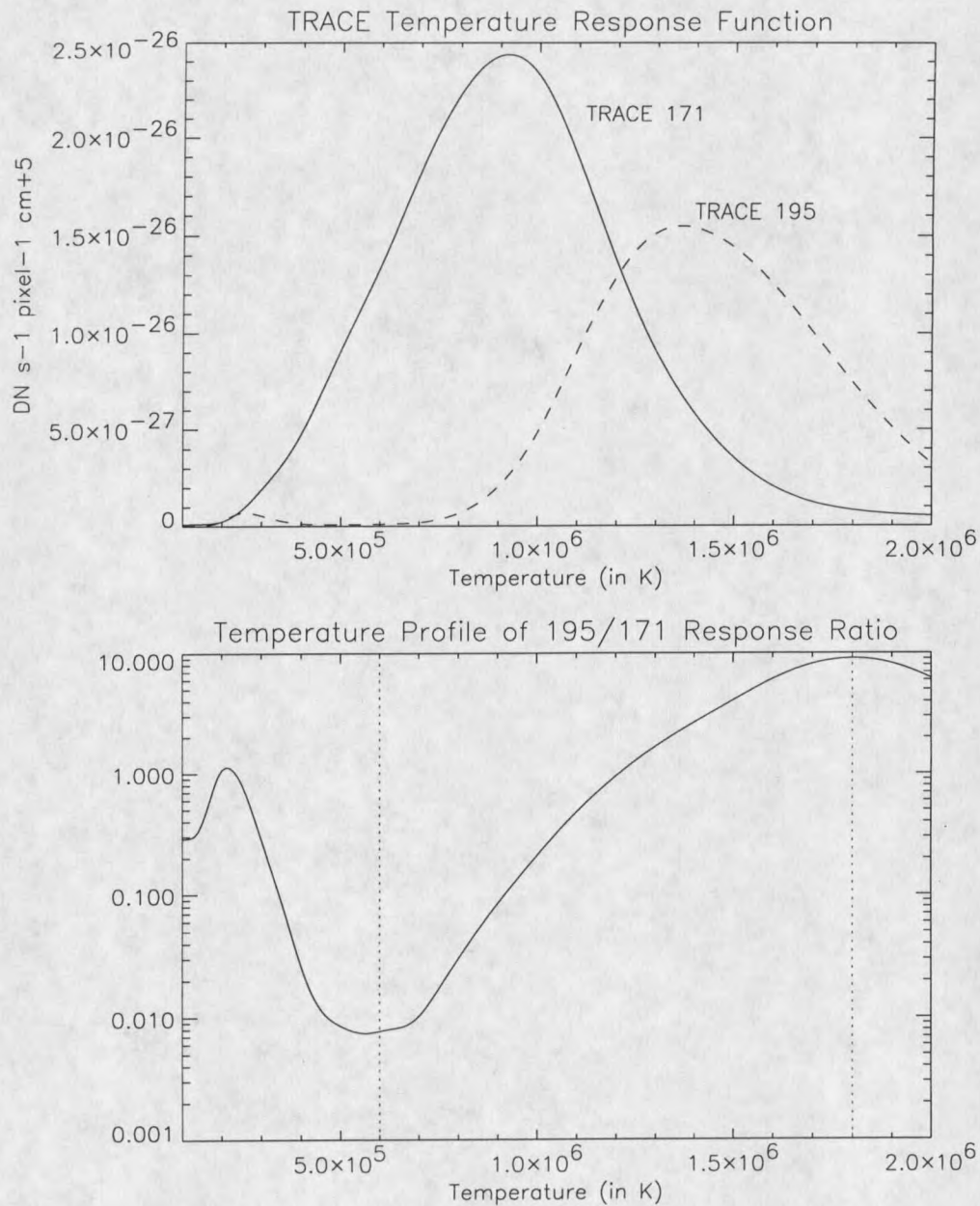


Figure 3.2: Response functions for the *TRACE* 171 Å and 195 Å passbands. The top graph shows the response functions of the two *TRACE* EUV filters as a function of temperature. Response functions are plotted in units of $\text{DN s}^{-1} \text{ pixel}^{-1} \text{ cm}^5$. The solid line represents the 171 Å passband; the dashed line is the 195 Å passband. The bottom graph plots the ratio of the 195 Å to 171 Å response functions as a function of temperature. If the *TRACE* observations are between 0.6 and 1.8 MK, such a ratio can be used to give at least some idea of local temperature.

as to its nature. The bright front passes through with some alacrity (around three minutes through any one point in space), and residual heating is not left behind, implying that the region being compressed must cool on the same rapid time scale over which it heats up. (This rapid localized temperature change can be observed in Movie 2.6, in particular as the wave passes through the southeast corner of the field of view.)

The cooling times generally considered for the corona are radiative and conductive. Unfortunately, for this type of quiet sun, these cooling times are *much* longer than the ~ 3 minutes observed in the data. Priest (1984) calculates a radiative cooling time for $T_0 \sim 1.5$ MK and a particle density of $n_0 \sim 10^8 \text{ cm}^{-3}$ that is around nine hours!⁵ Conductive cooling times are slightly more reasonable; for a loop of length $L_0 = 100$ Mm, conductive cooling takes place in about 30 minutes. This, however, is still too long by an order of magnitude. In fact, these differences are so pronounced that it is unlikely that either radiative or conductive cooling have much effect at all.

Since the timescales of wave influence are so short compared to amount of time required for typical coronal heating or cooling, it would seem that the change in temperature created by the wavefront is entirely self-contained, and there is no observable mechanism for energy loss. The temperature increase appears to

⁵Priest, E. R., p. 278

be essentially reversible; therefore, it is not unreasonable for us to consider the compression front adiabatic.

Creating Meaningful Wave Profiles

If we know to look for a specific increase in temperature and emission measure, we can move beyond surface comparisons of the different data sets. Both these quantities can be determined from a combination of 171 Å and 195 Å data using `trace_teem.pro` in the SSWIDL library. While the two-dimensional nature of the data can lead to spatial ambiguity in these calculations, we attempt to constrain our study to the wave front by analyzing base difference images only. This is reasonable if we assume that any changes are due to only the wave, that the wave is spatially localized, and that its temperature does not extend out of the range of *TRACE* observation limits. The extremely quiet sun through which the wave passes satisfies the first criterion; we account for the second two in the physical constraints on the wave (discussed in Chapter 4).

To consider changes in the data due to the wave in a meaningful way, we want to follow the propagation of the wave along its most natural trajectory. Even though Figure 2.2 shows a wave that, at least in part, seems to propagate radially, we know from the *SOHO*-EIT observations that this may not be the best approximation. Therefore, we choose propagation trajectories based on the fronts found using our

automated mapping techniques. The details behind determining trajectories in an automated way are discussed in Appendix A, and the final propagation tracks themselves are shown in Figure A.3.

We have chosen to follow three of these natural trajectories (shown as thick lines in Figure A.3) to examine the intensity dynamics of the wave in space and time. The starting points of these paths are roughly evenly spaced along the first measured wavefront, and they each travel through distinct regions, so we expect to observe slightly different dynamics along each trajectory.

For a given observation, each path is divided into 100 equally-spaced points. Since the data are inherently noisy, we think of each path as a band, and determine the value at any single point by averaging it with several pixels on either side. With an average calculated for each point, the result is a one-dimensional wave profile which is essentially a “slice” through the image. We get these slices for each of the three trajectories for each piece of emission measure data.

However, emission measure is not a quantity from which we can easily obtain plasma values. Emission measure is related to plasma density such that

$$EM(\mathbf{x}) = \int n_e^2 dh \quad (3.16)$$

for the column depth of the image. To find ΔEM , we use emission measure base

difference images. Here, the emission measure data shown in Figure 2.2 have the same pre-event image subtracted from each frame. The positive changes in these data can be used to determine the density enhancement due to the wave, assuming

$$\sqrt{\frac{\Delta EM(\mathbf{x})}{h}} = \Delta n_e. \quad (3.17)$$

This requires that we constrain the possible height which is producing the change in emission measure. Based on the scale of the wave cross-section, such as that seen in Figure 2.1, we take $h \sim 100$ Mm.⁶

With this assumption of h , we can calculate a density enhancement due to the wave. Figure 3.3 shows “slices” of this density enhancement taken along the three chosen trajectories. These density enhancements are determined with respect to the emission measure data from 15:26:49 UT. This is actually the second image in the data set, but similar calculations using the first image showed no measurable pulse until the third frame of the data set. The second image is still pre-event, and is actually less noisy than the first, so the resulting density enhancements are better defined.

Propagations are visible along all three paths. At later times, the wave becomes less of a uniform pulse, and instead can be tracked through serial brightenings of

⁶Examination of Figure 3.3 also shows that the cross-section of the wavefront is of the order of 100 Mm.

individual structures. Along Track 1, for instance, there appear to be coronal features at 140 and 200 Mm, and from 15:37:20 UT on, we can see the density enhancement decay in the first structure and then reemerge in the second. Both the second and third tracks show nearly identical sets of four spikes just past their midpoints. While not visible as a coherent coronal structure in Figure 2.2, it may be the same set of loops lying perpendicular to both paths (which are traveling roughly parallel past their midpoints).

A strong, persistent enhancement spike appears at 15:31:04 UT about 100 Mm along the second trajectory. Examination of Figure 2.2 (in particular the movie) reveals that this spike corresponds to bright ejecta which occur contemporaneously with the wave. Harra & Sterling (2003) examine these ejecta using *SOHO*-CDS data, and show that the ejecta behave independent of the propagation. The spike in Track 2 persists through the entire wave observation, and convolves with the front from 15:31:04 through 15:34:19 UT, resulting in an overestimate of the effect of the wave.

Calculating Energy Flux

In seeking to understand the physics of the wave, the density is not the most meaningful quantity. Because it is the wave that travels, rather than the material that is being compressed, the density enhancement is important, but is not in and

