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Hard X-rays from "Slow LDEs"

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Abstract. We define "Slow LDEs" as soft X-ray flare events with gradual rise phases, as well as long decay times. Celebrated examples of such events include February 21, 1992 (the *Yohkoh* "candle flame" cusp event) and August 28, 1992 (a prototype coronal X-ray dimming event). We have found another striking example in an event of January 20, 1999, which exhibits a fan-like X-ray structure above the post-flare loop system, as also observed in the August 28, 1992 event. Such events may seem thermal in their nature, since by definition they have no impulsive phase. We confirm, however, that such events invariably exhibit hard X-ray bremsstrahlung emission, a signature of non-thermality. The slow LDEs also follow the pattern of the Neupert effect. We have surveyed the *Yohkoh* data for events of this type, and find several examples of spiky arcades with inflows. The slow LDEs therefore also appear to follow the pattern of post-flare magnetic reconnection. We speculate that still slower and weaker flare-like events – the quiet-Sun arcade events related to CMEs – might follow this pattern as well. Current hard X-ray imaging instruments have been unable thus far to image the weak coronal hard X-ray component associated with events of these types, but HESSI may be able to do so.

1. Introduction

A solar flare normally consists of an impulsive phase, marked by hard X-rays and microwave gyrosychrotron emission, and a gradual phase, marked by soft X-rays, Hα brightenings, and microwave free-free emission. In some cases the impulsive phase may seem weak or non-existent. We here term the most extreme examples of such events "slow LDEs," as illustrated in Figure 1(a), where the rise phase extends over $\sim$one hour. A "slow LDE" has a long GOES duration, as in a normal LDE (Kahler 1977), but also a gradual rise phase. Its GOES time profile resembles a microwave "gradual rise and fall," known to result from a thermal emission mechanism, free-free emission from the same hot plasma responsible for the soft X-ray source (Hudson and Ohki, 1972). Because of the lack of prominent non-thermal effects, one might suspect that such an event could have an explanation in an ideal MHD stability only resulting in heating, without significant signatures of non-thermality.

The existence of purely thermal flares would thus suggest the existence of a physically distinct class of flaring, since we know that normal impulsive flares have energetically significant particle acceleration (Lin and Hudson, 1976). We have previously reported slow LDE events with significant hard X-ray emission (Hudson et al., 1994; cf. Cliver et al., 1986). As found by Dennis and Zarro (1993), even gradual X-ray events follow the Neupert effect (Neupert 1968), so that a *weak but long-lived* hard X-ray burst will accompany a slowly-rising soft X-ray burst. We have now surveyed the first eight years of the *Yohkoh* data for events of this type, and have made a preliminary analysis of some of their properties.

In carrying out this work we anticipate observations from HESSI that will help in settling one of the important questions – does the gradual energy release of an LDE, seen in its most isolated state in a slow LDE, differ from the impulsive energy release of a more typical flare? Late-phase energy release, theoretically capable of supporting particle acceleration, has been known since Skylab (eg Moore et al., 1980). However the decay phase of an LDE flare normally shows only a passive exponential decline, with no evidence for active behavior. In this work we are inspired by the recent discovery of downward flows above certain LDE arcades (McKenzie and Hudson, 1999), which strongly suggests the presence of the large-scale magnetic reconnection process long anticipated theoretically (e.g. Forbes and Malherbe, 1986). Because only a fraction of arcade events show these flows, and only a fraction of all LDEs are "slow," we have included a comparison of these phenomena in our survey.

2. Data Analysis

We have based our event selection on the GOES soft X-ray light curves. An initial screening based on the published times of start and maximum (NOAA Solar-Geophysical Data) stipulated a 30-minute interval between the reported times of onset and maximum, and an M 1.0 peak soft X-ray threshold. Then we inspected the individual events and rejected those for which (a) the rise phase of the main peak did not exceed 20 minutes, or (b) appreciable time variability appeared in the GOES light curve superposed on the gradual rise. Surprisingly, several of the events thus selected had relatively fast decay times, so we required further that the decay phase (the half-maximum point of the decay) exceeed 30 min. These criteria have subjective biases, and in fact the GOES data normally have a non-zero background level that systematically affects the results. Nevertheless the selection process definitely isolated smooth-looking GOES light curves of the type seen in Figure 1(a). A future better look at this problem might use the SXT light curves themselves, in order to avoid the GOES background problem, and make a more objective definition of rise time. Following these rules we found a total of 53 events over the approximately eight years of the *Yohkoh* database (Table 1). This amounts to about 7% of all of the M and X flares during the eight-year interval between September 1, 1991, and September 1, 1999.

