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THE RELATION BETWEEN EIT WAVES AND SOLAR FLARES

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ABSTRACT

In order to determine whether EIT waves are generated by coronal mass ejections (CMEs) or pressure pulses in solar flares, 14 non-CME–associated energetic flares, which should possess strong pressure pulses in their loops, are studied. They are selected near solar minimum, as this favors the detection of EIT waves. It is found that none of these flares are associated with EIT waves. Particular attention is paid to AR 0720, which hosted both CME-associated and non-CME types of flares. The *SOHO*/EIT images convincingly indicate that EIT waves and expanding dimmings appear only when CMEs are present. Therefore, it is unlikely that pressure pulses from flares generate EIT waves.

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

Online material: color figures

1. INTRODUCTION

Large eruptions, such as solar flares or coronal mass ejections (CMEs), generate strong perturbations in the magnetized solar atmosphere, which propagate out as various types of waves. These waves can be observed at different wavelengths depending on the temperature of the media. For example, more than 40 years ago, arclike Hα disturbances were found in some flare events to propagate through the chromosphere over distances on the order of 5×10^5 km with velocities ranging from 500 to 2000 km s^{-1} (Moreton & Ramsey 1960). They came to be called Moreton waves, and it was suggested that the footprints of a fast-mode wave or shock wave sweeping through the chromosphere, as the wave moves through the tenuous corona, would produce the apparent propagation of Hα disturbances (Uchida 1968). Without the knowledge of CMEs at that time, the driving source was naturally considered to be the pressure enhancement of the flares in Uchida's model. Since then, it has been believed that there is a blast wave emanating from the flaring site, which is responsible for the Moreton wave, as well as type II radio bursts (see, however, Cliver et al. 1999 for an alternate view).

With the observations of the EUV Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*) spacecraft, an almost isotropic diffuse wave front in the low corona was found to propagate outward from the flaring active region with a velocity of ∼250 km s^{-1}, concurrent with the eruption of a CME (Thompson et al. 1998). The phenomena were labeled "EIT waves." They are anisotropic when the magnetic field on the Sun becomes complicated, and they tend to not pass strong magnetic features or neutral lines (Thompson et al. 1999). The wavelike features are reminiscent of the expected coronal counterparts of Hα Moreton waves, which were possibly observed by Neupert (1989). Therefore, they were thought to be the coronal counterparts of Moreton waves (or coronal Moreton waves for short) and were explained as flare-ignited blast waves (e.g., Warmuth et al. 2004; see Cliver et al. 2005 for more references). However, there are several problems concerning the blast wave model (see Chen & Fang 2005 for a review). The first is the velocity discrepancy between EIT and Moreton waves, since the velocities of the former, 170–350 km s^{-1} (Klassen et al. 2000), are about a third or less of those of the latter, which are of the order of 1000 km s^{-1} (Smith & Harvey 1971). Moreover, the existence of a stationary EUV wave front near the footpoints of the magnetic separatrix provoked Delannée & Aulanier (1999) to suggest that EIT waves should not be fast-mode waves. Therefore, Chen et al. (2002, 2005) proposed a model to reconcile the velocity discrepancy between EIT waves and Moreton waves and to explain the existence of a stationary EUV wave front, as well as the lack of correlation between EIT wave speeds and type II burst speeds found by Klassen et al. (2000). In this model, the coronal Moreton wave corresponds to the piston-driven shock wave straddling over the CME, whereas the EIT wave is generated by the successive opening of coronal field lines during the eruption of CMEs and propagates several times slower than the Moreton wave. Both waves were thought to be linked to CMEs.

To properly address this debate, at least two questions need to be answered: (1) Are there two types of EUV waves associated with CMEs as suggested by Chen et al. (2002)? (2) Are EIT waves driven by flares or CMEs? As for the first question, with a combination of full-disk *SOHO*/EIT data and high-cadence *TRACE* data, Harra & Sterling (2003) found some evidence for two types of EUV waves. Future EUV missions with a high cadence and a large field of view are expected to test their conclusion. Regarding the second question, Biesecker et al. (2002) found an unambiguous correlation between EIT waves and CMEs, and a significantly weaker correlation of EIT waves with flares. Kay et al. (2003) also found that all "EIT wave"–associated flares are accompanied by CMEs. Recently, Cliver et al. (2005) pointed out that about half of the EIT waves observed from 1997 March to 1998 June were associated with small solar flares below the C class, which implies that it is unlikely that it is the pressure pulse in the flare that causes a fast-mode wave to be observed as EIT waves. Along the same line of thought, but with an opposite approach, we select energetic solar flares without associated CMEs near solar minimum in order to check whether the pressure pulse in the flaring loops can ignite an EIT wave. The intense flares are selected since they are more apt to generate strong perturbations, while the solar minimum favors the detection of EIT waves. Particular attention is paid to NOAA AR 0720, where five major flare events occurred within a day. Since some of the flares are CME-