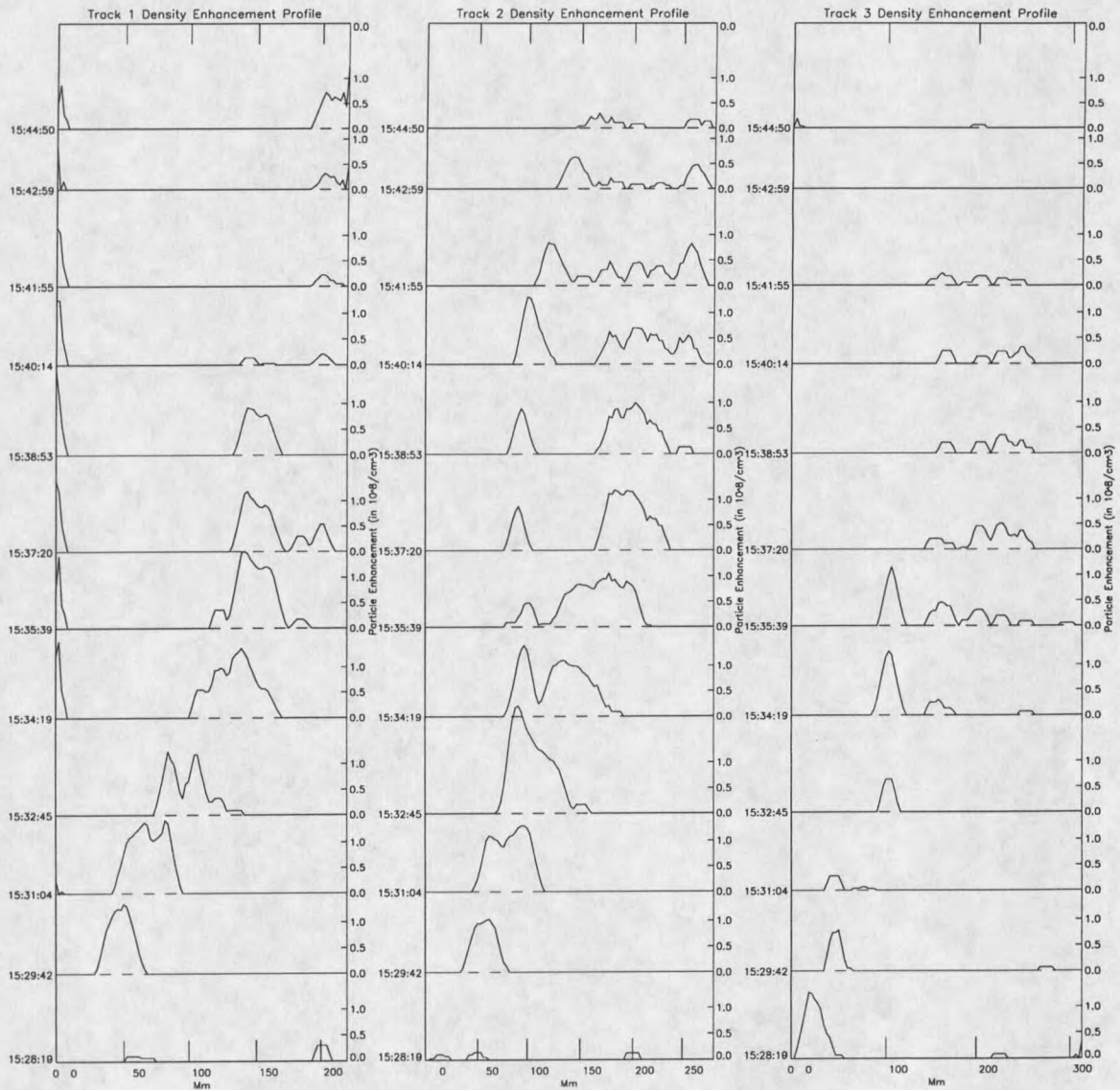


Figure 3.3: Density profiles for three trajectories from 13 June 1998 event. The three plots shown above map density enhancements along the three trajectories chosen in Figure A.3. The lowest graph shows the earliest density enhancement calculation, and subsequent times are shown in higher plots. Each plot is labeled with its corresponding time. All density enhancements are determined with respect to the emission measure data from 15:26:49 UT, before the wave enters the *TRACE* field of view.

of itself a conserved quantity. To understand the wave's evolution, we must find its energy flux.

The energy flux of a fast-mode magnetoacoustic propagation is defined as

$$F = \rho_0 |\delta v|^2 v_{fm} \quad (3.18)$$

where $\rho_0 = n_e m_e$ is the initial mass density, δv is the change in velocity of particles caused by the perturbation, and v_{fm} is the fast-mode speed of the ambient plasma. However, we are not able to measure δv in our data, so we must find a way to define the energy flux using variables we *can* determine.

If we start from the linearized continuity equation [Equation(3.5)], we can relate δv to the local change in density $\delta \rho$ by making (3.5) look like

$$\frac{\delta \rho}{\rho_0} = \frac{\mathbf{k} \cdot \delta \mathbf{v}}{\omega}, \quad (3.19)$$

taking ρ_1 as $\delta \rho$ and $\mathbf{v}_1$ as $\delta \mathbf{v}$. To simplify further, we must make some approximations. To eliminate the vector quantity, we take $\delta \mathbf{v} \parallel \mathbf{k}$. This leaves us with an $\omega/|k|$ term in (3.19), for which we can substitute the local phase velocity. In our case, we want the phase velocity to be our local measured fast-mode speed v_{fm} . However, our fast-mode measurement will only be reasonable if we can neglect the magnetic field component, in particular its direction. If we work from the assump-

tion that the plasma $\beta \gg 1$ (expected for a magnetically-dominated region such as the corona), the contribution from the magnetic field component is negligible; therefore, we can take the simplification $\omega/|k| = v_{fm}$. Ultimately, (3.19) can be written as

$$\frac{\delta\rho}{\rho_0} = \frac{\delta v}{v_{fm}}. \quad (3.20)$$

Here, $\delta\rho$ is the local density enhancement shown in Figure 3.3. Substituting (3.20) back into (3.18), we find

$$F = \frac{\delta\rho^2}{\rho_0} |v_{fm}|^2 v_{fm}. \quad (3.21)$$

The density enhancement $\delta\rho$ and fast-mode velocity v_{fm} can be measured directly in the data. Because the velocity calculation requires position changes between fronts, we will only be able to determine fluxes for nine of the density profiles, limiting our flux measurement to the time period 15:29:42-15:41:55 UT. Fortunately, this encompasses the bulk of our useable density data.

The initial density ρ_0 is not found so easily, but it can be approximated (or at least constrained) using our emission measure data. The same theories used in Equations (3.16) and (3.17) apply here, but the change in emission measure is ill-defined, because we have no dynamic event to use for comparison. It is most reasonable to take the emission measure over the entire column depth (while still choosing the finite height h for integration) and then treat the solution for density

as an upper limit. Conversely, any energy flux calculation becomes a lower limit, but to attempt to further constrain the data would be highly artificial.

Having measurements for all the variables in Equation 3.21, we are able to calculate a flux along each trajectory. A total energy flux at each point in time is obtained by summing over the entire density enhancement. The progression of flux along each track as a function of time is shown in Figure 3.4. Along Track 2, after 15:35:39 UT, the density peak of the ejecta is ignored, and only the continuing propagation is included in the energy flux measurement. This means values in the range 15:31:04 - 15:34:19 UT may be spurious, and show more flux than expected. The solid line is our total energy flux calculation, while the curves show expected ideal drop-offs. The superimposed dotted line is the change in flux that would be expected for an ideal MHD wave propagating radially. This change in flux reflects the r^{-2} expansion that accompanies a spherical propagation. The dash-dot line is the drop-off associated with a surface wave or one confined to a narrow wave guide (r^{-1}).

For all three tracks, the dropoffs resemble the r^{-2} or r^{-1} curves only *after* 15:34:19 and 15:35:39 UT. At earlier times, Tracks 1 and 3 show marked flux increases, while Track 2 shows extreme variations in flux measurement, as might be expected with the overlapping ejecta. When the flux finally does stop increasing, the propagation is sufficiently noisy where is difficult to tell if a spherical or a radial

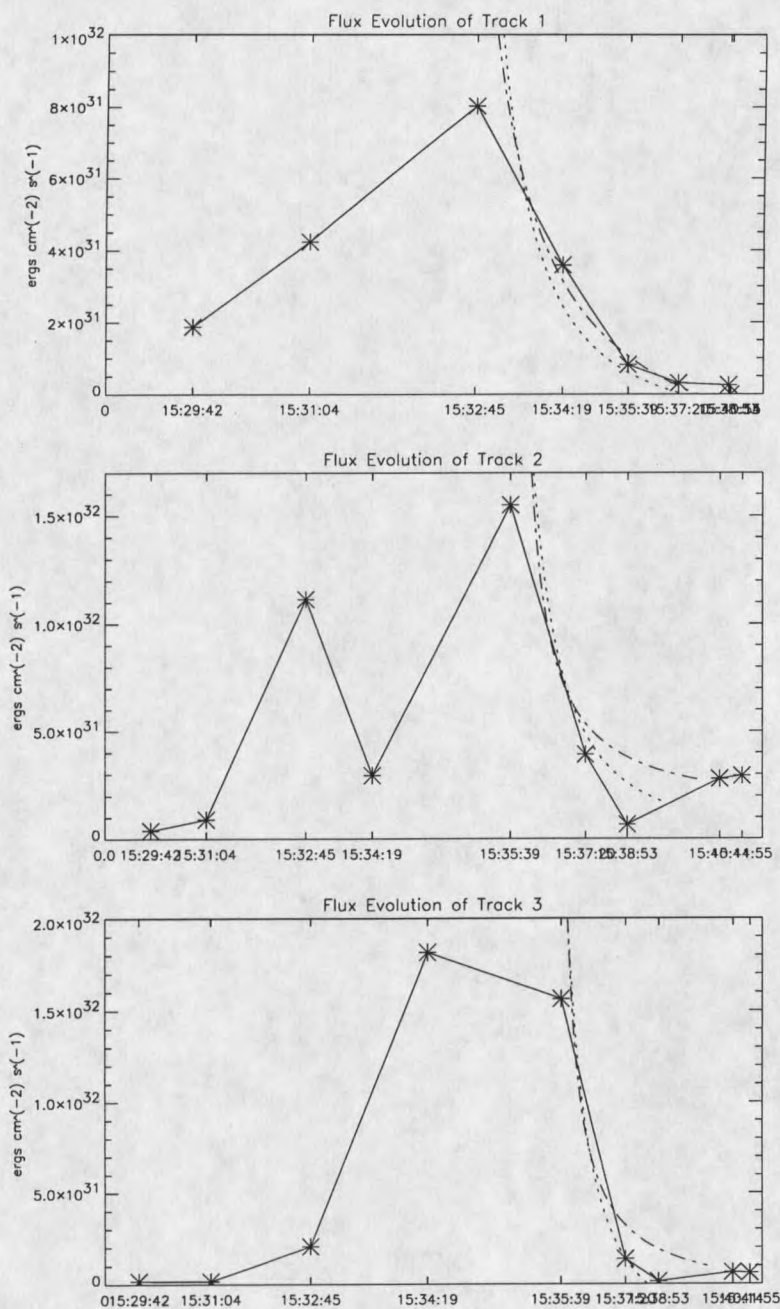


Figure 3.4: Integrated energy flux along each track as a function of time. The solid lines and each star represent the integrated energy flux along a track at that point in time. The dotted and dot-dashed lines show the expected flux drop-offs for a spherical and surface wave, respectively. In all three cases, there is a noticeable increase in flux early in the event, and only after 15:34:19 or 15:35:39 UT does the flux decrease start to resemble the theoretical drop-off.

propagation makes a better match. Ultimately, the *radial* wave may actually be the better fit; the flux does not diminish quite quickly enough to match the r^{-2} tail. However, the fit is really not good enough to draw any conclusions.

The increase in flux throughout the propagation is unexpected. Two possible explanations emerge for this behavior. Since the wave is a compression event displaying heating, it could be that, during the earliest observations, part of the event was sufficiently hot that it was unobservable by either the *TRACE* 171 or 195 Å passbands. As the event progressed, the decay of the front led to less heating in the compression, causing material to “appear” in temperatures observable by *TRACE*. This theory is problematic because many aspects of the event contradict the idea of excessive heating. If higher temperatures were reached, it would be reasonable to expect observations of this front by *Yohkoh-SXT*; no such data exist. In addition, the source of such great heating implies some sort of shocking behavior, which require faster velocities than typical EIT waves.

The other possibility is that, during the first few minutes of observation, we are actually watching the driver continue to form the wavefront. The pulse would have continued to form until about 15:32-15:35 UT, at which point we start to observe the expected flux evolution. This would imply a more extended driver, as opposed to extremely localized, impulsive events usually assumed to cause such propagations. Coincidentally, the persistent dimming region that follows the front

appears to stabilize and stop expanding at about the same time that the flux dropoff begins. Perhaps the bulk of the CME serves as a continuous driver, and it is not until the bulk of it is detached from the corona that wave begins to develop freely.

