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CORONAL LOOP OSCILLATIONS AND FLARE SHOCK WAVES

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ABSTRACT

A statistical analysis of coronal loop oscillations observed by the *Transition Region and Coronal Explorer* (*TRACE*) shows that 12 of 28 cases were associated with metric type II bursts. The timing is consistent with the idea that in many cases the loop oscillations result from the passage of a large-scale wave disturbance originating in a flare in the nearby active region. The *GOES* classifications for these flares range from C4.2 to X20. Typically, the oscillating structures are not disrupted, implying that the disturbance has passed through the medium, which has returned to an equilibrium near that seen prior to the event. This is consistent with the Uchida interpretation of the disturbance as a weak fast-mode blast wave (i.e., a simple wave at a low Alfvénic Mach number) propagating in the ambient corona. We note that all 12 of the associated events were also associated with coronal mass ejections (CMEs) and conclude that the CME eruptions in these cases corresponded to only partial openings of the active-region magnetic fields.

Subject headings: shock waves — Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: flares

1. INTRODUCTION

The existence of large-scale coronal waves associated with solar flares was first established via interpretation of the meter-wave type II radio bursts (e.g., Wild et al. 1963). The emission frequencies for these bursts drifted monotonically downward. This suggests outward motion in a gravitationally stratified corona, on the hypothesis of radiation at the plasma frequency and its harmonic. The observing frequencies (typically below 100 MHz) establish that the emission "ignites" at densities below about 10^8 cm^{-3}. With models of density versus height inferred from coronagraphic observations, the speeds of these "slow drift" bursts typically imply exciter speeds of about 10^3 km s^{-1}. The "fast drift" bursts, now called type III bursts, often precede the type II ignition and frequently correspond to what we now term the "impulsive phase" of a flare. For these flare-associated type III bursts, the inferred densities can be as high as 10^{10} cm^{-3}.

Following these radio observations, Hα observations revealed the existence of chromospheric waves of comparable speeds (Moreton & Ramsey 1960); we now call these "Moreton waves" (see Warmuth et al. 2004a, 2004b for a recent study). This presented a puzzle, because the density and temperature of the chromosphere do not correspond to wave speeds as high (up to ~2000 km s^{-1}) as those observed. The theory of Uchida (1968) resolved this issue by interpreting the Moreton waves as the chromospheric skirts of globally expanding weak, fast-mode magnetohydrodynamic shock waves. The shocked nature of the waves had already been inferred from the need for particle acceleration in the preferred type II emission sequence: shock wave → charge separation → Langmuir waves → electromagnetic waves. The Uchida theory noted the likelihood of refraction of the fast-mode waves in the corona, which should have an Alfvén speed increasing with height as a result mainly of the exponential decrease of density. This refraction would concentrate energy into the chromosphere, and the wave motion there (first down, then up) would correspond to the "winking filament" phenomenon observed in narrowband Hα observations (Dodson & Hedeman 1964).

Further observational development came with the discovery of the "EIT[3] waves" (Moses et al. 1997; Thompson et al. 1998). The original thought was to identify these with the type II bursts and Moreton waves, but it now appears that this is only rarely possible (Biesecker et al. 2002). The majority of EIT waves now appear to be the result of coronal mass ejection (CME) evacuation of the lower corona and can be identified with soft X-ray dimmings (Hudson & Webb 1997). The fastest of the EIT waves are consistent with Uchida's weak fast-mode shocks, describable as blast waves caused by flares (Warmuth et al. 2004a, 2004b); the slower ones probably correspond to motions of the medium itself during the CME evolution (perpendicular flows), rather than to simple waves propagating in a fixed corona.

