

## ARE “EIT WAVES” FAST-MODE MHD WAVES?

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### ABSTRACT

We examine the nature of large-scale, coronal, propagating wave fronts (“EIT waves”) and find they are incongruous with solutions using fast-mode MHD plane-wave theory. Specifically, we consider the following properties: nondispersive single pulse manifestations, observed velocities below the local Alfvén speed, and different pulses which travel at any number of constant velocities, rather than at the “predicted” fast-mode speed. We discuss the possibility of a soliton-like explanation for these phenomena, and show how it is consistent with the above-mentioned aspects.

*Subject headings:* MHD — Sun: corona — Sun: coronal mass ejections (CMEs) — waves

### 1. INTRODUCTION

Long before the availability of direct observations in 1997 (Thompson et al. 1998), attempts were made to explain the physics of large-scale coronal pulse waves. The original evidence of these wave fronts appeared in chromospheric H $\alpha$  observations of “Moreton waves”—semicircular propagating depressions, which traveled away from flaring regions at speeds orders of magnitude above the chromospheric sound speed (Athay & Moreton 1961). Uchida (1968) theorized that Moreton waves were a secondary effect caused by the “skirt” of a coronal fast-mode magnetoacoustic shock wave extending down into the chromosphere. They manifest themselves in running difference images as dark fronts followed by light fronts, as shown in Figure 1.

The advent of continuous soft X-ray and extreme-ultraviolet (EUV) observation—made possible by instruments such as the *Yohkoh* Soft X-ray Telescope (SXT) and the *SOHO* Extreme Ultraviolet Imaging Telescope (EIT)—made it possible to test the Uchida (1968) theory, and indeed all manner of large-scale coronal pulse waves have been observed. Wave fronts have been recorded in soft X-ray (Hudson et al. 2003; Warmuth et al. 2005; Khan & Aurass 2002), EUV (Thompson et al. 1998; Wills-Davey & Thompson 1999; Biesecker et al. 2002), and even as a secondary response in He  $\lambda$ 10830 (Gilbert et al. 2004). Moreton waves have some cospatiality with EUV waves (Eto et al. 2002; Okamoto et al. 2004) and have been particularly well correlated with soft X-ray observations (Narukage et al. 2002, 2004), lending credence to the original Uchida (1968) postulation.

However, Moreton waves are observed in conjunction with only a tiny fraction of coronal observations. The large majority of single-pulse wave fronts are seen only by EUV instruments, with no apparent chromospheric or soft X-ray counterpart. These EUV fronts (often called “EIT waves”) have some of the same general characteristics as Moreton waves, but in many respects they are quite different. While it would appear that Moreton waves may fit the Uchida (1968) fast-mode MHD shock model, we postulate that existing MHD models of EIT waves are not consistent with aspects of available data, and suggest that mechanisms which encompass nonlinear wave pulse propagation appear more promising to explain the breadth of observed EIT wave phenomena.

#### 1.1. Properties of Moreton and EIT Waves

Moreton waves and EIT waves can be described as “single-pulse” phenomena. Figure 2 shows examples of two different EIT wave events—one observed by *SOHO* EIT, and one by the *Transition Region and Coronal Explorer* (TRACE). These waves are associated with impulsive events, and although actual causality has still not been determined, Biesecker et al. (2002) and Cliver et al. (2005) find a strong correlation with coronal mass ejection (CME) initiation. There is also evidence that both EIT waves and Moreton waves displace large magnetic structures: EIT waves have been observed directly instigating loop oscillations (Wills-Davey & Thompson 1999), and Moreton waves have been associated with “winking filaments” (Okamoto et al. 2004).

However, other aspects of EIT and Moreton waves are sufficiently different that some have theorized they are two entirely different populations that originate from different instigators (Chen et al. 2002, 2005; Eto et al. 2002). Although both are single pulses, Moreton waves are strongly defined, narrow, semicircular fronts, while EIT waves are broad ( $\sim 100$  Mm), extremely diffuse, and (when unimpeded) produce circular wave fronts. Moreton waves have relatively short lifetimes (usually  $< 10$  minutes), and have shown cospatial observational signatures between the chromosphere and the soft X-ray corona (Khan & Aurass 2002; Narukage et al. 2002). EIT waves are primarily visible in the lower corona (at 1–2 MK), but typically have lifetimes of over an hour and can travel the entire diameter of the Sun while remaining coherent (Thompson & Myers 2007). Moreton waves typically travel at speeds of  $\sim 400$ – $2000$  km s $^{-1}$  (Becker 1958; Smith & Harvey 1971); such velocities are thought to be comparable to or much larger than the local Alfvén speed. In recent work, Narukage et al. (2004)—having calculated local fast magnetoacoustic speeds of  $700$ – $1000$  km s $^{-1}$ —find that Moreton waves occur at speeds of  $M > 1$ , and disappear as they slow to  $M = 1$ . EIT waves, on the other hand, travel much more slowly, at average velocities ranging from  $25$  to  $450$  km s $^{-1}$  (Thompson & Myers 2007), which correspond to  $0.03 < M < 0.53$ . Although there is some evidence of Moreton and EIT waves traveling cospatially (Thompson et al. 2000; Okamoto et al. 2004), most studies conclude that, while they appear to originate together, the two must be inherently different (Chen et al. 2002, 2005; Eto et al. 2002).