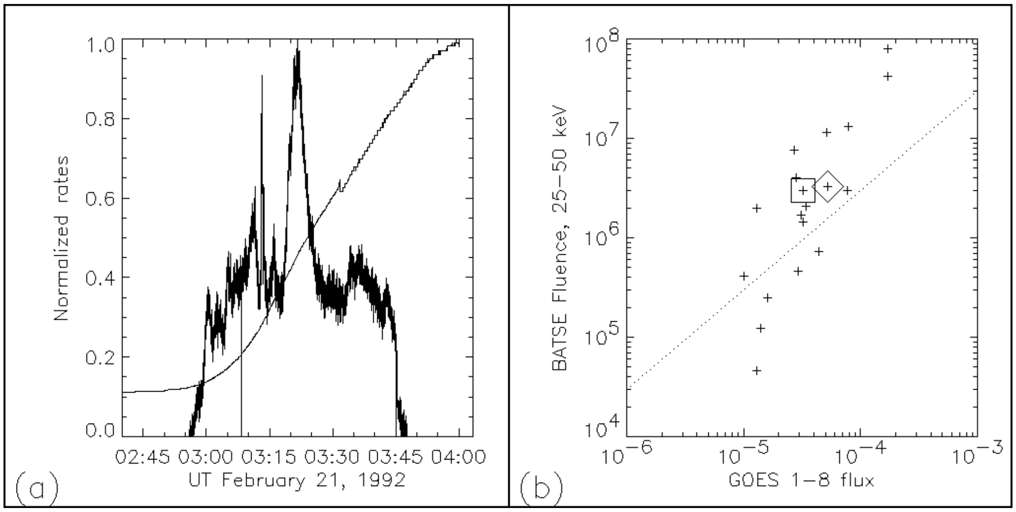

Figure 1. (a): The "slow LDE" event of February 21, 1992 (Tsuneta et al., 1992), showing the GOES soft X-ray (1–8 Å) and BATSE (25–50 keV) light curves. (b): The correlation between hard X-ray fluence and peak soft X-ray flux for 19 slow LDEs: square, February 21, 1992; diamond, January 20, 1999 (McKenzie and Hudson, 1999). The dotted line shows unit slope for reference.

For each event we also searched for hard X rays via the BATSE database, finding 19 events with appreciable overlap between the slow soft X-ray rise phase and BATSE coverage. In these cases the BATSE 25-50 keV data tended strongly to show a long-duration hard X-ray event, as illustrated by the prototype event in Figure 1(a) (February 21, 1992). This event (Tsuneta et al., 1992) had other unusual characteristics (Chertok et al., 1995) and has generated much literature because its morphology strongly resembles that expected from the classical reconnection model (Forbes and Acton, 1996; Tsuneta, 1996).

For the most recent *Yohkoh* observations, ie those corresponding to the rise phase of the new solar maximum, we have a new observing program favorable to the detection of coronal velocity fields associated with flares – the observing sequences place more emphasis on larger fields of view than in the earlier observations. Using these data, McKenzie and Hudson (1999) found evidence for infalling dark features in the late phase of a slow LDE (January 20, 1999, one of the events in Table 1). Further work has disclosed several other examples of this phenomenon ("supra-arcade downflows"), and we have found a total of 4 such events in the slow LDE list for the time range January 1, 1998 through May 8, 1999. This represents about 1/3 of the slow LDEs during this time, so a relationship may well exist. The supra-arcade downflow events thus recognized all have spiky structures. This in fact may account for the detectability of the flow field, providing a source of tracers that the movie representations can show to be in motion. We do not currently understand what causes the multi-spike morphology in some events, nor the spatial periodicity of the spikes.

3. Energetics

Do the hard X-rays detected in the rise phases of slow LDEs establish an energy flow depending strongly on particle acceleration, as for ordinary flares? Figure 1(b) answers this question with a "yes." Here we have correlated the hard X-ray fluence with the soft X-ray peak flux. We find a loose but definite correlation with a degree of scatter – similar to that found for flares in general – for the subset of 19 flares. The hard X-rays generally occur over long periods during the rise phase of soft X-ray emission, thus extending the validity of the Neupert effect (Neupert 1968) to this class of event.

A more quantitative energetics analysis would require hard X-ray imaging spectroscopy. The *Yohkoh* HXT instrument in principle allows us to study the spectral variations of the hard X-ray sources as a function of position (eg Takakura, 1995). The scope of the work presented here does not allow us to present HXT imaging observations of the many interesting flares listed in Table 1, but McKenzie and Hudson (1999) note that the dominant hard X-ray source for the slow LDE of January 20, 1999, occurred at a footpoint location. We might expect a more diffuse coronal hard X-ray source based upon the non-imaging observations from OSO-7 (Hudson, 1978) or the *Hinotori* imaging observations (Kawabata et al., 1983). Metcalf et al. (1996) succeeded in making HXT images of the flare shown in Figure 1(a), but only in low-energy channels that may or may not reflect the non-thermal process the BATSE data show.