The Dispersion of the Wave

So far, the basis of our discussion has assumed an ideal homogeneous MHD medium. However, our understanding of the corona tells us it is *not* homogeneous. There are gravitational density stratifications; the observed temperature increases with altitude; even the magnetic fields are inordinately complex.

Our observations of the 13 June 1998 event are sufficiently detailed that we should see evidence of such non-homogeneous circumstances in the data. Simplistically, we might expect the wavefront to propagate as a spherical shell. This would cause it to interact with regions of decreasing density, which will lead to *dispersion* in the wave. Such dispersion is related to the width of the pulse; as the wave disperses, the pulse will spread, and this spread should be measureable.

We consider the first initial 7-9 timesteps along each track in our pulse width measurement. Beyond this, the far end of the pulse begins leaving the field of view, and the width measurement can no longer be considered accurate.⁷ A gaussian is

⁷In the case of Track 3, the amplitude of the pulse also decreases to the point where fitting a

fit to each pulse we intend to measure, and the value of the width is derived from the full width at half max. Figure 3.5 shows the overlays of the gaussians and the width measurements.

If dispersion is present, a graphing of these widths as a function of time will show that they increase. This makes the results in Figure 3.6 rather unexpected. Instead of increasing, the widths of the wave profiles seem only to fluctuate, and perhaps remain roughly constant. It is possible that some increase is observable along Track 3, but it can't be distinguished from the noise.

While the results are reasonably noisy, these measurements do not appear to show measurable dispersion. The results suggest the possibility that, in fact, the wave is not being affected by dispersion, which is inconsistent with the assumption that such a wave must travel ubiquitously at least for part of its lifetime. We will come back to these results in Chapter 4, but at present, they contradict our intuition and conventional wisdom.

Loop Oscillations Instigated by MHD Waves

The earliest work on the effects of large-scale MHD propagations centered around coronal loop oscillations. Studies by Aschwanden et al. (1999) and Schrijver & Brown (2000) examined events observed by *TRACE* – the Bastille Day

curve is difficult.

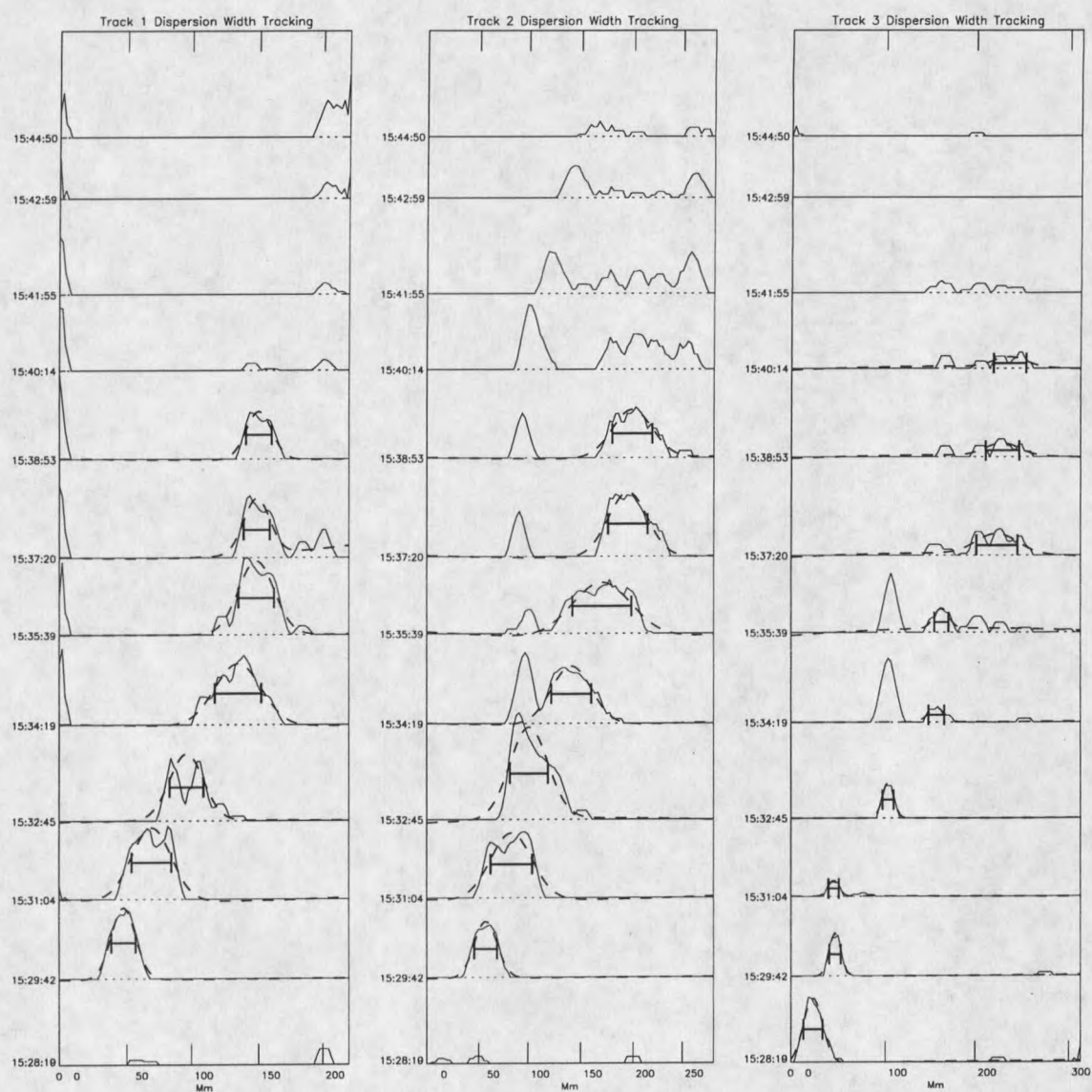


Figure 3.5: Mapping of width measurement for dispersion tracking. This plot is the same as in Figure 3.3. Gaussian fits have been overlaid as dashed lines for the width measurement. The width itself has been draw in where appropriate.

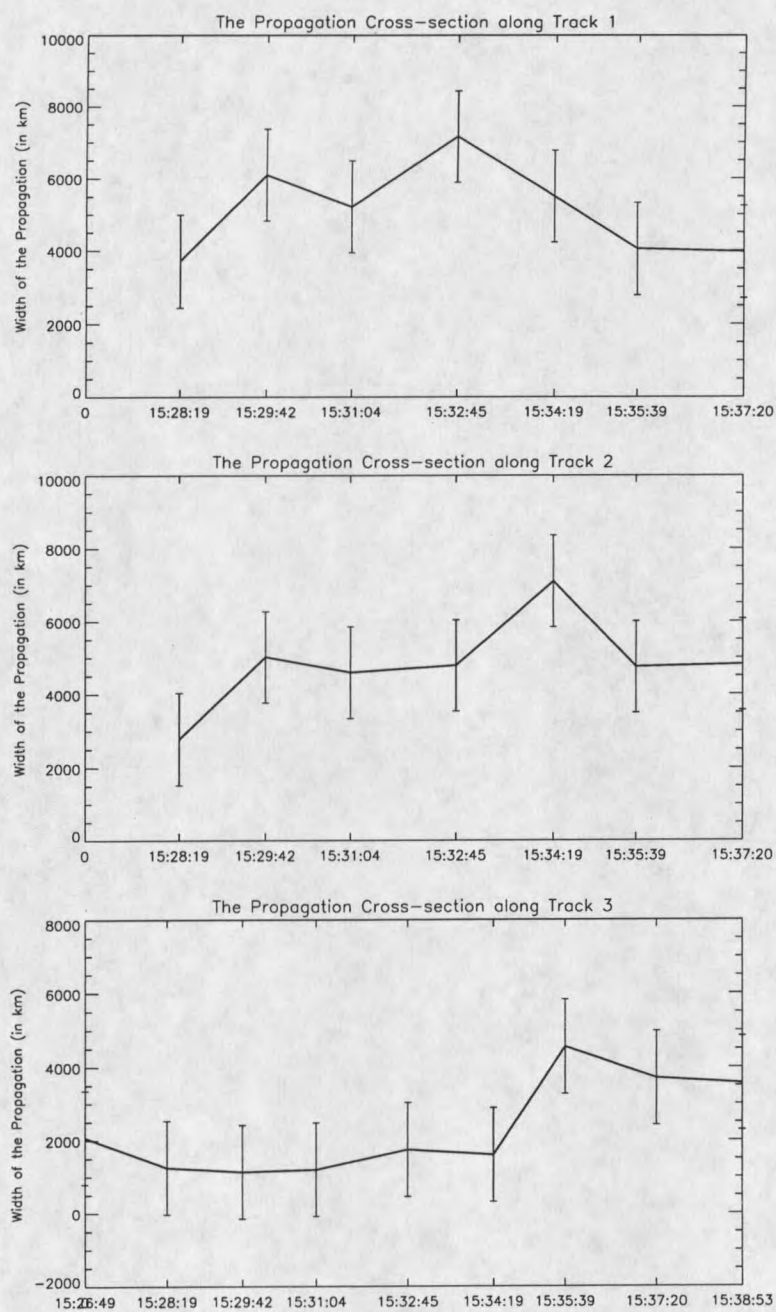


Figure 3.6: Change in pulse width as the wave propagates. These graphs show the width of the pulse along each track as a function of time. The data are noisy, but the results show no measurable dispersion.

Flare in particular – in order to track the periods and damping rates of oscillating magnetic structures.

Discussion of oscillation excitation was less than thorough. Schrijver & Brown (2000) only make a passing reference to a “coronal blast wave.”⁸ Aschwanden et al. (1999) do make an attempt to find an instigating propagation, but they assume a circular front, and their analysis does not appear to have produced the front shown in Figure 2.16. This ultimately presents problems with their results, as one of the oscillating loops is situated *parallel* to their circular front, making it unclear how an oscillation would be instigated. The data in Figure 2.16 show that this loop happens to be in the path of early asymmetrical motion of the front, as it “swings around” the western side of the active region. Under these circumstances, the loop is now perpendicular to the propagation front, creating the instigator Aschwanden et al. (1999) requires.

Subsequent studies of coronal loop oscillations (i.e. Aschwanden et al. [2002]; Schrijver, Aschwanden, & Title [2002]) have found that large-scale coronal wavefronts are one of two excitation mechanisms (the other being filament eruptions). In fact, in data shown by Aschwanden et al. (2002) and Schrijver, Aschwanden, & Title (2002) these instigators appear to produce different oscillation signatures –

⁸They also distinguish between genuine oscillating structures and field distortions that relax back to their initial conditions. As an example, they refer to Wills-Davey & Thompson (1999), even though that work concluded that part of an oscillation had been observed in the truncated data set.

propagating fronts produce regions separated by some distance initiating oscillations progressively farther away from an impulsive event, while filament eruptions cause a cascade of related oscillations in a structure such as an arcade (comparable to shaking one end of a slinky). Specifically, a wavefront appears to “drag” loops along and “snap” them back, while a filament eruption “nudges” a field.

Musielak & Ulmschneider (2003) have recently modeled the excitation of oscillations by MHD pulses. In the case of a single pulse, free (as opposed to driven) oscillations are produced which move at the characteristic frequency of the plasma and with amplitudes that decay at a rate of $t^{-2/3}$. While these results reflect the sort of behavior seen in loop oscillations, the severe damping rate and the variety of observed periods suggest other contributing factors.