The work of Uchida (1968) and Narukage et al. (2004) would appear to explain the nature of Moreton waves—they exist as a result of coronal shock fronts. EIT waves, however, have proved

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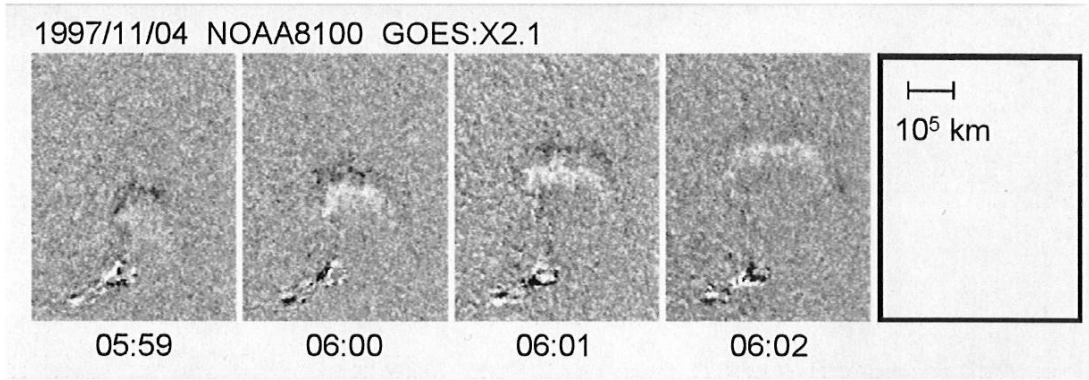


FIG. 1.— Example of a Moreton wave observed in  $H\alpha$  on 1997 November 4 by the Flare Monitoring Telescope of Kyoto University’s Hida Observatory. This event was produced in conjunction with a *GOES* X2.1 flare. This figure reprinted with permission from Narukage et al. (2003; Poster at *SOHO* 13 Conf., Waves, Oscillations and Small-Scale Transient Events in the Solar Atmosphere: A Joint View from *SOHO* and *TRACE* [Palma de Mallorca]).

much more difficult to comprehend. Although Moreton waves are always viewed in conjunction with EIT waves, the converse is not true, even in high-cadence data. Wills-Davey (2002, 2006) present a quantitative analysis of a *TRACE*-observed EIT wave from its inception, and no corresponding Moreton wave is observed.<sup>2</sup>

Any complete theory of EIT waves must explain

1. why EIT waves are observed as single pulses,
2. how most EIT waves are manifested in the absence of Moreton waves,
3. why many EIT wave velocities are slower than predicted Alfvén speeds,

<sup>2</sup> This contradicts the findings of Harra & Sterling (2003), but their conclusions about the same wave front are the result of visual inspection, whereas the work of Wills-Davey (2002,2006) is quantitative.

4. why individual EIT waves travel at approximately constant speed, but that speed varies greatly between EIT waves, and
5. how EIT waves can maintain coherence over distances comparable to the solar diameter;
6. additionally, it should confirm why EIT waves sometimes generate loop oscillations.

1.2. Existing Coronal Pulse Wave Models

At present, multiple published explanations exist to explain EIT waves (Chen et al. 2002, 2005; Warmuth et al. 2001; Wang 2000; Wu et al. 2001; Ofman & Thompson 2002; Ofman 2007). In each case, some of the requirements listed in § 1.1 are fulfilled, but no one numerical or theoretical model explains all six properties.