Recently, EUV observations of the corona by *TRACE* (Handy et al. 1999) and SUMER (Wilhelm et al. 1995) have introduced a new factor—the systematic observation of oscillations in loops. Theoretical work underpinning this "coronal seismology" (e.g., Roberts 2000) has anticipated the observations. The *TRACE* loops (Aschwanden et al. 1999) typically vibrate at periods of tens to hundreds of seconds and damp after a few cycles; they appear to be "kink mode" oscillations in which the loop is bodily displaced while the footpoints remain fixed. The *TRACE* oscillation events result from nearby flares and filament eruptions (Wills-Davey & Thompson 1999; Schrijver et al. 2002). This Letter points out the striking affinity of flare blast waves for such oscillations, as evidenced by meter-wave type II bursts. The significance of this identification is that it enables us to use the EUV observations to learn about the origin of these blast waves. The plasma motions that produce them occur at the beginning of the impulsive phase, based on timing (Švestka & Fritzová-Švestková 1974; Vršnak et al. 1995) and direct X-ray observations (Hudson et al. 2003). Thus, by presumption they originate at the actual site of the "trigger" that releases flare energy, a process that is not understood but has the greatest importance in flare and CME physics.

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[3] The Extreme Ultraviolet Imaging Telescope; see Delaboudinière et al. (1995) for details.

TABLE 1
Oscillation Events with Metric Type II Bursts

Date	Oscillation Start	Type II Start	*GOES* Start	*GOES* Max	*GOES* Class
1998 Aug 30 ……	18:04:44	18:10:00	18:00	18:05	M1.3
1999 Jul 19 ……..	~02:19:00	02:16:00	01:49	02:15	C4.2
1999 Oct 20 …….	06:04:00	06:10:00	05:53	06:22	M1.7
2000 Feb 10 …….	01:56:21	01:47:00	01:40	02:08	C7.3
2000 Aug 25 ……	14:46:28	14:35:00	14:21	14:35	M1.4
2001 Apr 02 …….	21:46:45	21:48:30	21:32	21:51	X20
2001 Apr 12 …….	10:16:23	10:16:30	09:39	10:28	X2.0
2001 May 13 ……	03:03:07	03:01:50	02:58	03:04	M3.6
2001 May 15 ……	02:57:41	03:00:20	02:53	03:00	M1.0
2001 Sep 07 …….	~15:35:00	15:30:40	15:26	15:38	M1.2
2001 Sep 15 …….	11:23:59	11:22:15	11:04	11:28	M1.5
2001 Nov 04 ……	<16:14:00	16:10:00	16:03	16:20	X1.0

2. DATA

The *TRACE* observations showed a variety of phenomena, typically in the motions of thin coronal loops observed in the 171 Å passband corresponding mainly to temperatures of about 1 MK. The loops executed several oscillations, with the appearance of a standing wave having nodes at the footpoints. The first observation (Aschwanden et al. 1999) showed loops oscillating at a period of 280 ± 30 s, associated with an M4.6 flare. A subsequent report (Schrijver et al. 2002) listed 17 events triggered by flares or filament eruptions, with most of the oscillation periods between 2 and 7 minutes. This paper and an accompanying paper on interpretations (Aschwanden et al. 2002) provided abundant information on this sample of events, which has now been extended by entries on the *TRACE* group's Web page[4] to a total of 28. Schrijver et al. (2002) note that the original list of 17 events was compiled by visual inspection of *TRACE* movies by the observers, with further checks of movies of X-class flare observations. The full list of 28 studied here includes notable events found later and should not be construed as a complete sample.

We have surveyed the tabulated reports at the times of the 28 loop oscillation events reported by the *TRACE* group. Of these, 12 have reported type II bursts. This high rate of coincidence is consistent with the remarks made by Schrijver et al. (2002) identifying the source of the oscillations with an "outward-moving exciting wave" related to the flare (or mass ejection). Metric type II bursts are not so common (e.g., Wild et al. 1963). Thus, the association of loop oscillations and type II burst occurrence is highly significant. Our primary survey was based on the tabulated entries for type II bursts, but we have also studied direct records for 14 of the 16 nonassociated events. This deeper look did not lead to any further type II signatures. The data thus indicate that a large fraction of the oscillation events do have the type II association, but also that a substantial fraction does not.