Nakariakov et al. (1999) modeled loop oscillations instigated by a pulse perturbation moving perpendicular to the field. If viscosity and resistivity are included in the calculation, an MHD density front can produce sufficient drag to displace the loop top.

Because of the differences among the myriad *TRACE* observations, Schrijver, Aschwanden, & Title (2002) note that the instigator itself may contribute to the loops’ behavior. The most likely relationship may be between the amplitude of the wavefront and that of the oscillation – a bigger pulse will drag the field farther along. As yet, this idea has not been considered in detail.

Initial work by Schrijver & Brown (2000) related the five-minute periods observed during the Bastille Day Flare to a resonance with photospheric five-minute oscillations. However, Schrijver, Aschwanden, & Title (2002) found periods that varied by as much as an order of magnitude, suggesting that frequencies were not a result of external resonances and most likely derived from another source. Calculations by Nakariakov & Ofman (2001) assume that the observed oscillations are kink eigenmodes, and hence the periods are determined by the Alfvén transit time. This implies that oscillation times should relate to loop lengths, field strengths, and densities, making possible a range of oscillatory behaviors. Such variation could also account for the period differences observed by Schrijver, Aschwanden, & Title (2002).

The rapid damping of the oscillations has produced a range of theories. Nakariakov et al. (1999) can account for it by assuming a Reynolds number that is $10^8 - 10^9$ smaller than the value typically used. Aschwanden et al. (2002) interpret the oscillating loops not as first-order kink eigenmodes, but as “impulsively generated MHD waves,” which propagate back and forth in the loop at the Alfvén speed, and damp the oscillation through leakage at the footpoints. Goossens, Andries, & Aschwanden (2002) find that, if the *TRACE* observations are “quasi-mode” kink oscillations, they will decay rapidly without the need to invoke an anomalously low Reynolds number. This theory also provides an explanation for the variety

of periods seen in the *TRACE* data, relating the oscillation period to the field strength of a given flux tube.

The theories put forward by Musielak & Ulmschneider (2003) and Goossens, Andries, & Aschwanden (2002) relate oscillation periods to the characteristics of a flux tube. However, there is some evidence in the data that, in events that produce multiple loop oscillations, the observed periods can be remarkably similar. Of four such events discussed in Wills-Davey & Thompson (1999), Aschwanden et al. (2002), and Schrijver, Aschwanden, & Title (2002) three showed comparable periods among all the loops affected by the same instigator. This was true regardless of the number or size of the loops. If Goossens, Andries, & Aschwanden (2002) are correct, perhaps all of the flux tubes have similar field strengths. However, such observations suggest that the oscillation period may be a property of the event, and not necessarily inherent in the loop.

There are, as yet, no theories explaining why propagations seem to selectively cause oscillations. The only thoughts we can offer here pertain to Figure 2.6, and the relationship between temperature and oscillating structures. During the 13 June 1998 event, many fine-scale structures were affected by the propagation and showed the beginnings of oscillatory behavior. When the temperature data is considered, virtually all of the oscillating structures are seen to be of a similar temperature, and cooler than the surrounding medium. It is possible that the

fine-scale structures are lower in the atmosphere than the hot structures in which they appear embedded. If the driver were somehow constrained to a low altitude – for instance, through a natural wave guide – it would be possible to selectively effect cool structures while ignoring hotter ones. The idea of altitude constraints will be considered in more detail in Chapter 4.

Coronal Seismology

There is no easy way to determine *in-situ* coronal plasma properties. Narrow-band EUV detectors peak preferentially, but, because the response functions include a range of temperatures, any intensity value produced by a such an instrument suffers from a temperature–density ambiguity. Even when contemporaneous data sets are available and ratio methods can be used to isolate temperature and emission measure, the data still lack the crucial third dimension needed to isolate the properties of individual structures. At present, the values used for temperature, density, and magnetic field strength in the corona are the result of theory, modeling, or extrapolation of photospheric or off-limb observations. Often, order-of-magnitude estimates are used, or known active region values are scaled to accommodate the quiet Sun. At best, these methods are inexact, and in no way offer the opportunity to measure plasma properties directly.

The temporal and spatial detail available from *TRACE* provides with the opportunity to learn about the corona using an entirely new method of study. Our discussion of waves in the Introduction was meant to show, among other things, that the properties of any wave – standing or propagating, transverse or longitudinal – are a function of the medium through which it passes. This fact offers scientists a “back door” examination technique; measurements of wave properties can ultimately offer clues about the medium itself. Using “seismology” in this way can help us to measure *in-situ* values that may be difficult to find by other means. Within solar physics, this idea has already spawned helioseismology; instruments such as GONG (i.e. Leibacher et al. [1998]) and *SOHO*-MDI (Scherrer et al. [1996]) use acoustic waves within the Sun to map the solar interior, determine internal rotation, and even study structures on the far side of the Sun.

In a similar manner, *coronal seismology* can be used to understand the local medium. Using *TRACE* data, we can directly measure properties of a wave or oscillation – periods, amplitudes, velocities, decay rates etc. Then, applying the MHD wave theories discussed on pages 63-66, these properties can be used to determine local values of the medium – in particular, density, temperature, and/or magnetic field strength. *TRACE* observations provide only local fast-mode velocities and density changes (relying on certain assumptions). To find multiple local plasma properties, it is likely some approximations will have to be made. Which

values are assumed and which are solved for will depend on the type of wave being measured. At the very least, though, such solutions can be used to determine if the generic values used are internally consistent.

Using wave physics in this way was first suggested by Uchida (1968) , who in his models found that propagating fast-mode MHD waves were refracted away from regions of high Alfvén speed. He thought that the directionality of Moreton waves could be explained by magnetic structures in the corona which served as wave guides. Expanding on this, he proposed that Moreton waves could be used to “[analyze] coronal structure,” a rather revolutionary idea in a time before extensive coronal observations.

Meyer (1968) took Uchida’s idea one step further, actually applying wave physics to data in order to determine local plasma parameters. Using a Moreton wave and assuming that it was a fast-mode wave with the wavefront extending up into the corona, he derived a local ambient quiet Sun field of 6 G.⁹ Follow-up work on this approach was never done, and calculating local magnetic fields using coronal seismology techniques was not attempted again until the work of Nakariakov (2000) and Nakariakov & Ofman (2001). These newer studies consider oscillating loop structures, such as those discussed on pages 85-92. By interpreting

⁹For this type of derivation to work, Meyer (1968) assumes that the wavefront is traveling at the local fast-mode speed, and is not shocked. Newer observational evidence suggests that such a Moreton wave was probably associated with a coronal shock front. As a result, the magnetic field estimate calculated by Meyer (1968) would have been too high.

the oscillations as global kink modes, they relate the magnetic field strength (B_0) of a loop to its length (L), its oscillation period (P) and the internal (ρ_0) and external (ρ_e) densities:

$$B_0 = \frac{\sqrt{2}\pi^{3/2}L}{P}\sqrt{\rho_0(1 + \rho_e/\rho_0)}. \quad (3.22)$$

This calculation requires an assumption about the value of the local density, but, taking $\rho_e = 0.1\rho_0$ and considering a range of values $1 \times 10^9 \text{ cm}^{-3} < \rho_0 < 6 \times 10^9 \text{ cm}^{-3}$, Nakariakov & Ofman (2001) determine that their magnetic field is in the vicinity of 4 to 30 G.

Observations of propagating waves offer a bit more detail than the oscillating loops studied in Nakariakov (2000) and Nakariakov & Ofman (2001). These data provide fast-mode velocities at multiple points in space, and they give direction as well as magnitude. If we assume that the ambient field structure undergoes minimal change due to the wave, we can find coronal properties over large areas of the quiet Sun, as opposed to individual loops.

The level of coherence of the pulse also has implications. In regions where the front is able to maintain its integrity, there must be little change in the ambient medium on the scale of the width of the pulse. Conversely, if the front disperses quickly, it has presumably entered an area where the factors that contribute to

the fast-mode speed (density, temperature, and/or field strength) vary. For the 13 June 1998 event (Figure 2.1), the easternmost edge of the front stays well-defined until it leaves the field of view. The northward-propagating component, however, quickly becomes dim and spreads out when it reaches the center of the frame. The easternmost edge is traveling over a region of moss, which is associated with relatively uniform, vertical field. The center of the field of view, on the other hand, is substantially dimmer than the rest of the image, suggesting the wave enters a region of lower density. The wave also speeds up in the center of the field of view, which is consistent with a decrease in density. At first glance, our assumptions about the data are reflected in the behavior of the wavefront.

As Equation (3.14) shows, the MHD fast-mode velocity is dependent on sound speed, Alfvén speed, and relative field direction. The sound speed and Alfvén speed are themselves dependent on the temperature, density, and field strength. As with the Nakariakov & Ofman (2001) calculations, assumptions must be made about some properties so that we can solve for others. In a case such as this, where a propagation passes through extremely quiet Sun, it seems reasonable to start with the assumption of a potential field, provided the resulting structures are a rough match to those seen in the data. If we then assume small variations in temperature and density (not unreasonable considering the coherence of the wave), it may be possible to perform a least- χ^2 fit at every point in space for which there

is a defined fast-mode velocity. The result would be individual temperatures and densities over a range of points in space that coincide with the trajectory of the wave.

The coronal seismology measurement postulated above is not a part of this body of work, but would be an interesting future project.¹⁰ However, any results will still not account for the two- to three-dimensional ambiguity inherent in the wave's trajectory. Any fast-mode velocity we find is assumed known at a *point* in space, as opposed to over a column depth. There is growing evidence, though, that these propagations may be confined to a guided layer in the corona, which may help to negate the problems of two-dimensional observation in three-dimensional space. We consider the effects of coronal structure on wave propagation in Chapter 4.

¹⁰In light of discussions in Chapters 4 and 5, however, EIT waves may be insufficient in scope for use in global coronal seismology. Study on this problem is ongoing.

CHAPTER 4

SPATIAL CONSTRAINTS ON WAVE PROPAGATION

Up to now, we have been discussing MHD propagations in the context of data. Working from the observations themselves, we have successfully shown that the 13 June 1998 event is a fast-mode MHD wave, and we have discovered that the wave itself shows no measurable dispersion, which suggests propagation through a homogeneous MHD medium. But we have still not accounted for our observations in the context of current theories of coronal wavefronts. What do the theories predict about MHD propagations? If our data deviate from these theories, can we account for the discrepancies?

The Appearance of a Fast-mode Propagation in the Corona

Over the years, the number of theories postulated to explain Moreton waves and related phenomena has been minimal. Since Uchida (1968) put forth the idea that Moreton waves are the skirts of large-scale coronal shock fronts, it has generally been considered the seminal paper; most newer theories and models use Uchida (1968) as a starting point.

Uchida's theory requires that the skirt of a wavefront intersect with the chromosphere, causing a depression which travels much faster than the Mach number of the surrounding medium. To produce this intersection, Uchida requires a shock front strong enough to continuously interact with the chromosphere but still move at coronal speeds. Under these conditions, the wave propagates ubiquitously in the corona. Figure 1.3 in Chapter 1 shows the trajectory of such a propagation on the limb.