Chen et al. (2002, 2005) and Warmuth et al. (2001) each develop models that focus on the *relation* between the Moreton and EIT waves, leading to explanations where the Moreton wave is

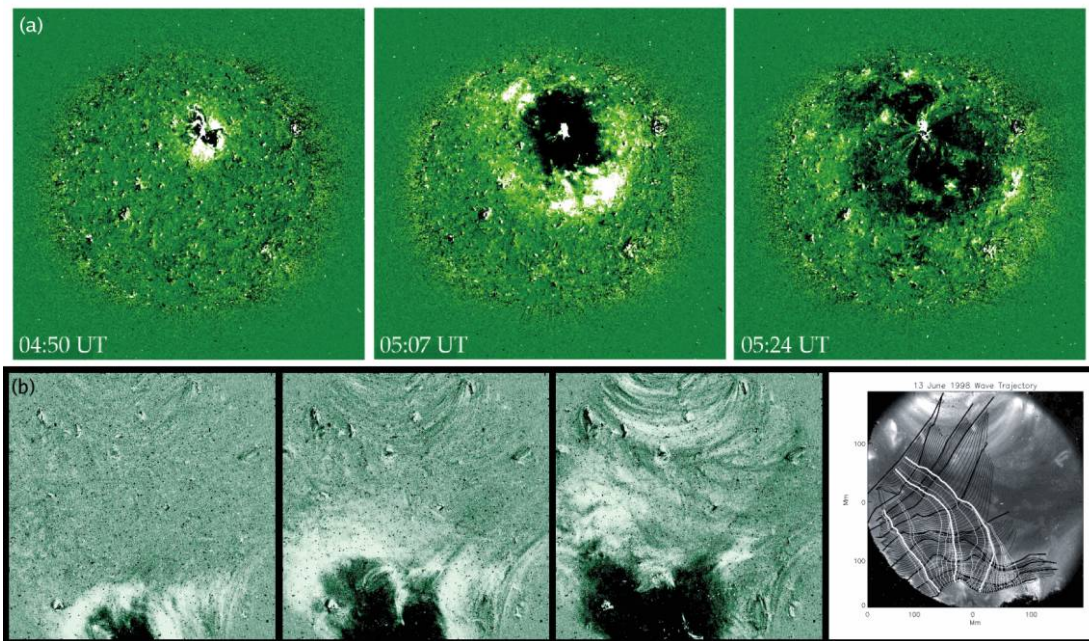


FIG. 2.— Two examples of EIT waves as observed by different EUV instruments. (a) Running difference images of an EIT wave seen by *SOHO* EIT on 1997 May 12, and studied in detail by Thompson et al. (1998). (b) Base difference images and measured fronts from Wills-Davey (2006) of an event observed by *TRACE* on 1998 June 13. (In running difference images, each frame is subtracted from the one following. In base difference images, all frames have a single pre-event image subtracted from them.) Panel (a) reprinted with permission from B. J. Thompson.

the primary source of a secondary EIT wave—a scenario which is inconsistent with the bulk of “EIT wave only” observations. In addition, the models created by Chen et al. (2002, 2005) demonstrate Moreton wave propagation over large distances but EIT wave propagation over much smaller distances—the opposite of what is seen in observations.

In cases where EIT wave only numerical simulations have been developed, the physics driving EIT waves is derived from the original Uchida (1968) theory: EIT waves are treated as fast-mode magnetohydrodynamic (MHD) waves. Starting from this premise, Wang (2000), Wu et al. (2001), Ofman & Thompson (2002), and Ofman (2007) have created computer-generated coronal waves that imitate data very closely. Unfortunately, the successful implementation of these models requires unusually low quiet Sun magnetic field strengths as well as a high plasma  $\beta$  corona. In addition, both the Wang (2000) and the Wu et al. (2001) simulations reproduce only the same oft-studied event from 1997 May. The wide variety of EIT wave velocities and morphologies may be beyond the capability of these models; indeed, when Wang (2000) models a second event from 1997 April, he reproduces the velocities of the 1997 May rather than the 1997 April wave.

The problem may lie in the treatment of EIT waves as fast-mode MHD pulses. While a fast-mode MHD wave does have some of the properties associated with EIT waves, many aspects of these coronal pulse waves contradict predicted fast-mode behavior. In addition, Wills-Davey (2003) and Warmuth et al. (2004b) have found observational evidence that these waves are highly nonlinear, with density perturbations of 40% to more than 100% above the local background.

In this paper, we discuss the discrepancies between the predicted behavior of MHD waves and EUV observations, and consider the ramifications of the MHD solution on other aspects of coronal physics (§ 2). With these discrepancies in mind, we show that aspects of a single-pulse solution can account for the properties of EIT waves (§ 3).