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TABLE 1
BASIC PROPERTIES OF THE 14 NON-CME FLARE EVENTS

No.	Date	Time	*GOES* Class	Optical Class	Radio Bursts
1	1997 Sep 02	12:28–12:45	M1.0	1N	DCIM
2	1997 Nov 24	19:30–21:00	M1.6	...	...
3	1997 Nov 26	18:35–19:35	M2.1	SF	...
4	2005 Jan 14	21:08–21:39	M1.9	2N	...
5	2005 Jan 15	00:30–02:30	X1.2	1B	No
6	2005 Jan 15	04:10–04:25	M1.3	2N	III
7	2005 Jan 15	04:25–05:30	M9.0	2N	No
8	2005 Jan 15	11:40–12:15	M1.2	SF	...
9	2005 Jan 16	21:55–23:20	M2.4	1N	III
10	2005 Jan 17	03:00–5:00	M2.7	...	No
11	2005 Jan 18	11:30–12:40	M1.7	...	No
12	2005 Jan 19	06:58–07:55	M6.7	2N	III
13	2005 Jan 19	15:35–16:10	M1.6	2F	III
14	2005 Jan 23	01:30–02:40	M1.0	...	No

associated and others are not, these events are specially useful for investigating the relation between EIT waves and solar flares. Data analysis and the results are presented in § 2, which are followed by discussions in § 3.

2. DATA ANALYSIS AND RESULTS

For this research, *GOES* data are used to choose solar flares; EIT data are used to identify EIT waves; and the CME catalog[3] (Yashiro et al. 2004) of LASCO is applied to check whether there is a CME associated with the flare. Since the occurrence of EIT waves favors a simple magnetic background, we select events occurring only in the years of 1997 and 2005, which are close to solar minimum. Since the CME Catalog is updated only to 2005 July, our sample does not contain data for later eruptions.

First, flares with a *GOES* class above M1 are targeted. In order to get a sample of flares without associated CMEs, only the flares with durations less than 2 hr are considered, since these flares tend to be less associated with CMEs (Sheeley et al. 1983). In this Letter, the duration is measured from the beginning of the impulsive phase to the late decay phase when the X-ray intensity goes back to the level before the event. By these criteria, 46 flares, which have corresponding EIT data, are selected. The CME catalog is then used to screen out the flare events that are related to CMEs. We also examined the preliminary CME list[4] for some faint CMEs that are not included in the CME catalog. Finally, we identified 14 non-CME flare events, and the remaining 32 flare events are called the reference group hereafter for comparison with the non-CME flare group. To ensure that the events are not associated with any CME, only the flares without a CME spanning over the flare site and appearing at 2 $R_\odot$ within 3 hr relative to the start time of the flare are included into the non-CME group (the 2005 July 16 flare event at ∼04:00 UT is special; the associated CME appeared at 2 $R_\odot$ about ∼3.5 hr before the flare, while the CME showed a significant acceleration exactly in the impulsive phase of the flare). Therefore, several flare events with physically unassociated CMEs occurring concurrently by chance are included in the reference group. Note that the time for CMEs to appear at 2 $R_\odot$ is backward-extrapolated according to the records in the CME catalog. Some of the properties of these 14 non-CME flare events are listed in Table 1, where the occurrence of any radio burst near the impulsive phase reported by Solar-Geophysical Data is also indicated (ellipsis points are used where data are not available). Note that the optical importance is shown for comparison since many EIT wave events are associated with SF-class flares (Klassen et al. 2000). The EIT data corresponding to these flares are then examined, and the results are presented in § 2.1. During the survey, it was found that NOAA AR 0720 is very unique. It hosted 22 intense flares with a *GOES* class above M1 during its passage across the solar disk in 2005 January, where three M-class and two X-class flare events occurred on January 15. Some of them are associated with CMEs, and others are not. The corresponding results from EIT observations are described in § 2.2.