Uchida created his theory having never seen a coronal wavefront. At the time, he needed only to produce features of the Moreton wave, and possibly produce artifacts that could account for Type-II radio bursts. Now, with access to continuous coronal data, if Uchida's theory were correct and such a wave were observed in the corona, what would it look like? The Moreton wave front itself is narrow, requiring the coronal observations immediately above to have a similar structure. In fact, in order for the wave to maintain coherence over large distances ($\gg$ *width of the front*), the entire front would have to be similarly compact. With such a structure, the observations could take one of two forms: we might see a curved thin edge (if the top of the front were optically thin to our instrument) or we might see the expanding cap of the front. Additionally, instruments that observe preferentially in different temperature ranges would see different aspects of such an expansion. An EUV instrument would only see the lower part of a front,

hence the thin edge described above. A soft x-ray telescope which looks at structures higher in the atmosphere (especially a broadband instrument like *Yohkoh*) should be able to see the expanding top, possibly for an extended period.

This description fits well for at least two sets of observations. An event seen on 24 September 1997 by Thompson et al. (2000) shows a Moreton wave cospatial with a thin, bright front in *SOHO*-EIT (Figure 1.6). Additionally, a cospatial “rounded” propagation is observed in the upper corona by *Yohkoh*-SXT. Khan & Aurass (2002) also observe a Moreton wave, an EIT wave, and a “rounded” SXT propagation contemporaneously. In both cases, Moreton wave velocities in excess of 500 km/s are recorded.

These data suggest that Uchida’s model can be used to explain events where both Moreton and coronal waves are observed. However, the phenomenon described by Uchida (1968) does not fit so well with the 13 June 1998 *TRACE* data. In that case, there is neither a chromospheric nor a soft x-ray component. The propagating front is wide and diffuse, unlike the narrow shock wave Uchida’s model predicts. There is also no evidence of a “rounded” top similar to those seen in the *Yohkoh*-SXT data (though this could be an artifact of the limited range of observable temperatures). Finally, the average velocity (~ 300 km/s) is too slow to create the shock assumed in Uchida’s theory.

These attributes are not unique to the 13 June 1998 event; they are a good

description of any typical EIT wave. Despite the fact that the characteristics of EIT waves differ substantially from the expectations of the Uchida model, many early papers referred to EIT waves as “coronal Moreton waves” and worked under the assumption that the same physics was at work. The only alternate theory, proposed by Delannée & Aulanier (1999), interpreted the EUV propagation as fast opening of field lines rather than a fast-mode MHD wave. This theory was designed primarily to account for the persistent dimming following many EUV fronts, and does not explain related events such as coronal loop oscillations.

Recently, Chen et al. (2002) has produced a model which relates EIT waves to chromospheric propagations. In their simulations, a piston shock produces a double wave front. The first is a narrow, fast shock front (the Moreton wave), followed by a larger density perturbation moving at a fraction of the speed (the EIT wave). This theory is intended to explain work done by Eto et al. (2002) and Narukage et al. (2002), where Moreton waves are observed shortly before much slower EIT waves. However, at present, no single data set exists which conclusively shows a shock front followed by a slow, diffuse compression wave.¹ In addition, the fast majority of EIT wave observations have no associated Moreton wave, assumed to be the indicator of a coronal shock front.

The main problem with the Uchida (1968) and Chen et al. (2002) models is

¹There is some evidence, discussed on page 51, that the event observed on 30 August 1998 was preceded by a fast shock front. However, these data are far from conclusive.

that they require the existence of a Moreton wave, or at least a shock. Moreton waves have always been, and continue to be, extremely rare, while EIT waves are observed all the time. A separate theory is required which will explain EIT waves without invoking Moreton waves, and which figures out how they can be observed in EUV wavelengths but not chromospheric lines or soft x-rays.

Using the 13 June 1998 Event to Constrain Theory

We are fortunate to have observations from 13 June 1998 in multiple *TRACE* passbands, two of which show evidence of the wave event. By comparing the two data sets, we are able to isolate characteristics of the event in a way that would not be possible with only single-passband observations. So far, we have considered ratios of the two data sets, and have dealt with changes which we can attribute to the wave; by limiting ourselves to differences, as opposed to totals which may encompass the entire column depth, we hope to constrain our measurements to the immediate vicinity of the wave.

All of emission measure and temperature data, however, assume that the 171 and 195 Å observations be cospatial in three dimensions. Even the measurements that deal only with spatial variations of temperature and emission measure require that the pulse be localized and that values over the column depth of the wave do

not vary significantly. If, for instance, we were looking at the wave “edge-on” – such that the wave column depth $\gg$ the width of the front – it would be difficult for us to isolate where in the atmosphere the changes in temperature or emission measure applied.

However, multiple instrument and temperature observations help us constrain the altitude of the wave somewhat. Since no evidence of the propagation is observed in chromospheric or soft x-ray data, we can be relatively confident that the wave is somehow confined in the EUV corona. If we examine the 171 and 195 Å very specifically, we find we can constrain that height even further.

Since EIT waves are only ever observed to propagate through regions of *large-scale extremely diffuse quiet sun*, and don't seem to strongly affect or interact with more compact structures, it is reasonable to consider the simplest descriptions of local plasma properties. Therefore, much of our modeling assumes a hydrostatic atmosphere where temperature increases with altitude, and weak, uniform magnetic fields.

In Figure 2.1 (a) and (b), which shows observations of the 13 June 1998 event in *TRACE* 195 Å the wavefront manifests itself as a propagating intensity increase. In the case of a compression wave, this increase should be due to two effects: an increase in density, and additional heating. Let us assume for a moment that this wave is ubiquitous and affects material at a range of altitudes. We expect some

of the cooler plasma at lower altitudes to be heated by the adiabatic compression within the wave, resulting in increased emission from this region at the peak 195 Å temperature. However, some of the plasma at higher altitudes is already in the peak temperature regime of the 195 Å passband before the wave reaches it. Here, the heating created by the compression wave should cause a slight *decrease* in emission, since material will now be hotter than the preferential 195 Å temperature. In spite of this decrease, this plasma population is less dense than the lower altitude material being heated into the 195 Å passband, so we would still expect increased overall emission.

If the wave really did exist at all altitudes in the corona, as predicted by the Uchida (1968) model, every temperature regime would experience similar behavior. The only exceptions would be the very lowest temperature (and altitude) plasma, where emission would only decrease because there is no lower material to be heated into the preferential temperature regime.

Remarkably, this description coincides quite well with the wavefront in *TRACE* 171 Å [Figure 2.1 (c) and (d)]. The propagating dimming observed in these data suggests that material is being heated away from the peak passband temperature of 1 MK. However, no cooler material is being heated *into* the 1 MK regime, implying a lack of adjacent cooler coronal material.

For such a situation to occur, the propagation must extend all the way to the

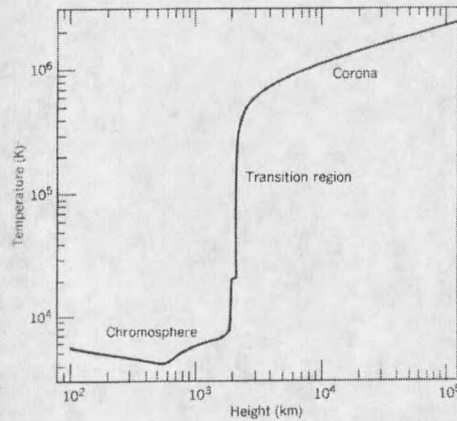


Figure 4.1: Temperature as a function of height in a model solar atmosphere. This graph (reproduced from Foukal [1990]) shows different temperature regimes in the corona and their corresponding altitudes. The chromosphere and corona have temperatures that vary slowly spatially, while the transition region is essentially a temperature discontinuity between the two. According to this plot, the corona has a minimum temperature of about 5×10^5 K, which is within the response range of the *TRACE* 171Å passband.

base of the corona, and include all available material down to the transition region.

Is such an observation feasible in the *TRACE* 171 Å temperature range? Figure 3.2 shows the temperature response function of the 171 Å detector. According to this graph, *TRACE* should be able to observe in EUV down to $< 5 \times 10^5$ K.

Compare this temperature to Figure 4.1, reproduced from Foukal (1990). This graph models the temperature distribution of the solar atmosphere from the chromosphere up into the corona. While the figure is designed primarily to show the steep temperature gradient of the transition region, it also serves to show that temperatures in the corona bottom out around 5×10^5 K. Because the *TRACE*

response extends below this temperature, it implies that the 171 Å passband is observing structures at the lowest coronal altitudes, and that the wavefront likely does include material down to the transition region.

With this conclusion, we can constrain the altitude of the 13 June 1998 event with a well-defined minimum and reasonable but less-defined top. The fast-mode wave does not extend so high as to affect the 2-3 MK plasma observed at the *Yohkoh*-SXT temperature minimum, but it does reach all the way to the base of the corona. Knowing these physical limitations, we now need a physical mechanism to “trap” a wave below some maximum altitude. We find that this answer lies in the structure of the corona itself.

Modeling an Unshocked MHD Wave in a Simplified Corona

If we go back to early theoretical work on Moreton waves, we find that Uchida (1968) did not put forth the only theory. A competing idea was offered around the same time in Meyer (1968). Meyer also assumed that Moreton waves were related to fast-mode MHD disturbances in the corona, but rather than modeling a shock wave that could penetrate all layers of the atmosphere, he assumed the following:

“The propagation of this mode in the corona is strongly influenced by downward refraction in the coronal density gradient and upward reflection in the chromospheric interface. The refraction is caused by the density-dependent increase of

the Alfvén speed with height and prevents the energy from escaping upwards. The sudden density increase between corona and chromosphere produces almost complete reflection.”²

While Meyer’s description does not seem to apply to the coordinated observations of Moreton and SXT waves, such an idea may be sound when considering unshocked coronal propagations. Additionally, Meyer’s postulation does not take into account the coronal temperature gradient (he assumed an isothermal medium). Sound speed scales as $\sqrt{T}$, so regions of higher temperature should refract sound waves in the same way that lower densities refract Alfvén waves. Since fast-mode MHD waves have contributions from both the Alfvén and sound speeds, regions of higher temperature and lower density should have an even greater refraction effect.

Meyer (1968) merely postulates this theory as consistent; here, we run a simplified model to see if a fast-mode wave encounters a point of total reflection while still in the corona. For this model, we assume a hydrostatic corona stratified gravitationally. When determining the magnetic field, we limit ourselves to regions of large-scale, extremely diffuse corona (for instance areas where magnetic carpet features connect to active regions or other large structures over great distances), since these are the sorts of fields through which EIT waves appear to propagate. Therefore, we take the magnetic field to be uniform and vertical, with a value

²Meyer, F., p.486.

of 1 G, consistent with our flux calculations in Chapter 3. Referring to Equation (3.9), this will give us a variation in Alfvén speed dependent only on density. While these quiet Sun regions clearly possess more complicated field structures, there is no overall field-dependent trend we can turn to, so we leave modification of this area of the model to future studies, in which potential field representations of actual solar data should be used.