## 2. INCONSISTENCIES ARISING FROM A FAST-MODE MHD SOLUTION

At first glance, the choice of a fast-mode MHD solution seems the most appropriate to explain EIT waves. Fast- and slow-mode MHD wave mode speeds can be written as

$$v_{f,s}^2 = \frac{1}{2} \left( v_A^2 + c_s^2 \pm \sqrt{v_A^4 + c_s^4 - 2c_s^2 v_A^2 \cos 2\theta} \right), \quad (1)$$

where  $v_A^2 = B^2/(4\pi\rho)$  defines the local Alfvén speed, and  $c_s^2 = (\gamma k_B T)/m$  the local sound speed. Note that  $v_f \geq v_A$  and  $0 \leq v_s \leq c_s$ , depending on  $\theta$ . This means that any event with a speed below  $v_A$  cannot be considered a fast magnetosonic wave.

To reproduce EUV observations, the chosen wave solution must be a compressive MHD wave that can travel ubiquitously through a magnetized plasma. Pure Alfvén waves cannot produce the necessary compression to be seen as a brightness enhancement. Slow-mode magnetoacoustic waves are compressive, but their propagation is limited by magnetic field direction; the slow-mode velocity vanishes for propagation perpendicular to field lines. Not only would this prevent the observed ubiquitous propagation through the quiet corona, but *TRACE* observations show evidence of EIT waves successfully crossing coronal loop structures (Wills-Davey & Thompson 1999).

However, fast-mode MHD waves have the double advantage of being compressive and existing for all magnetic field orien-

tations. These are the properties that led Uchida (1968) to use fast-mode MHD shocks for his original Moreton wave solution, and motivate their continued use in more recent simulations. Unfortunately, a fast-mode solution presents problems when trying to recreate some of the properties of EIT waves. In particular, it becomes difficult to explain

1. observed speeds,
2. theoretical assumptions of a low- $\beta$  corona (due the fact that many EIT waves travel slower than the local sound speed),
3. the variety of observed propagation speeds, and
4. the nature and duration of pulse coherence.

### 2.1. Velocity Magnitudes

One inconsistency between a fast-mode MHD wave model and observed EIT wave behavior concerns EIT wave speed magnitudes. Magnetic field orientation constrains a fast-mode MHD wave to a velocity range  $v_A \leq v_{\text{fm}} \leq (v_A^2 + c_s^2)^{1/2}$ . Previous studies of EIT and Moreton waves have defined initial conditions such that the resultant local Alfvén or fast-mode speed is also the EIT wave speed as observed for a particular event in the data (Wang 2000; Wu et al. 2001); therefore, since EIT waves have been observed at any number of speeds (Thompson & Myers 2007), we take myriad existing work into account and determine as large a range of quiet Sun fast-mode speeds as we can from the data.

Various studies have determined plasma conditions for the base of the quiet corona. Magnetic field strengths have been measured at anywhere from 2.2 G (Fludra et al. 2002; Falconer & Davila 2001) to 10 G (Pauluhn & Solanki 2003), while multiple studies have found density measurements close to  $2 \times 10^8 \text{ cm}^{-3}$  (Aschwanden & Acton 2001; Feldman et al. 1999; Doscheck et al. 1997).

Such findings lead to a wide range of possible Alfvén speeds. Gopalswamy & Kaiser (2002) assume a magnetic field strength of 2.2 G and a density of  $5 \times 10^8 \text{ cm}^{-3}$ , resulting in  $v_A = 215 \text{ km s}^{-1}$  and  $v_{\text{fm}} = 230 \text{ km s}^{-1}$  at the base of the quiet corona, where  $v_{\text{fm}}$  is the fast-mode speed perpendicular to the magnetic field. We consider the Gopalswamy & Kaiser (2002) velocities a lower bound for fast-mode speeds. By taking the highest measured field strength (10 G) and the most predominantly measured density ( $2 \times 10^8 \text{ cm}^{-3}$ ), we find that the Alfvén speed in the quiet Sun can reasonably extend as high as  $1500 \text{ km s}^{-1}$ . These values provide us with a (rather broad) range of possible quiet Sun Alfvén speeds.

Since the minimum fast-mode speed is constrained by the Alfvén speed, any EIT wave must travel faster than  $v_A$  for a fast-mode MHD solution to be valid. Until now, most studies have considered sample sets weighted toward faster waves (e.g., Gopalswamy & Kaiser 2002; Warmuth et al. 2004a; Narukage et al. 2004) because they have focused on events correlated with shocked Moreton waves; in such samples (with mean velocities of  $\sim 200\text{--}400 \text{ km s}^{-1}$ ) problems with the fast-mode velocity are not as readily apparent.

