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

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.

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MONTANA STATE UNIVERSITY — BOZEMAN
Bozeman, Montana

May 2003

APPROVAL

of a dissertation submitted by

Meredith Jennings Wills-Davey

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.

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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 fruitition. 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.

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ABSTRACT

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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

[1]In 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

$$\psi(t) = A\cos(\omega t). \tag{1.1}$$

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

[2]This 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 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 recorrection. 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

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

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

$$\omega^2 = \frac{\gamma k_B T}{m} k^2 \tag{1.3}$$

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

$$v_{ph} = \frac{\omega}{k}. \tag{1.4}$$

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

$$\mathbf{v}_{gr} = \frac{\partial \omega}{\partial \mathbf{k}}. \tag{1.5}$$

In the case of the sound wave in Equation (1.3), or any dispersion relation where ω and $\mathbf{k}$ 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 occured nearly simultaneously at disparate points on the disk far more often then 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

[3]Dodson, H. W., p. 382.

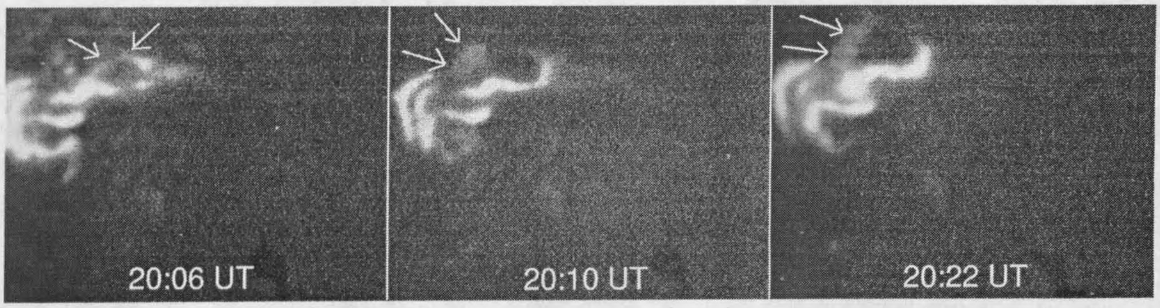

Figure 1.1: Hydrogen-α observation from the McMath-Hulbert Observatory, May 10, 1949. The stills shown above are from Dodson (1949). In her paper, Dodson discusses an "ejection" of "plage-intensity" that originates near the center of the flare. The arrows [inserted by this author] point out what may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