We do *not* assume an isothermal corona for this calculation. Rather, since temperature variation with altitude is observed but not well-modelled, we consider a range of temperature gradients with height, and see how this affects a reflection point. Equation (3.15) shows that greater temperature regions will possess greater sound speeds. Additionally, scale height is also temperature-dependent, where the scale height $\Lambda(z)$ is defined as

$$\Lambda(z) = \frac{k_B T(z)}{mg} \quad (4.1)$$

so different temperature spatial variations will lead to different density stratifications such that

$$\rho(z) = \rho_0 \frac{T_0}{T(z)} e^{-\int_0^z \frac{1}{\Lambda(z)} dz}. \quad (4.2)$$

With altitude dependence for both Alfvén and sound speeds, and a known direction for the magnetic field, we can use Equation (3.14) to find local fast-mode

speeds. We consider a region with a depth of 240 Mm, and initiate all waves at an altitude of 40 Mm. We can find the altitude at which a ray-traced wave vector turns over by using the relation

$$v_f = \frac{v_i}{\sin \theta}, \quad (4.3)$$

where v_i is the fast-mode speed at the starting altitude, θ is the initial direction of propagation with respect to vertical, and v_f is the fast-mode speed at the turnover altitude. Using our model, we take the fast-mode speed at each of 200 layers in our model, and use this to work backwards and find the initial required propagation angle.

We consider four types of temperature gradients in our atmosphere – isothermal, linear, quadratic, and a gradient based on observational results from Mariska & Withbroe (1978). For the isothermal scenario, we look at both 1.5 and 2 MK cases.

Figure 4.2 shows the relation between initial propagation angle and turnover altitude for each of the five cases. In each case, initial trajectories close to vertical do escape into the upper corona. However, in every case, the majority of the trajectories are reflected back, as would be expected from a wave guide situation.

Such results suggest that the lower corona is a strong wave guide for fast-mode

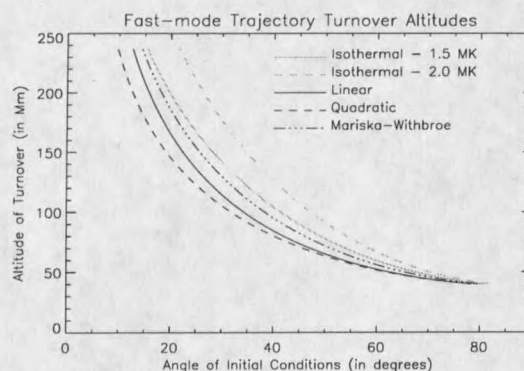


Figure 4.2: Altitudes of reflection for fast-mode waves. This graph shows the ultimate altitude of reflection as a function of the initial angle of propagation for five different temperature gradients. The grey solid and dashed lines refer to isothermal conditions of 1.5 and 2.0 MK, respectively. The black solid line is for a linear increase in temperature, the black dashed line considers a quadratic increase, and the dot-dashed line represents an observational model put forth by Mariska & Withbroe (1978). All temperature models show that fast-mode waves which initially travel close to vertical can escape the atmosphere, but that the majority of propagation angles are reflected back down into the lower corona.

MHD waves. Unless the initial conditions of a wave are just right, that propagation will be confined as postulated by Meyer (1968). This finding is quite consistent with coronal data. If waves are physically confined to low-temperature plasmas, and cannot propagate to higher altitudes or higher temperature regions, it might explain the abundance of EIT – and lack of SXT – waves. When we have seen wavefronts in the soft x-ray corona, they are always fast, strong propagations, unlike the slower, diffuse nature of EUV fronts.

CHAPTER 5

CONCLUSION

Our use of the *TRACE* data in this research has afforded us the first opportunity to thoroughly consider the nature and effects of fast-mode MHD propagations in the corona. The earliest work (i.e. Uchida [1968] and Meyer [1968]) presented valid theories, but lacked the coronal data necessary to test them. More recent observations using *SOHO*-EIT have been limited in their temporal and spatial resolution, so only the simplest events can be observed and the most basic measurements taken.

By using *TRACE* data, we have been able to prove *observationally* that most of the waves observed in EUV are fast-mode MHD waves. We have improved analysis by developing automated methods for determining propagating fronts and the natural trajectories over which they travel. In the case of the 13 June 1998 event, we have found that the flux of the front increases substantially during the first part of the event (due to some as-yet-undetermined mechanism), but that, when the front stops increasing and begins to propagate freely, it produces no measurable dispersion, which suggests the possibility of a homogeneous MHD medium.

Stemming from the theories of Meyer (1968), we have modelled the behavior of a fast-mode wave in a stratified MHD atmosphere, and have shown that such fronts are constrained to a wave guide low in the corona.

Implications of a Coronal Wave Guide

EIT Observations

Our determination of a coronal wave guide in Chapter 4 may have important implications for *SOHO*-EIT observations up to this time. In Chapter 2, we showed that the slow cadence of the EIT “CME Watch” limited the instrument’s dynamic wave observations to events no faster than ~ 480 km/s. Even with this established maximum speed, however, there seems to be remarkable consistency among the *SOHO*-EIT propagation events. Studies such as Thompson et al. (1998), Klassen et al. (2000), Pohjolainen et al. (2001), and Narukage et al. (2002) all discuss EUV wavefronts moving at ~ 300 km/s and displaying “bright fronts” in 195 Å data.

Before our wave guide analysis, the assumption might have been that the detector was somehow preferentially observing propagations of a certain speed because they emitted near the peak of the temperature response function. In light of the discussion in Chapter 4, however, it may actually be more reasonable to assume

that the events all look similar because they are constrained by similar physics. 300 km/s is certainly a reasonable fast-mode velocity for 1-1.5 MK corona. If a fast-mode wave is trapped in the lowest layers of the corona, and is able only to propagate through diffuse, weak field, it will necessarily always encounter regions of comparable temperature, density, and magnetic field. This would mean the constraints of the wave guide have reduced the wave's environment to one of relatively constant fast-mode velocity, and all EIT waves move at roughly the same speed because they are all unshocked fast-mode waves experiencing the same atmospheric conditions.

Coronal Seismology

The apparent temperature and spatial constraints discussed in Chapter 4 present obvious limits on the applicability of these waves to coronal seismology. Ideally, propagating waves are useful in coronal seismology because they encounter a range of different structures over large distances. The introduction of a wave guide will likely affect the sorts of environments a propagation can interact with. While mapping of the local wave speed will still be possible, the wave will probably only interact with the lower regions of the corona. Because these fronts only travel through diffuse field to begin with, it is doubtful that we can use such propagations to learn about strong spatial plasma gradients; the similarity of EIT waves

alone suggests that they are confined to a largely uniform medium. Of course, the lack of strong variability in the medium could be seen as advantageous: since we expect to see only small local perturbations in density and temperature, we may ultimately be able to vary both and determine local differences using least- χ^2 fitting. Ultimately, though, coronal seismology using EIT wave propagation may only be able to give us small results, not large ones. The promise of propagating MHD waves seen by Meyer (1968) and Uchida (1968) may be much more limited than we first expected.

The Wave Guide and the 14 July 1998 Event

Our observations of EIT waves suggest that the local fast-mode speed in the region to which the fronts are constrained is ~ 300 km/s. *SOHO*-EIT has been unsuccessful to date in observing any substantially faster waves. However, the 14 July 1998 event (the Bastille Day Flare) seen by *TRACE* shows velocities of up to ~ 500 km/s. Based on our results in Chapter 4, this suggests that the observed wavefront may be undergoing shocking.

At the time of this writing, a great deal more analysis needs to be done on the wave associated with the Bastille Day event, at least as much as was put into the 13 June 1998 event. At present, these data appear to be our best opportunity to

understand the crossover between EIT wave propagations and Moreton and SXT wavefronts. It is even possible that chromospheric observations of this event, if available, may reveal the depression commonly associated with a Moreton wave.

The observation of a *bright front* in the 171 Å passband certainly suggests that the transition region and perhaps the chromosphere are being influenced. The argument of compressive heating – which accounts for the propagating “dark” front in the 13 June 1998 data – requires that material cooler than 1 MK be affected by the front. Since the temperature transition between the corona and the transition region occurs within the 171 Å response curve, material *cooler* than that seen in 171 Å must be heating – hence the probable effect on the transition region.

Theories on Fast-Mode MHD Propagation in a Real World Context

The discussion of theories put forth in Chapter 4 to explain large-scale coronal propagations – in particular, those of Uchida (1968) and Meyre (1968) – might suggest that the shallow, wave guided events examined in this research operate under quite different principles and mechanisms than Moreton and SXT waves. Certainly the observed morphologies seem disparate enough. However, it is important to remember that, in the end, both the Uchida (1968) and the Meyer (1968)

models were designed under the same conditions using the same physics.

Uchida's primary focus was on highly energetic events. He wanted to model high-velocity events that could also produce Type-II radio bursts. This required that some component escape the solar atmosphere. To achieve these ends, Uchida was led to models that relied on shocking, and he never really considered less energetic instances. However, under the right conditions, Uchida's model resembles Meyer's. In Figure 1.3, for instance, the shallowest propagation trajectories (the dashed lines) never escape and are trapped in the corona.

Meyer, on the other hand, simply postulates the wave guide as an explanation, and doesn't go to any great lengths to apply this idea. His hand-waving intuition does turn out to be correct, but, because he doesn't use his postulation to model a secondary phenomenon, the physics is left more open-ended, and hence is applicable to lower-energy events.

It would appear that both models describe the same phenomenon in the same way, and that their differences are simply due to assumptions about the energy of the event. In all likelihood, such coronal propagations probably happen at a range of energies. If the energy is high enough, the result is a Moreton wave and a front that escapes into the upper atmosphere or beyond; otherwise, the wave is contained near the base of the corona.

The range among wave observations implies that *some* transition must exist that leads to the production of a Moreton and an SXT wave; perhaps a sufficient amount of shocking is necessary. Right now, the data and the theories are woefully inadequate to address this question, and this work remains in the future.

APPENDICES

APPENDIX A

DEVELOPMENT OF AUTOMATED MAPPING PROTOCOLS

The Necessity for Automation

As a visual event, the 13 June 1998 wave front is dramatic. For a casual observer, it has the same visceral effect that might be produced by a spectacular flare or well-defined coronal mass ejection. However, when images from this same event are viewed individually as stills, the wave is unobservable in the original *TRACE* data. Even in difference images stills, the bright front of the wave is only apparent as a coherent structure for the first half of the event; dynamic imaging is required to follow the wave in its entirety.

These observation difficulties make apparent not only the extreme dimness and diffuseness of this event, they also speak to the prowess of the human eye in the detection of motion. A human observer is extremely adept at filtering through noise, and will interpret the structural relationships even in dim, diffuse movement.