For comparison, Figure 3 shows all the mean velocities recorded by Thompson & Myers (2007); of the 175 EIT waves occurring between 1997 March 25 and 1998 June 16, 160 were observed in multiple frames. Only a small fraction of the Thompson & Myers (2007) EIT waves have average speeds close to  $300 \text{ km s}^{-1}$ ; the large majority are noticeably slower. The velocities shown in Figure 3 are inconsistent with a minimum Alfvén speed of  $215 \text{ km s}^{-1}$ . Of the 160 observed events, 101 have average speeds below our minimum  $v_A$ . Such a large discrepancy suggests that some physical assumption is incorrect.

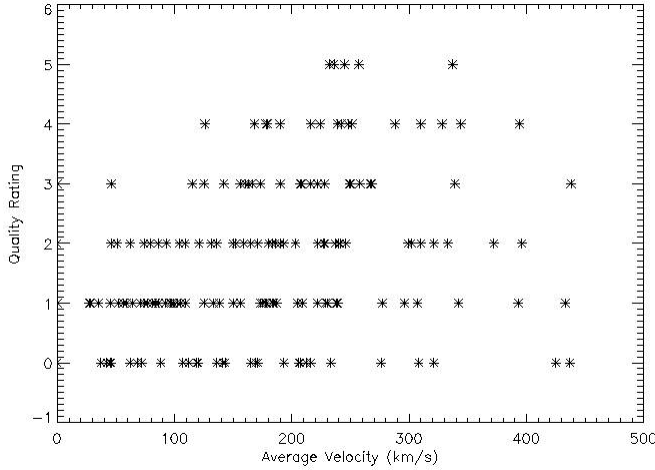


FIG. 3.—Distribution of average EIT wave speeds with respect to “quality rating,” a subjective measure corresponding to the observer’s confidence in the velocity reading, with zero being a low-confidence score (Thompson & Myers 2007). While quality ratings have no quantifiable validity, these data suggest a correlation between density enhancement and speed. Note the substantial velocity spread, with events traveling at an average speed in the range  $25 \text{ km s}^{-1} < v < 438 \text{ km s}^{-1}$ , and many traveling below the minimum calculated Alfvén speed of  $215 \text{ km s}^{-1}$ .

A lower  $v_A$  would be possible if we found that the measured values for  $B$  were too high and/or the measured densities too low. The Lin et al. (2004) direct measurements of coronal magnetic field find 4 G 75 Mm above an active region; presumably field strengths are lower in the quiet corona through which the waves propagate. However, since the density falls off as  $\sim e^{-z/\Lambda}$ , where  $\Lambda$  is the pressure scale height, we actually expect the Alfvén speed to increase with altitude. Using extrapolation methods, recent studies have also found “true” quiet Sun magnetic fields in the range of 20–40 G (Krivova & Solanki 2004; Domínguez Cerdeña et al. 2003); these values would increase calculated Alfvén speeds by as much as an order of magnitude. Alternatively, the problem could lie with the assumption of a fast-mode solution.

It may be possible that Figure 3 actually shows a superposition of two different types of wave events; there is a slight visual break at around  $\sim 260 \text{ km s}^{-1}$ , suggesting we may be observing clustering of two populations. If this is the case, it is possible that the higher speed events (26 of 160) may be consistent with fast magnetosonic wave simulations (see, for example, Wang 2000; Wu et al. 2001; Ofman & Thompson 2002; Ofman 2007). However, the slower events would still need a separate explanation.

### 2.2. Requirements of a Coronal Plasma

To further emphasize the potential problems with treating EIT waves as fast-mode waves, we consider the requirement that  $v_{\text{fm}} \geq v_A$ . By assuming that EIT waves (as fast-mode waves) travel at  $v_{\text{fm}}$ , we set an upper bound for  $v_A$ . According to Figure 3, this would give us Alfvén speeds ranging  $27 \text{ km s}^{-1} \leq v_A \leq 438 \text{ km s}^{-1}$ .

We can determine the validity of these possible Alfvén speeds by considering them in the context of plasma  $\beta$ . The  $\beta$  value describes the ratio of gas pressure to magnetic pressure, and is often written  $\beta = (8\pi p)/B^2$ . This also means that

$$\beta \sim \frac{c_s^2}{v_A^2}, \quad (2)$$

with a difference of a factor  $2/\gamma$  (where  $\gamma$  is the ratio of specific heats), which is of order unity. Most EIT waves are observed in the

195 Å passband, which is most sensitive to plasma at  $\sim 1.5 \text{ MK}$ . We take the sound speed at this temperature ( $185 \text{ km s}^{-1}$ ) as a reasonable value for  $c_s$ . Using the average velocities shown in Figure 3 to define  $v_A$ , we find that the plasma  $\beta$  associated with EIT waves can extend from  $\beta \sim 0.20$  to as much as  $\beta \sim 50$  using these values of  $c_s$  and  $v_A$ .