[4] Also see http://canopy.lmsal.com/schryver/Public/TRACE/looposcillations/paperI/SchrijverAschwandenTitle.html for movies and other material.

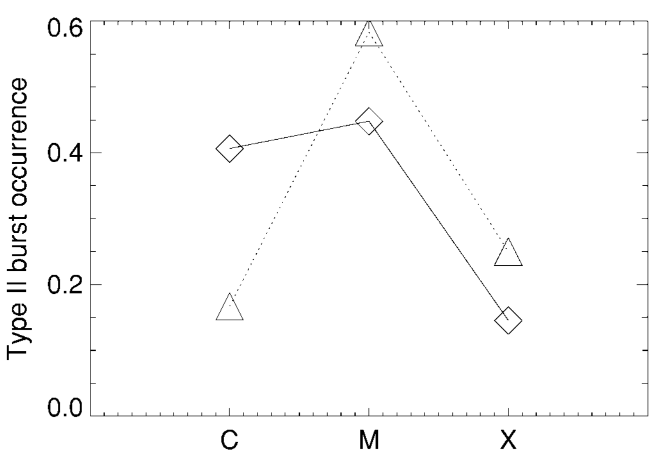

Fig. 1.—Distribution of flare *GOES* classes for the oscillation events (*triangles*) with type II bursts, compared with the type II burst occurrence pattern (*diamonds*; data for 2000–2004 taken from the online NOAA events listings). The statistics for the oscillation events are poor, corresponding to a total of only 12 cases.

Table 1 shows the list of associated events, including CME occurrence. Most of the flares are of *GOES* M class, with two C-class and three X-class events, and this distribution (with poor statistics) is consistent with the observed distribution of flares with metric type II bursts, as shown in Figure 1. We obtained the statistics of type II burst occurrence from the online "events" resource at NOAA. These pages are preliminary summaries, so these results are not definitive. They show (for the years 2000–2003) a total of 70 X-class flares, of which 49 had type II bursts listed (70% ± 10%).

The relative timing of the beginning of the oscillations and the type II bursts is another strong argument for the notion that flare blast waves are the exciting agent. The mean time difference between oscillation and burst onset is 1.6 ± 5.3 minutes. The oscillations can apparently precede the onset, or vice versa, but the time difference is never higher than 12 minutes. This temporal association is much better than with, say, flare onset or CME launch times (note, however, that CME launch times are only extrapolated and are therefore notoriously inaccurate). The fact that the bursts can appear before *or* after the oscillation begins can be explained by the different distances of the oscillating loops from the blast wave source and by the time it takes for the disturbance to steepen into a shock (i.e., a higher ambient Alfvén speed leads to later shock formation, and hence to later radio emission). Of the 12 events associated with type II bursts, all but two oscillation onsets occurred during the *GOES* soft X-ray rise phase, as expected from this association.

3. CMEs VERSUS BLAST WAVES

The suggestion of this Letter is that the strong association of *TRACE* oscillation events with type II bursts indicates that some of them are directly caused by flare blast waves. We interpret this wave as a fast-mode disturbance that is either a shock wave with low Alfvénic Mach number or else the related disturbance that has not met the shock condition. The "outward-moving exciting wave" of Schrijver et al. (2002) would therefore be the same kind of disturbance that produces the Moreton wave in Uchida's theory. Alternatively, however, since the CME association of the *TRACE* loop oscillations is even stronger (at least 24/28), one might consider the CME flow field itself to be the exciter. We believe this to be physically less likely, although the *TRACE* movies show apparent examples of excitation by filament eruption, as noted by Schrijver et al. (2002). We present the following arguments to establish consistency with the blast-wave hypothesis:

1. The timing is consistent with the blast-wave explanation, although one cannot compare directly to the CME observations.
2. The transfer of energy between a blast wave and remote coronal structures is known to be possible, both from the Hα (hydrodynamic) observations of phenomena such as winking filaments (e.g., Athay & Moreton 1961) and also from remote decimetric brightenings (Pohjolainen et al. 2001) that are nonthermal in nature.
3. The locations of the oscillating loops are generally consistent with the nonradial motion expected for the blast wave.
4. The observation that only certain loops oscillate, whereas other nearby loops remain stationary, is consistent with the highly directional nature of flare blast waves (Smith & Harvey 1971; Warmuth et al. 2004a).
5. In some cases, the *TRACE* movies show little evidence for dimming, which is a guide to the CME flow field (Hudson & Webb 1997).
6. The oscillating loops are not seen to erupt (of course). They are thus adjacent to the CME, rather than in its direct flow field.
7. The *GOES* event distribution of oscillation-related events is weighted toward the more energetic flares, as is that for type II bursts.
8. A fast disturbance, at the Alfvén speed or higher, may be able to couple energy more directly into loop motions.

We propose item 8 only as a suggestion, but Steinolfson (1985) and others have shown that the Alfvén crossing time for a moving structure determines how strong the wave itself will be. Most of the arguments cited above are consistency checks that are necessary but not sufficient to prove the point; any direct comparison with CME observations is unfortunately impossible, because of the low altitudes of the oscillating loops.

In a particular event analyzed by Wills-Davey & Thompson (1999), the *TRACE* field of view missed the flare itself, but it did get an excellent view of the flare wave as it impinged on the loops of a neighboring active region. These then displayed oscillatory motions. The analysis included ray tracing, revealing motions that were consistent with the wave-front refraction expected in Uchida's theory. The flare in this case was a C2.9 event at a distance on the order of 0.5 $R_\odot$ from the oscillating loops. The relatively low exciter speed (400–800 km s^{-1}) inferred by Wills-Davey & Thompson (1999) would be consistent with a fast-mode disturbance. No type II burst was reported for this event, which is consistent with the inference of a low Alfvénic Mach number.

The following picture emerges. An eruptive flare involves the outward expansion of some portion of the magnetic field of the active region, plus some of the corona above it, in the form of a CME. An energetic enough event will also frequently create a blast wave that propagates through the undisturbed part of the corona. Note that the blast wave need not necessarily reach the shock condition, which could help explain some oscillation events without associated type II bursts. Under suitable geometric and magnetic conditions, this blast wave can transfer some energy into the loop oscillations that are observed. The loops may settle into a somewhat displaced equilibrium if the restructuring associated with the CME requires it. Some of the loop oscillation events, even those associated with type II bursts (specifically, the 1999 July 19 and 2000 August 25 events) do not appear to have the proper timing for the blast-wave association. We note this and the suggestion by Schrijver et al. (2002) of the possibility of oscillation enhancements on magnetic separatrix surfaces in the corona as evidence that the blast-wave hypothesis cannot explain all events.

4. CONCLUSIONS

We suggest the identification of the source of some of the *TRACE* kink-mode oscillations with the weak fast-mode shock wave envisioned by Uchida (1968) to explain the meter-wave type II radio burst and the Moreton wave. These global waves have several other manifestations. The waves originate in compact structures near solar flares (Hudson et al. 2003; Klassen et al. 2003). The physics of wave excitation remains unclear at present, but it may be closely coupled to the basic mechanisms of flare evolution. It seems clear that we should see these oscillations not as the motions of individual magnetic flux tubes, but of the entire magnetic field (e.g., Uralov 2003) of the active region, which may erupt in part (the CME) or may remain essentially unchanged after the propagation of the blast wave through nonerupting regions. The EUV loops observed by *TRACE* provide further detailed information about the propagation of these waves. The loop oscillations themselves must be understood in the context of a global process. In the best cases, it may be possible to model the wave propagation in a realistic model of the active-region magnetic field.

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