Because it is so easy for observers to visually identify motion, the bulk of the previous research done on EIT waves has relied on visual inspection to find waves fronts (i.e. Thompson et al. [1998]; Eto et al. [2002]; Narukage et al. [2002]). When EIT data are used, this technique is not unreasonable. Since fronts observed by *SOHO*-EIT are constrained to have long life times and travel large distances, a considerable amount of diffusion is to be expected. At later times, the observer must rely on recognizing an ill-defined collection of positive points in noisy difference images, where edge-detection is at best difficult. Often, images

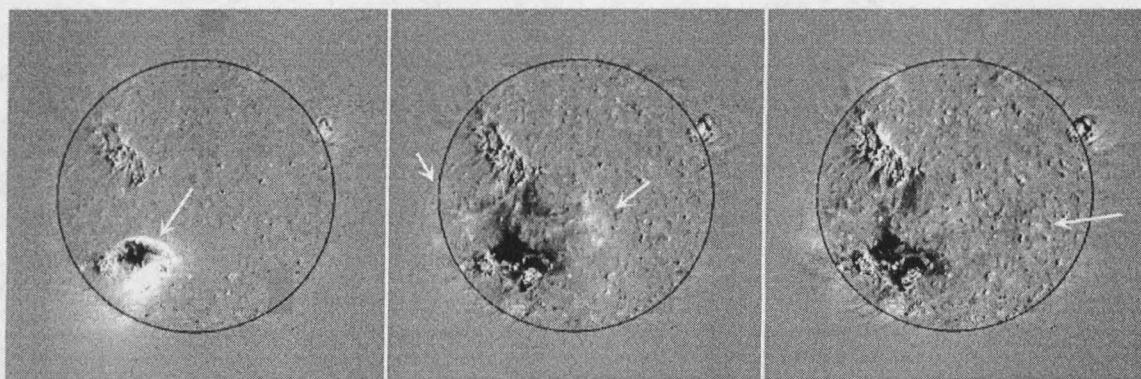


Figure 1: Stills showing the progress of an EIT wave. These data are a series of running difference images, derived from *SOHO*-EIT data taken 24 September 1997. (This figure is reproduced by permission of B. J. Thompson.) By the third frame, the front is hard to distinguish, and the researcher has identified it only with arrows. These data demonstrate the difficulty of automating front-finding techniques in the *SOHO*-EIT data.

subsequent to the initial wave front can only be studied dynamically; some studies show stills (such as those seen in Figure A.1) with fronts that are not entirely obvious to the reader. Work by Ballai (2002) demonstrates the difficulty of using automated techniques to find fronts in EIT data. In his studies, the spatial position of the wave front was indistinguishable from noise, even when difference images were examined.

The problem with relying on visual inspection to find and measure wave fronts is one of reproducibility. For extremely diffuse data (Figure A.1), it is easy to believe that different observers will produce different results. However, the effects can also be more subtle. In the initial work on the 13 June 1998 event (Wills-Davey & Thompson [1999]), the progress of the front was determined visually.

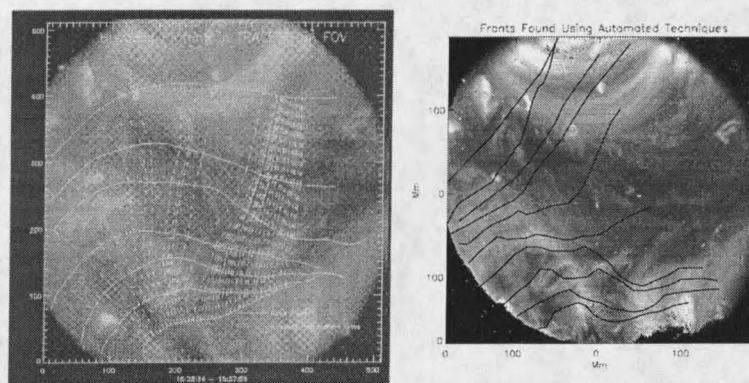


Figure 2: Comparison of front-finding techniques for the 13 June 1998 event. This figure offers a comparison between the propagation fronts found using visual versus automated techniques. The image on the left was produced by M. J. Wills-Davey in 1998, using visual inspection to follow the progress of the front, and appears in Wills-Davey & Thompson (1999). The image on the right was produced in 2002 using the automated techniques described in this appendix. There are noticeable differences between the fronts found using the two techniques, especially in the northwest region of the field of view.

Later, when automated techniques were applied to the same data set, there were pronounced differences between the results of the computer and the results of the researcher. The comparison is shown in Figure A.2. Part of the difference comes from changes in the definition of what constitutes the propagation front. However, other inaccuracies, such as those in the upper corners, may likely be due to “creation” of continuity on the part of the researcher; in this case, I saw motion in areas where the wave was extremely dim, and probably convinced myself that I saw propagation happen in a certain way.

If differences like this can exist even in the most well-defined data set currently available, it brings into question the accuracy of any EIT wave front found

through visual inspection. While this technique is still necessary in the analysis of *SOHO*-EIT data, I have gone to great lengths to automate my examinations of the *TRACE* data. In the following sections, I describe the algorithms used to map wave fronts, determine propagation trajectories, and follow loop oscillations and other fine-structure motions. Constraints on these techniques are also discussed.

Tracking the Wave Front

When the 13 June 1998 event is observed in base difference images, it appears primarily as a bright front. The way this front interacts with the surrounding structures suggests it is fast-mode MHD wave (discussed in more detail in Chapter 3). It is basically a compression wave,¹ and, in an optically thin atmosphere such as the corona, we would expect DN values to exhibit a gaussian structure. We define the "front" as the point along the wave of maximum compression – the maximum height of the gaussian. These criteria are different from those used in visual inspection; there, the edge of the bright region defined the "front." Visually this stands out, but it is really just the transition of the gaussian from positive to zero, and may not be as physically meaningful as the maximum of the bright region. As the wave diffuses, this edge should travel faster than the point of maximum compression, leading to consistently overestimated front speeds.

¹See the discussion on page 73

With the 13 June 1998 event, we have the advantage of data in multiple wavelengths. Early studies (Wills-Davey & Thompson [1999]) focused primarily on the 195 Å data; however, evidence of the wave appears in *TRACE* 171 Å as well. Since intensity values in a given *TRACE* passband depend on the response function, a proper combination of the two data sets should produce more meaningful quantities; this idea is the basis for simple temperature derivation (subject to myriad constraints). For our purposes, we consider a simple ratio of the two *TRACE* passbands to see if a meaningful wavefront can be found, and is not an artifact of the 195 Å data. If this front can be established, it is then reasonable to consider more in-depth convolutions of the data, such as temperature or emission measure maps. From these, it is possible to derive quantities such as density, flux, and dissipation.

Since the position of the front is determined by a maximum, differencing the data with extremely quiet initial conditions should not overly affect the spatial position of the maxima; similar results should be obtainable from original data. However, using difference images allows the researcher to more easily check the effect of noise on the definition of the front. Since we are only interested in compression, or increased emission measure, we further eliminate sources of noise by only considering positive points in the data. These criteria will also help in future calculations of density enhancement.

Having transformed the data to a more analyzable form, we consider the images

individually and in chronological order. For the 13 June 1998 data, ten of the thirteen images displayed measureable fronts. For the first and the last two images, too little of the bright front is in the field of view. For a given image, we divide the data into pixel-wide vertical bins. We then find local maxima along these bins. Visually, the position of the front will be apparent in a fraction (but not all) of the vertical bins. (The front only progresses into the east side of the data gradually, and never extends west out of the field of view.) The bins outside of the front are eliminated, and the sources of noise in the bins that contain the front (for instance, bright points or ejecta) are reduced. In some cases, this noise reduction can be used to better define the front.

The points that remain are still noisy, but now can be fit with a low-resolution spline. The low resolution serves to smooth some of the noise out of the function. Each spline function is further fit with a smoothing function (using IDL `smooth.pro`), resulting in the curves shown on the right side of Figure A.2.

Two regions of the data proved problematic. While there is some evidence that the wave affects the northwest corner of the field of view (discussed in Chapter 2), the inherent dimness of the region makes the data too noisy to locate a bright front, even in difference images. Therefore, no wave appears in this section of the image when our algorithms are used. This does not mean the front does not pass through the northwest corner; it is simply not measureable using these techniques.

Data in the northeast corner also suffers from noise limitations. By the time the front reaches this region, it has dissipated to the point where a gaussian fit is difficult and the point of maximum compression is hard to find. Additionally, the measurement of the last two fronts occurs with part of the wave outside of the field of view; this may account for the apparent slowing at the last front.

Determining the Wave Trajectory

Knowing the position of the front over time, we attempt to find the most natural trajectories between fronts. With an ideally smooth data set, Huygens plotting is a reasonable choice. In Huygens plotting, the end of the trajectory vector is at a point on the later front that is closest to the original site on the earlier front.

Unfortunately, in the 13 June 1998 data, the known wavefronts are sufficiently far apart spatially that using Huygens vectors creates artificially straight and "jerky" trajectories. To create smoother and more meaningful trajectories, we subject a contour image of the wave fronts to a convolution in time. Each front is assigned a constant value in units of seconds, and we then convolve the image with a smoothing kernel over each pixel until we have well-defined time gradients between the fronts. The gradients are then broken down into ten-second contours.

The new contours have the double advantage of being closer spatially and

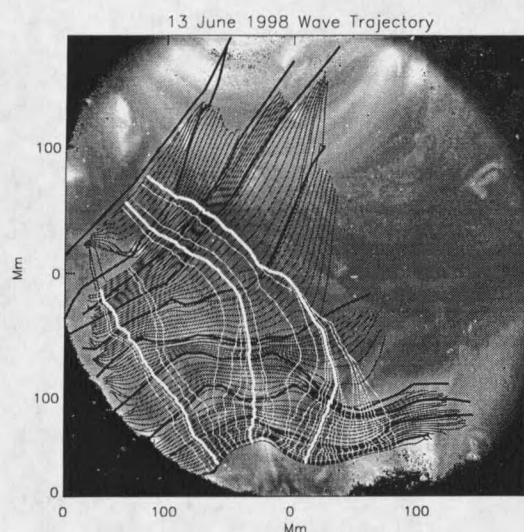


Figure 3: Propagation fronts and trajectories determined through automated mapping. This figure maps the motion of the wavefront seen on 13 June 1998. The thick grey fronts are derived from actual data, tracing out the maxima of the bright front in ten of the observations. The thin grey fronts are interpolations between the known data, spaced in ten-second intervals. The white tracks running roughly perpendicular to the fronts are trajectories determined using Huygens plotting. Three of the trajectories are emphasized for study in Chapter 3.

inherently smoother. Huygens plotting using these new convolved fronts gives trajectories that are smoother and appear more natural.² Figure A.3 shows the original data fronts mapped with the convolved fronts and propagation trajectories.

Three of the trajectories in Figure A.3 are emphasized. These three are taken as example trajectories to follow the progress of the wave's intensity. They are considered in more detail in Chapter 3.

²To double-check the validity of the convolved contours, we compared the trajectories they produce to those found using only the known fronts. Neglecting the differences in resolution, the trajectories found using these two methods were remarkably similar. This gives us confidence that convolved contours are a reasonable approximation.

Tracking Fine-scale Motion Excited by the Wave Front

In Chapter 2, coronal loop oscillations were discussed in the context of EIT waves. Early work by Wills-Davey & Thompson (1999) examined two loop oscillations that were visible in the *TRACE* 171 Å data, but harder to observe in 195 Å. However, by using ratio data from the two passbands, it was possible to automatically track many more structures with oscillatory motion.

Structural motions used in the mapping were first determined by eye; the nature of the tracking algorithm requires that the structure vibrate fairly uniformly about a central axis, so only well-defined first-order modes were considered. With the oscillating loop chosen, points are mapped along the loop (again, by eye) in the earliest image and fit with a spline interpolation. The accuracy of these points is helpful, but is not overly critical. Using the spline interpolation as a central axis, we define a two-dimensional array along and perpendicular to the oscillating loop. The perpendicular component is a cross-section of the loop. For subsequent images, a two-dimensional array is chosen at the same spatial points, disregarding any loop motion. If the structure is dynamic, then a cross-correlation of two cospatial loop cross-sections will show that the loop profile has shifted.

Figure 2.4 shows the location of each of the seven structures that were measured with this cross-correlation technique, and Figure 2.5 shows the average motion of

the loop around the initial conditions. These structures are discussed in more detail in Chapter 2.