It has become widely accepted that coronal morphology is magnetically dominated, and is often approximated by a force-free field. By definition,  $\beta$  must be small in a magnetically dominated plasma, and only for  $\beta \ll 1$  is a force-free field model reasonable; some recent work has discussed the possibility of coronal plasma  $\beta$ s close to unity (Gary 2001; Aschwanden et al. 1999), but these measurements have typically been taken above active regions and are assumed to apply to current-filled loops. In any case, it is rare to find a theoretical  $\beta$  much larger than unity.

Some fully three-dimensional quiet Sun models (such as that of Wu et al. 2001) have implied that  $\beta$  can be as high as  $5 \leq \beta \leq 50$  in active region latitudes, over  $\pm 30^\circ$  (see Fig. 2 of Wu et al. 2001). While it is true that we have no direct measurements for values of density or magnetic field in the corona, under such conditions (and over such an extended area), the morphology of the corona in EUV images demonstrates that the  $\beta$ -parameter must be low; magnetic structures dominate everywhere.

Until observations imply that there are extensive (of order several hundred Mm) areas of the corona with such high  $\beta$ , we will instead be swayed by existing coronal limb observations. If the  $\beta$  values found using the Thompson & Myers (2007) data are valid, then large portions of the quiet Sun cannot be magnetically dominated. Such large possible  $\beta$  values either contradict the validity of the corona as a low- $\beta$  plasma, or offer additional evidence that EIT waves cannot be modeled using fast-mode waves.

### 2.3. Propagation Speed Differences

The fact that a broad range of speeds is observed at all should cause us to question the validity of fast-mode waves as an EIT wave solution. In a linear regime, the wave speed corresponds to the reaction speed of the medium; wave velocities are directly correlated to observable properties, such as density or magnetic field strength. Observations of EIT waves show that pulses maintain coherence over global distances. This lack of decoherence suggests that the plasma properties of the quiet corona are often uniform. If EIT waves were actually fast-mode MHD waves, this underlying global sameness would constrain EIT waves to a narrow range of velocities close to the expected fast-mode speed. The simulations of Wang (2000) and Wu et al. (2001), which propagate fast-mode waves through mildly structured quiet corona, produce just this type of result; Wang (2000) finds that even quiet-Sun changes over time are not large enough to substantially affect the fast-mode speed.

While EIT observations lack the temporal cadence to show whether EIT waves travel at constant speed, the range of speeds found by Thompson & Myers (2007) makes it difficult to justify the existence of a “preferred” EIT wave speed. In addition, the Thompson & Myers (2007) data show strong evidence of waves with different speeds traveling through the same region of quiet Sun in the space of a few hours. In the case of one particularly productive active region, seven waves were produced over a 36 hr period (from 1998 May 1 to 1998 May 3) with speeds of  $85\text{--}435 \text{ km s}^{-1}$ , a difference of a factor of 5. In each case, the wave traveled a distance of  $\sim 1 R_\odot$  through the same general area of quiet Sun.

Explaining each of these wave fronts as fast modes would require that the quiet Sun fast-mode speed change globally on

timescales shorter than a few hours. Since EIT waves are strongly associated with CMEs, it may be that CMEs corresponding to EIT waves produce large-scale topology changes which then affect the global fast-mode speed. However, the lack of global changes shown by difference images suggests that this is unlikely.

#### 2.4. Pulse Coherence

Morphologically, EIT waves appear as single-pulse fronts. To date, there has only been one observation of a pulse wave (in this case, a Moreton wave) that appears to include multiple fronts, related to the X10 flare of 2003 October 29 (Neidig 2004); unfortunately, no contemporaneous EUV data exist.

Numerical simulations have shown that a fast-mode MHD solution can generate a wave packet comparable to EUV observations. A wave packet of fast-mode MHD waves can produce a single-pulse front; however, the differing phase speeds within the packet would leave it highly susceptible to dispersion resulting from conditions such as density stratification and magnetic field variations. If the scale of the fluctuations is much smaller than the wavelength (as in the case of magnetic field loops), these fluctuations will not affect the coherence of the wave; however, the pulse width appears to be about a scale height (Wills-Davey 2003), allowing for significant effects due to density variations. Since the dispersing medium is ubiquitous, the packet would begin to break apart almost immediately, and would appear as periodic “ripples” on either side of the main front.