We describe here a comparison between the energy of non-thermal hard X-rays, as observed by *Yohkoh* HXT, and the total flare energy, as inferred from the GOES soft X-ray photometry. We select as an example the prototype supra-arcade downflow event of January 20, 1999. From a comparison of the HXT counting rates in its 15-23 keV and 23-33 keV channels, we find a power-law fit for the photon spectrum of

$$\frac{dN}{dh\nu} = 144 \times (\frac{h\nu}{20keV})^{-4.22} \;\; ph(cm^2 sec\ keV)^{-1}.$$

From Hudson et al. (1978), we can convert this into a total thick-target electron energy above 20 keV, 2×10^{30} ergs. By comparison the GOES peak flux and duration give a total soft X-ray radiated energy of 8×10^{29} ergs for the 1-8 Å band. Hence we confirm that the non-thermal electron energy is a major fraction of the total flare energy even for a "slow LDE."

4. Conclusions

The hard X-ray emission detected from the rise phases of the slow LDE events surveyed here reveals their inherently non-thermal nature. The acceleration of energetic electrons appears to begin at the very onset of the event in many cases, and there is a rough correlation between the hard X-ray fluence and the soft X-ray peak flux as expected from the Neupert effect. Because these flares may be powerful (all those in the present study are greater than GOES M-class) they can be detected in hard X-rays in spite of their slow rise times. We thus speculate that fainter events, perhaps even quiet-Sun arcades far from sunspot groups, may also produce proportionally weak hard X-ray emission.

The scope of this survey has not allowed us to do a full analysis of the HXT observations of these events. We therefore cannot comment on the possible relationship between the rise-phase hard X-rays and the coronal hard X-ray sources of the types found by Hudson (1978) and Masuda et al. (1994). We hope that HESSI observations can help to probe these relationships.

The soft X-ray morphology of the events resembles that of other LDEs, ie large arcades of loops. There may be a connection between these slow-rise and the "supra-arcade downflows" observed by McKenzie and Hudson (1999). These downflows may require the existence of a spiky superstructure above the arcade, a pattern found only in a subset of arcade events (Švestka et al., 1998). The slowness of the rise phase of an arcade event may therefore have something to do with the formation of such a spiky crown.

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Table 1: A Yohkoh "Slow LDE" list

M1.9	22-OCT-91	18:27	M7.7	6-MAR-93	20:17	
M1.7	25-OCT-91	10:41	M2.9	15-MAR-93	19:45	
M1.4	25-OCT-91	16:56	M2.3	23-MAR-93	01:17	
X1.7	26-OCT-91	18:46	M1.6	7-MAY-93	20:20	
M4.7	29-OCT-91	18:09	M4.?	14-MAY-93	21:54	
M3.4	4-NOV-91	22:52	M5.4	7-JUN-93	13:51	
M1.6	1-DEC-91	05:35	M1.8	28-JAN-94	15:40	
M1.2	8-DEC-91	05:19	M4.0	20-FEB-94	01:04	
M3.2	16-DEC-91	12:11	M2.8	27-FEB-94	08:25	
M1.6	21-DEC-91	17:51	M3.2	19-OCT-94	20:47	
M2.7	28-DEC-91	21:27				
M2.7	30-DEC-91	19:04	M2.4	27-MAR-98	21:49	
M3.6	3-JAN-92	08:53	M1.4	20-APR-98	09:38	SAD
M4.4	6-FEB-92	09:39	M1.0	16-JUN-98	18:03	
M3.2	21-FEB-92	02:20	M3.1	16-AUG-98	17:37	SAD
M1.3	26-FEB-92	22:58	M1.3	3-SEP-98	03:45	
M7.8	15-MAR-92	01:22	M7.1	23-SEP-98	06:40	
M1.1	4-MAY-92	20:08	M2.8	30-SEP-98	13:08	SAD
M7.4	8-MAY-92	15:12	M8.4	5-NOV-98	19:00	
M1.0	25-JUN-92	06:16	M2.3	23-DEC-98	05:13	
M1.1	28-JUN-92	02:13	M5.2	20-JAN-99	19:06	SAD
M1.6	28-JUN-92	13:53	M1.0	14-FEB-99	09:59	
M1.5	8-SEP-92	08:01	M1.3	21-FEB-99	13:03	
X1.7	30-OCT-92	16:59	M3.0	27-JUL-99	12:58	
X9.0	2-NOV-92	02:31	M1.?	6-AUG-99	13:50	
M1.3	18-NOV-92	19:18	M1.2	7-AUG-99	18:52	
M5.1	2-MAR-93	20:38	M1.8	20-AUG-99	12:36	

Note: "SAD" denotes detection of "supra-arcade downflow"

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