Constraints of Current Data

The automated measurement techniques described in this chapter were designed specifically for the 13 June 1998 data. As the other data sets in Chapter 2 show, this event has an extremely well-defined bright front compared to other *TRACE* data. It is also observed in multiple wavelengths, allowing us to use ratio or emission measure images in determining wavefront propagation. Only the 14 July 1998 event has a similarly robust data set. The other two events discussed in Chapter 2 are more limited.

The 30 August 1998 event is particularly problematic. The lack of a discernable wavefront (and the possibility of fast “pre-wave” front), forces us to consider only straight-line velocities. In addition, the position of the instigating event and loops near the edge of the field of view give us an incomplete picture of the oscillating loops themselves. At best, we can use the 30 August 1998 event to test for consistency in theories of coronal propagation.

Even as more EIT wave events are found in the *TRACE* data, it is unlikely that good complete data sets will be available. *TRACE* has had on-going quad

shutter problems, which have limited contemporaneous observation in multiple EUV wavelengths. To date, we know of no additional propagation events seen in both 171 Å and 195 Å, and most of the events that are recorded are in the less preferable 171 Å passband. As a result, much of the analysis we will discuss in Chapter 3 may only be possible with the 13 June and 14 July 1998 data sets.

APPENDIX B

MAGNETOHYDRODYNAMICS AND THE SOLAR CORONA

Compared to many coronal events, EIT waves are large and produce changes that take place over relatively long time-scales. These characteristics allow us to consider them as *hydrodynamic* phenomena. Since the corona is magnetically-dominated, we must in particular talk about these waves in the context of *magnetohydrodynamics (MHD)*.

A MHD environment can be determined if four conditions are fulfilled:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = \frac{1}{\rho} [-\nabla p + (\mathbf{j} \times \mathbf{B}) - \rho g \hat{r} + \mathbf{F}] \quad (2)$$

$$\frac{\rho^\gamma}{\gamma - 1} \left[\frac{\partial}{\partial t} \left(\frac{p}{\rho^\gamma} \right) + (\mathbf{v} \cdot \nabla) \left(\frac{p}{\rho^\gamma} \right) \right] = \nabla \cdot (K \nabla T) - L_r + \frac{j^2}{\sigma} + H \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \quad (4)$$

Equation (A.1), the *equation of continuity*, describes the conservation of mass flux. Equation (A.2) is the *equation of motion*, and shows the movement of the plasma is subject to the plasma pressure p , the Lorentz force $\mathbf{j} \times \mathbf{B}$, and gravity. Additional forces, such as viscosity, are included in $\mathbf{F}$. Possible energy contributions and losses are considered in Equation (A.3), which takes into account the heat flux $K \nabla T$, radiative losses L_r , and ohmic dissipation j^2/σ . Additional energy sources or sinks appear in H .

The first three equations are basically the hydrodynamic equations with minor modifications due to the magnetic environment. However, it is Equation (A.4), the *induction equation*, that tells us the most about the MHD nature of the environment. η is the *magnetic diffusivity*, and the value of this term with respect to the plasma can allow for certain simplifications in the MHD equations.

We can consider magnetic diffusion as a dimensionless quantity using the *magnetic Reynolds number*:

$$R_M = \frac{Lv_P}{\eta} \quad (5)$$

where v_P is a typical plasma speed and L is a typical length scale. R_M gives an idea of the strength of the coupling between the plasma and the magnetic field. Plasmas with a low magnetic Reynolds number diffuse across field lines, whereas those with high R_M are tightly bound to the fields that permeate them. If $R_M \gg$ or $\ll 1$, one of the two terms in Equation (A.4) will dominate. In the case of the Sun (and astrophysical plasmas in general), $R_M \gg 1$, causing the induction equation to reduce to

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \quad (6)$$

Equation (A.6) describes a perfectly conducting plasma. This elimination of the diffusivity term leads to *Alfvén's frozen-flux theorem*: in a perfectly conducting medium, the plasma and the magnetic field are constrained to move together.

This seemingly simple idea has powerful implications which affect all of solar physics. For instance, the reconnection postulated to cause flares violates this principle. For this research, though, it is enough to realize that the plasma and the magnetic field cannot be considered separately.

BIBLIOGRAPHY

- Aschwanden, M. J., De Pontieu, B., Schrijver, C. J., & A., T. 2002, *Sol. Phys.*, 206, 99
- Aschwanden, M. J., Fletcher, L., Schrijver, C. J., & Alexander, D. 1999, *ApJ*, 520, 880
- Athay, R. G., & Moreton, G. E. 1961, *ApJ*, 133, 935
- Aulanier, G., DeLuca, E. E., Antichos, S. K., McMullen, R. A., & Golub, L. 2000, *ApJ*, 540, 1126
- Ballai, I., & Erdelyi, R. 2002, in *Turbulence, Waves, and Instabilities in the Solar Plasma*, NATO Advanced Research Workshop, Budapest, Hungary, in press
- Becker, U. 1958, *Zeitschrift für Astrophysik*, 44, 243
- Beilenson, P. t. 1958, *The Four Seasons* (Mount Vernon, N.Y.: The Peter Pauper Press)
- Biesecker, D. A., Myers, D. C., Thompson, B. J., Hammer, D. M., & Vourlidas, A. 2002, *ApJ*, 569, 1009
- Chen, P. F., Wu, S. T., Shibata, K., & Fang, C. 2002, *ApJ*, 572, L99
- Chouduri, A. R. 1998, *The Physics of Fluids and Plasmas: An Introduction for Astrophysicists* (Cambridge, United Kingdom: Cambridge University Press)
- Delannée, C., & Aulanier, G. 1999, *Sol. Phys.*, 190, 107
- DeMoortel, I., Hood, A. W., & Ireland, J. 2002, *A&A*, 381, 311
- Dodson, H. W. 1949, *ApJ*, 110, 382
- Eto, S., et al. 2002, *PASJ*, 54, 481
- Foley, C. R., Harra, L. K., Matthews, S. A., Culhane, J. L., & Kitai, R. 2003, *A&A*, 399, 749
- Foukal, P. 1990, *Solar Astrophysics* (New York: John Wiley & Sones, Inc.)
- Goossens, M., Andries, J., & Aschwanden, M. J. 2002, *A&A*, 394, L39
- Handy, B. N., et al. 1999, *Sol. Phys.*, 187, 229
- Harra, L. K., & Sterling, A. C. 2001, *ApJ*, 561, L215
- Harra, L. K., & Sterling, A. C. 2003, *Max Millennium E-Print Archive*, <http://solar.physics.montana.edu/cgi-bin/eprint/full.abstract.pl?entry=520>

- Hill, S. M., & Pizzo, V. J. 2002, in Innovative telescopes and Instrumentation for Solar Astrophysics, Vol. 4853, Proc. SPIE, in press
- Khan, J. I., & Aurass, H. 2002, A&A, 383, 1018
- Klassen, A., Aurass, H., Mann, G., & Thompson, B. J. 2000, A&A Supp. Series, 141, 357
- Krucker, S., & Aschwanden, M. J. 1999, trace_teem.pro, Solarsoft Library, <http://www.lmsal.com/solarsoft/>
- Leibacher, J. W., & GONG Project Team. 1998, in Structure and Dynamics of the Interior of the Sun and Sun-like Stars, SOHO 6/GONG 98 Workshop, Boston, Massachusetts, 3
- Leibacher, J. W., & Stein, R. F. 1981, in The Sun as a Star, Nonthermal Phenomena in Stellar Atmospheres, NASA, Goddard Space Flight Center, 263
- Mariska, J. T., & Withbroe, G. L. 1978, Sol. Phys., 60, 67
- Meyer, F. 1968, in Structure and Development of Solar Active Regions, IAU, 485
- Moreton, G. E. 1960, Astronomical Journal, 65, 495
- Moreton, G. E., & Ramsey, H. E. 1960, PASP, 72, 357
- Musielak, Z. E., & Ulmschneider, P. 2003, A&A, 400, 1057
- Myers, D. C., & Thompson, B. J. 2002, Eit wave events online catalog, <ftp://eitv3.nascom.nasa.gov/pub/outgoing/MORETON/DCM/>
- Nakariakov, V. M. 2000, in Waves in Dusty, Solar, and Space Plasmas, Vol. 537, AIP, Leuven, Belgium, 264
- Nakariakov, V. M., & Ofman, L. 2001, A&A, 372, L53
- Nakariakov, V. M., Ofman, L., DeLuca, E. E., Roberts, B., & Davila, J. M. 1999, Science, 285, 862
- Narukage, N., Hudson, H. S., Morimoto, T., Akiyama, S., Kitai, R., Kurokawa, H., & Shibata, K. 2002, ApJ, 572, L109
- Ogawara, Y., et al. 1992, PASJ, 44, L41
- Pohjolainen, S., et al. 2001, ApJ, 556, 421
- Priest, E. R. 1984, Solar Magnetohydrodynamics (Dordrecht, Holland: D. Reidel Publishing Company)
- Richarson, R. S. 1951, ApJ, 114, 356

- Scherrer, P. H., Bogart, R. S., Bush, R. I., Hoeksema, J. T., Kosovichev, A. G., Nigam, R., Schou, J., & Duvall, T. L., Jr. 1996, in BAAS, Vol. 28, American Astronomical Society, 1298
- Schrijver, C. J., Aschwanden, M. J., & Title, A. M. 2002, Sol. Phys., 206, 69
- Schrijver, C. J., & Brown, D. S. 2000, ApJ, 537, L69
- Shibata, K., et al. 2002, in COSPAR Colloquia Series, Vol. 13, Multi-Wavelength Observations of Coronal Structure and Dynamics, 279
- Smith, S. F., & Harvey, K. L. 1971, in Physics of the Solar Corona, Vol. 27, 156
- Stein, R. F., & Leibacher, J. W. 1974, Annual Review of Astronomy and Astrophysics, 12, 407
- Stein, R. F., & Leibacher, J. W. 1981, in The Sun as a Star, Nonthermal Phenomena in Stellar Atmospheres, NASA, Goddard Space Flight Center, 289
- Thompson, B. J., Plunkett, S. P., Gurman, J. B., Newmark, J. S., St. Cyr, O. C., Michels, D. J., & Dolaboudinière, J.-P. 1998, GRL, 25, 2461
- Thompson, B. J., Reynolds, B., Aurass, H., Gopalswamy, N., Gurman, J. B., Hudson, H. S., Martin, S. F., & St. Cyr, O. C. 2000, Sol. Phys., 193, 161
- Uchida, Y. 1968, Sol. Phys., 4, 30
- Uchida, Y. 1970, PASJ, 22, 341
- Uchida, Y., Altschuler, M. D., & Newkirk, G. 1973, Sol. Phys., 28, 495
- Uchida, Y., Tanaka, T., Hata, M., & Cameron, R. 2001, Publ. Astron. Soc. Aust., 18, 345
- Vršnak, B., Warmuth, A., Brajša, R., & Hanslmeier, A. 2002, A&A, 394, 299
- Wang, Y.-M. 2000, ApJ, 543, L89
- Warmuth, A., Vršnak, B., Aurass, H., & Hanslmeier, A. 2001, ApJ, 560, L105
- Wills-Davey, M. J., & Thompson, B. J. 1999, Sol. Phys., 190, 467
- Wu, S. T., Zheng, H., Wang, S., Thompson, B. J., Plunkett, S. P., Zhao, X. P., & Dryer, M. 2001, JGR, 106, 25,089

MONTANA STATE UNIVERSITY - BOZEMAN



3 1762 10391950 0