Such immediate dispersion effects appear difficult to reconcile with observations of single coherent fronts propagating over global distances. The lack of temporal resolution in the *SOHO* EIT data may account for the lack of any observed periodicity (perhaps visible as multiple fronts) as the front widens and the amplitude decreases. However, multiple *TRACE* observations, despite a much higher cadence, have also failed to reveal any obvious periodicity in a wave as it decays.

Quantitative measurements of the 1998 June 13 EIT wave (Fig. 2*b*) show that the density enhancement cross section maintains coherence for some time (of the order of tens of minutes), and will even break apart slightly and reform in a pulse shape as it encounters different coronal structures (Wills-Davey 2006). In this quantifiable case, the wave amplitude decreases over time—in a manner consistent with radial expansion—but there is no measurable increase in the pulse FWHM (Wills-Davey 2003). In addition, no ripples appear around the main pulse as this occurs. To the extent that the pulse was measurable (before it became indistinguishable from noise), the data appear to be consistent with a wave propagating dispersionlessly.

This lack of dispersion also appears consistent with the wavelet analysis performed by Ballai et al. (2005). Over the length of the entire 1998 June 13 data set, their results show a roughly constant wavelet power spectrum band ranging from 285 to 560 s. They interpret this as a strong signal with an intensity period  $\sim 400$  s that *does not degrade*. While their results do not shed light on the nature of the pulselike structure of the front, they do appear to confirm that the wave packet remains intact throughout their measurements. Given some of the interference seen in the Wills-Davey (2006) cross sections, the Ballai et al. (2005) findings would suggest that the pulse is unusually stable to perturbations, and does not suffer from the dispersion expected for a linear fast-mode wave.

### 3. RESOLVING EIT WAVE INCONSISTENCIES

EIT wave velocities have presented two key problems: the speeds are too slow for a significant number of observations to be

explained using fast-mode MHD waves, and the plasma properties of a largely uniform quiet corona should not lead to such a wide range of constant wave speeds. However, if we instead understand EIT waves as a type of coronal MHD soliton—perhaps a two-dimensional slow-mode soliton—the velocity range becomes easier to explain.

One key difference between plane wave and soliton solutions is the velocity dependence. With a linear MHD solution, wave speed is determined solely by properties of the transmission medium. Soliton speed is additionally dependent on the amplitude of the pulse. In the case of MHD solitons, speed varies as a function of density enhancement (Buti 1991; Ballai et al. 2003).

Consider the velocity dependence shown in Figure 3. Although the “quality rating” is a visually determined observer-dependent ranking system, the data from Thompson & Myers (2007) still show that well-defined (more density-enhanced) waves travel faster. Speeds only approach, but do not reach, the Alfvén speed  $v_A$ ; Narukage et al. (2004) show that large-scale pulse waves traveling at or above  $v_A$  shock and appear as Moreton waves. The velocity-density enhancement dependence also allows for events of different speeds to pass through the same region of quiet Sun without requiring global restructuring.

In addition to solving the velocity discrepancies, a soliton explanation also provides some of the pulse stability and coherence needed to explain the properties of EIT waves. Because the stability of a soliton is dependent on both nonlinearity in the pulse and dispersion in the local medium, solitons are stable to small perturbations, allowing them to travel through thin cross-wise loop structures and over large distances of quiet Sun. As solitons are nondispersive, this explanation would also consider the lack of dispersion observed in strong events, such as the 1998 June 13 event (Fig. 2*b*).

While it is true that the slow mode experiences greater dissipation than other modes, because of their large width, EIT waves only need to remain coherent over  $\sim 10$  wavelengths to display typical behavior. If we consider the work of Ofman et al. (1999), who looked at slow MHD waves in polar plumes, they found that pulses maintained coherence for a minimum of three wavelengths and showed the sort of nonlinear steepening that would be counteracted by dispersion in a soliton-like system. This suggests that coherence over 10 wavelengths is not unreasonable.

Of course, the dynamics observed in EIT waves could not be the same as those seen by Ofman et al. (1999). Rather, since these wave fronts propagate laterally through the corona and are at least a scale height tall, they will rely on a different steepening/dispersion mechanism to create soliton-like behavior. The steepening could come from the fact that Alfvén speed increases with altitude in the corona. The dispersion mechanism could be lateral density stratification across the pulse itself. The fact that the medium is itself MHD also means that the wave must have a magnetic component. However, since such a large pulse must remain coherent to small perturbations (such as magnetic loops), it may imply that only very strong (i.e., active regions) or very defined (i.e., coronal holes) magnetic structures have any noticeable effect on the wave.