[3] See http://cdaw.gsfc.nasa.gov/CME_list.

[4] See http://lasco-www.nrl.navy.mil/cmelist.html.

2.1. *General Properties*

It is found that none of the 14 non-CME flare are associated with EIT waves. As a typical example, Figure 1 shows the pre-event EIT image (*left panel*), the base difference images near the peak (*middle panel*), and the decay phase (*right panel*) for the flare event occurring at ∼18:00 UT on 2005 January 14. Note that the solar rotation is corrected while subtracting the pre-event intensity to get the difference images. It can be seen that there is no signature of a wave or of expanding dimmings on the solar disk. The evident response of the ambient corona to this M1-class flare is that the coronal loops overlying the flare, as indicated by the arrow in the left panel, are displaced and that the brightness is changed as well. This is manifested by a slim arc-shaped dimming area appearing in the base difference images as indicated by the arrows in the middle and right panels. Similar results are also found for the other non-CME flare events. In comparison, for the reference group, 13 out of the 32 events are associated with EIT waves and/or large-scale expanding dimmings.

From Table 1, it can also be seen that type III or decimetric

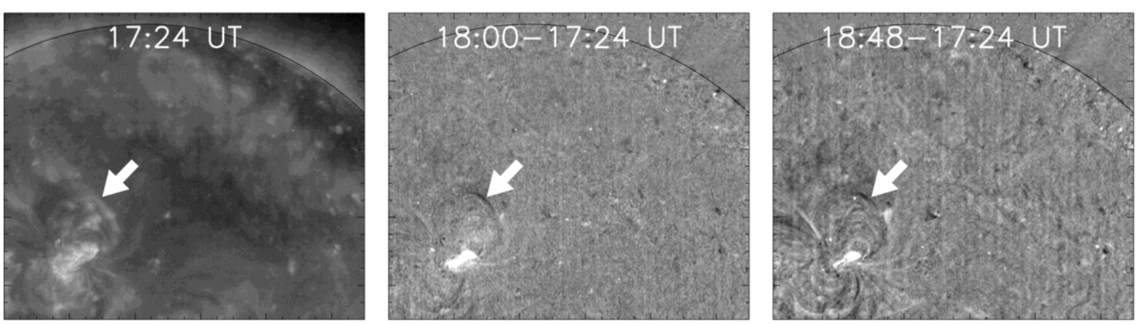

FIG. 1.—EIT 195 Å images showing the evolution of the non-CME flare on 2005 January 14. *Left*: Pre-event image. *Middle*: Difference image near the X-ray peak. *Right*: Difference image in the decay phase. [*See the electronic edition of the Journal for a color version of this figure.*]

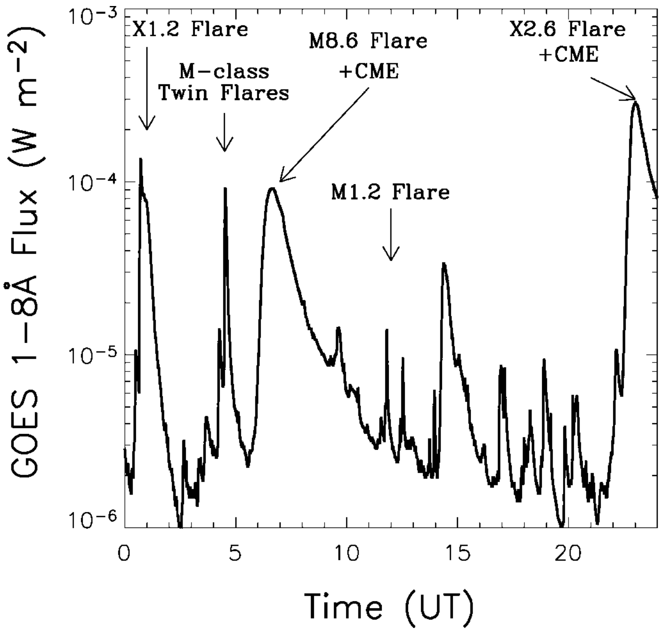

FIG. 2.—*GOES* 1–8 Å plot for 2005 January 15, where five major flare events from AR 0720 are indicated.

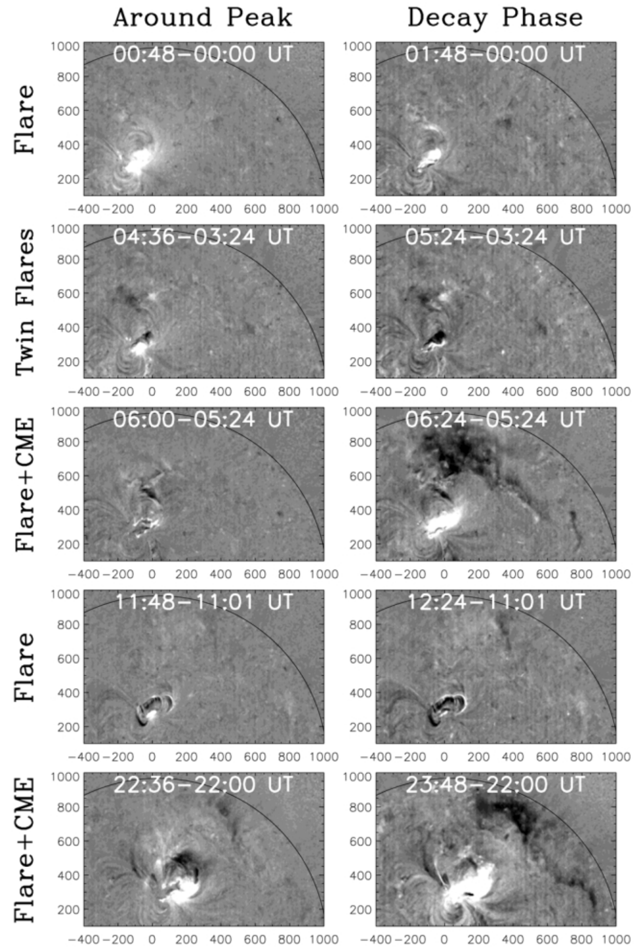

FIG. 3.—EIT 195 Å base difference images showing the evolution of the five flare events on 2005 January 15, where the third and fifth events (i.e., the third and fifth rows, starting from the top) are associated with CMEs. The heliocentric coordinates are in units of arcseconds. [*See the electronic edition of the Journal for a color version of this figure.*]

(DCIM) pulsation bursts may be associated with the non-CME flares, while no type II radio burst was observed. Contrary to this, about half the events in the reference group are accompanied by type II and/or type IV bursts.

2.2. *Eruptions from AR 0720*

Figure 2 shows the *GOES* 1–8 Å soft X-ray flux curve during 2005 January 15. Five solar flares above the M class occurred on this date in AR 0720, where two events are accompanied by CMEs, as indicated in the figure, and where the twin flares at ~04:30 UT are treated as one event. The evolutions of the base difference EIT images for these five events are depicted in Figure 3, with one row for each event. For each flare, the individual pre-event image is subtracted. It is seen that when there is an associated CME (the third and fifth events, i.e., the third and fifth rows starting from the top), EIT waves and expanding dimmings also appear, but they are otherwise absent. The EIT waves in the two CME-associated flare events propagate toward the northwest from the active region to the quiet region, avoiding other active regions to the south. This is a typical feature of EIT waves. For the flare events without EIT waves, a local dimming can be seen near the flare site.

3. DISCUSSIONS

As an important phenomenon, EIT waves and/or large-scale expanding dimmings represent the disk manifestation of CMEs. However, our understanding of EIT waves still remains controversial. With respect to their origin, some authors favor a flare-initiated blast wave (e.g., Warmuth et al. 2004; see Cliver et al. 2005 for more references), while Biesecker et al. (2002) and Cliver et al. (2005) concluded that EIT waves are related to CMEs from an observational point of view. Chen et al. (2002, 2005) proposed that EIT waves and expanding dimmings are generated by the successive opening of all closed field lines covering the erupting flux rope, which is intrinsic to CMEs. This model supports the proposal by Delannée & Aulanier (1999) that EIT waves are related to the magnetic restructuring in CMEs. The results of Kay et al. (2003) also favor the idea that a CME is a necessary condition for the appearance of EIT waves during flares, although most of the non-CME flares in their sample have peak intensities below the M class.