The effect of a soliton on the local medium can also account for loop oscillations. As a compressive wave packet with no related rarefaction, it must displace the medium in the direction of propagation, where the displacement will remain unless restored by some other force. While this argument can account for any linear compressive wave packet, it is still consistent with the effects of a soliton. In the case of an EIT wave, coronal material will be carried with the front. Wills-Davey & Thompson (1999) demonstrated this for the 1998 June 13 event, as they tracked

individual loops along with the wave. However, since the magnetic fields of the corona are anchored in the photosphere, after the wave has moved on, the individual loops will “snap” back. Wills-Davey (2003) found that most structures behaved in an overdamped manner when returning to their original positions, but some loops—often aligned perpendicular to the direction of propagation—showed oscillatory behavior.

Lastly, the production of a soliton does not require the presence of a shock, allowing for the existence of EIT waves in the absence of Moreton waves. While this still does not explain the relationship between Moreton and EIT waves, a soliton-like EIT wave can account for the vast majority of observations.

#### 4. DISCUSSION

The consistency of the properties of EIT waves has long motivated solar physicists to develop a physical understanding as to their nature. Developing this understanding has proved elusive in previous work. Unfortunately, fast MHD compressional waves do not properly describe dynamics of many EIT wave events. The physical properties of EIT waves—their single-pulse, stable morphology; the non-linearity of their density perturbations; the lack of a single representative velocity—instead suggest that they may be best explained as soliton-like phenomena.

While most fronts travel below the expected coronal Alfvén speed, as a general trend, larger density perturbations tend to move at faster velocities. There is also the observational evidence that many EIT wave pulse widths are close to one to two scale heights; this may be a visual effect, but it is possible that pressure and magnetic forces convolve to act as a wave guide, as predicted by Nye & Thomas (1976). It would be consistent with initial findings that flux is conserved as EIT waves propagate radially along the solar surface rather than spherically (Wills-Davey 2003). It might also account, at least in part, for the strong discrepancy between the number of EIT and SXT pulse wave observations (Sterling & Hudson 1997; Biesecker et al. 2002; Warmuth et al. 2005); SXT preferentially observes hotter structures with larger scale heights, and the maximum pulse height of EIT waves might be constrained by smaller, cooler loops.

The flux conservation found by Wills-Davey (2003) does demonstrate one surprising, unsoliton-like behavior: after a pulse stops forming, its amplitude appears to drop off as  $r^{-1}$ . This occurs in spite of the other, soliton-like properties observed in EIT waves. It is likely that flux conservation is a necessary aspect of radially propagating trapped MHD solitons, and that a decrease in amplitude is necessary to a conservative solution.

We feel the solitary wave hypothesis offers the most compelling explanation to date for the properties of EIT waves. While the derivation of a two-dimensional MHD soliton solution is perhaps beyond analytical scope, and therefore must be demonstrated numerically, the properties inherent in a soliton-like explanation should fit the data much better than the oft-used fast-mode solutions. It becomes possible to explain the lack of a “typical” EIT wave velocity; the amplitude-velocity relationship seen by Thompson & Myers (2007); and the consistent observations of single, coherent, nonlinear coronal pulses. While we do not pretend to offer a comprehensive explanation on the nature of EIT waves, by offering this interpretation, we hope to assist theorists and modelers by providing a new direction for study.

Developing a consistent theoretical understanding of EIT waves is particularly important in the context of new EUV missions. *TRACE* observations have already shown that wave parameters are easily quantitatively measured with sufficient spatiotemporal resolution (Wills-Davey 2006). If we can correctly model and reproduce EIT waves, we can use wave properties extracted from observations to inverse model the plasma parameters of the affected quiet corona. Missions like *STEREO* (Kaiser 2005) and *GOES-N* (Wilkinson 2005) will give us the opportunity to develop and test these observational modeling tools.

Using large-scale propagating waves for *global coronal seismology* has been postulated since Meyer (1968). However, its successful implementation requires a well-understood theoretical model. Previous studies (Meyer 1968; Ballai et al. 2003) have attempted to calculate quiet Sun magnetic field strengths with global coronal seismology using the assumption that Moreton waves and EIT waves can be modeled as MHD fast-mode waves. Meyer (1968) finds a field strength that appears high; Ballai et al. (2003) finds one that appears low. An accurate wave model may result in a more reasonable field strength calculation, allowing EIT waves to make the transition from coronal phenomenon to observational tool.

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