In this Letter, we selected 46 flares in 1997 and 2005 with a *GOES* class higher than M1. The energetic flares possess strong pressure pulses in the loops and hence are more apt to generate strong perturbations. It is found that for the 14 non-CME flares, none are accompanied by an EIT wave, nor are any events accompanied by a type II radio burst. In contrast, for the reference group events, where a CME that may or may not be related to a flare appears in the selected time window, ~41% (13/32) of the events are associated with EIT waves and/or expanding dimmings. It is noted that generally there is a local dimming (and/or brightening) area around non-CME flares in the base difference EIT images, which can be inside the source active region (Fig. 1), or even a place outside the active region that is probably magnetically connected with the flare site (e.g., the second row of Fig. 3).

The absence of EIT waves in the non-CME energetic flare events, with a significant contrast to the CME-associated flares, strongly suggests that EIT waves are not initiated by solar flares as blast waves. It may be argued that the environments around the source active regions may greatly decrease the detectability

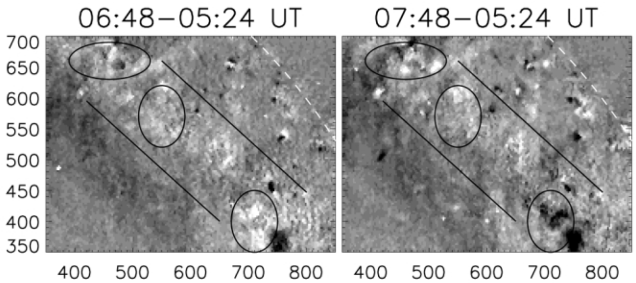

FIG. 4.—EIT 195 Å intensity evolution at the stationary "EIT wave" front, which is outlined by the parallel black lines. The intensity varies significantly with time in the patches outlined by the ellipses. The dashed white lines indicate the solar limb. The heliocentric coordinates are in units of arcseconds. [*See the electronic edition of the Journal for a color version of this figure.*]

of EIT waves for all the 14 non-CME flares, since the EIT waves are less observed when the magnetic configuration on the Sun is complex. With this and other factors, only one-fifth of front-side CMEs are associated with EIT waves in the data sample of Cliver et al. (2005). In this sense, the successive flare eruptions in AR 0720, with the same environments, provided us with an unprecedented opportunity to discriminate the favorable conditions for the EIT waves to appear. The EIT observations of the five flare events happening on 2005 January 15 in this active region, as shown in Figure 3, indicate that EIT waves and large-scale expanding dimmings appear only when the flare is associated with a CME, irrespective of the strength of the flare.

Traditionally, flares were divided into two-ribbon and compact flares. For the CME-associated flares, which are often two-ribbon flares, they can be well explained by the classical CSHKP model, in which a flux rope erupts and pulls up all the overlying field lines. The simulation of such a process by Chen et al. (2002) does indicate the existence of a propagating EIT wave that is immediately followed by expanding dimmings well behind the coronal Moreton waves. Non-CME flares, which are often compact flares, can be explained by the reconnection between the emerging flux and preexisting coronal loops (Heyvaerts et al. 1977), or they can be due to the loop-loop interaction in the corona (see Priest 1992 for a review). Note that the reconnection between the emerging flux and preexisting coronal loops is, in principle, also a kind of loop-loop interaction. After the loop-loop interaction, new loops are formed, and the magnetic connectivity is rearranged. Therefore, it is natural to see the local dimming and/or brightening in some areas, which are magnetically connected to the flare site.

It should be pointed out that the enhanced pressure in flare loops, which drives the chromospheric evaporation, can no doubt generate perturbations propagating outward, as discussed by Vršnak & Lulić (2000). And the pressure enhancements are generated continuously at the apparently moving footpoints of newly reconnected field lines and persist during the flare process, rather than being a pulse in each event. Therefore, perturbations emanate continuously from the flare site and could be observed in the corona if they are strong enough. In the 2005 January 15 06:00 UT event (the third row of Fig. 3), the EIT wave stops at 06:12 UT to form a stationary front, which is between the two parallel black lines in Figure 4 (see Delannée & Aulanier 1999 and Chen et al. 2005 for observations and explanations of stationary EUV fronts). The 195 Å intensity at the stationary front is oscillating for more than 1 hr, especially in the patches outlined by the ellipses. The intensity blinking may be the manifestation of the wave perturbations coming from the long-duration flare.

To summarize, the results of this Letter convincingly illustrate that EIT waves and/or large-scale expanding dimmings are CME-associated phenomena, which are not driven by the pressure pulses from the flaring loops. For the non-CME flares, which correspond to local magnetic restructuring rather than global magnetic restructuring as in CMEs, only localized brightening or dimming may be observed.

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