Earth Planets Space, **53**, 581–583, 2001

Hard X-rays from Slow Flares

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(Received June 14, 2000; Revised October 20, 2000; Accepted January 11, 2001)

"Slow LDEs" are those for which the rise phase is slow, as well as the decay phase. Such flares follow the Neupert effect, which implies that the non-thermal energy release has a similar relationship to heating as in a normal impulsive flare. Based on a sample of 53 slow LDEs during the first nine years of *Yohkoh* observations, we find 19 for which substantial overlap occurs with BATSE hard X-ray observations. These events tend strongly to have extended hard X-ray emission even though their hard X-ray emission does not tend to be "impulsive" in the sense of rapid variation. The hard X-ray fluences for these 19 events correlate with the soft X-ray peak fluxes, implying strong non-thermal particle acceleration even for these relatively slow energy-release rates. These events often correspond to the occurrence of "supra-arcade downflows," a phenomenon consistent with the classical reconnection model for gradual-phase flare energy release. This correspondence suggests a close relationship, not depending strongly upon time scale, between large-scale reconnection and the acceleration of non-thermal electrons.

1. Introduction

Hot coronal plasma emitting soft X-rays gives us a modern working definition of a solar flare. In the common view, this coronal energy storage drives the Hα chromospheric emission via conductive energy transport. The GOES photometry provides a convenient measure of this from a whole-Sun point of view, and the *Yohkoh* soft X-ray images give us images with much more sensitivity. In a flare, the so-called "impulsive phase" describes the early flare period during which non-thermal signatures predominate: microwave gyrosynchrotron emission, white-light and UV continuum, hard X-rays, and γ rays. The soft X-rays *integrate* the light-curve of the hard X-rays, according to the Neupert effect (Neupert, 1968; Dennis and Zarro, 1993).

The impulsive-phase emissions fluctuate much more rapidly than the soft X-rays, and this impulsiveness probably contributes to the terminology originally suggested by Kane (1969). However the distinction between the non-thermal emissions and the thermal emissions probably is more profound than this. The rapid variability seems natural because of the nature of the emissions, which require strongly non-Maxwellian velocity distributions both for electrons and ions. We identify a "slow LDE" as one with both slow rise and long decay. An LDE (Long Decay Event; see Kahler, 1977) is a long-lived gradual X-ray burst strongly associated with the occurrence of a CME (Coronal Mass Ejection). These maximally gradual events in principle might help to distinguish the non-thermal nature of the impulsive phase.

We have described the "slow LDEs" previously (Hudson and McKenzie, 2000); in that paper we noted that the slow LDEs have a possible relationship with the "supra-arcade downflows" (McKenzie and Hudson, 1999), apparently a signature of large-scale magnetic reconnection. This signature is especially prominent in the gradual phases of these flares, which invariably accompany CMEs and display a fan-like structure surmounting the X-ray arcade and extending to great heights in the corona (McKenzie, 2000). This paper summarizes the previously-published work (Section 2), not reproducing the list of events, and comments on the significance of the study in the context of large-scale magnetic reconnection. The implications are twofold: first, the slow LDEs appear to provide favorable conditions for the soft X-ray observation of reconnection outflows originating high in the corona; second, the initial stages of these events—not impulsive in the sense of rapidly varying, but distinctly non-thermal—suggest the need for a non-ideal process in the formation of these conditions. Section 3 discusses these implications.

2. Slow LDEs and Supra-Arcade Downflows

As noted in the earlier work, the slow LDE sample includes well-known cusp events as observed by *Yohkoh*, and associated with large-scale coronal reconnection because the cusp feature resembles the cartoons of the standard reconnection model ("CSHKP"; see e.g. Hudson and Cliver, 2001, for references) for solar flares and CMEs (e.g., Hudson and Cliver, 2001). Hudson and McKenzie (2000) also noted the coincidence (in four of sixteen cases) between "slow LDE" properties and the occurrence of supra-arcade downflows as detected by *Yohkoh* SXT. The common occurrence of supra-arcade downflows (McKenzie and Hudson, 1999; McKenzie, 2000) makes this somewhat unsurprising, but we estimate that only 7% of all M-class flares meet our "slow LDE" criteria. Thus it is possible that the slow LDEs lead preferentially to the spiky arcades in which we can see the downflows most easily.

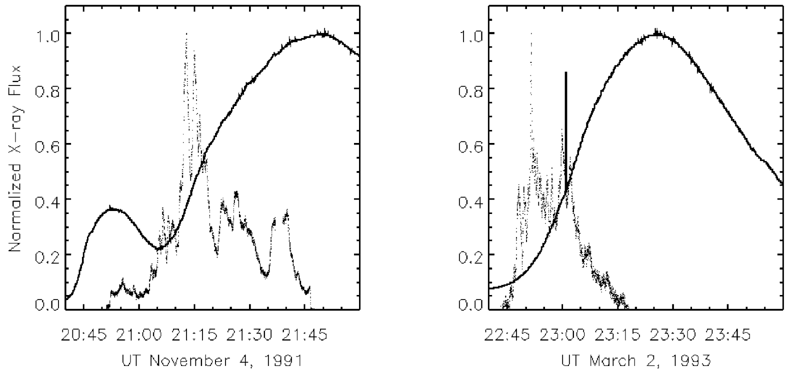

Fig. 1. Two examples of "slow LDE" events, showing soft X-ray light curves from the GOES 2–10 Å channel (line) and hard X-ray light curves from the CGRO/BATSE 25–50 keV channel (dots). In both cases the hard X-ray flux extends for long periods of time, roughly through the rise phase of the soft X-ray event.

The list of slow LDEs includes the prototype cusp event of February 21, 1992 (Tsuneta, 1996), and Fig. 1 shows two other examples. By using the large-area detectors of BATSE for detecting low levels of hard X-ray emission, Hudson and McKenzie (2000) showed that the fluences of non-thermal bremsstrahlung correlated with the peak soft X-ray fluxes for the 19 well-observed examples. This confirms the result of Dennis and Zarro (1993) in extending the Neupert effect to long-duration events.

3. Implications for Magnetic Reconnection

We first comment on the implications of the *Yohkoh* image morphology of these events in the context of the standard reconnection model. The observational information comes from McKenzie and Hudson (1999) and McKenzie (2000). Here we list some of the features of these events, adding comments in italics regarding how the observations compare with expectations from the standard model.

1) The supra-arcade flow field occurs between an assumed coronal reconnection site and the top of the loop arcade that forms via the reconnection process. *This is as expected from the standard model (CSHKP; see Hudson and Cliver, 2001).*

2) The flow velocity is lower than the inferred Alfvén velocity. *Possibly not inconsistent with CHSKP (Forbes and Acton, 1996; Magara et al., 1996).*

3) The flow field may consist of dark or bright features, the latter often suggesting loop retractions, and the motion of these features correlates with waving motions in the fan structure. *The appearance of "patchy reconnection" (Klimchuk, 1997) is not a part of the standard model because of the complicated field connectivity.*

4) Upward flows above the arcades have not been seen. *The standard model requires both upward and downward reconnection outflows.*

5) The flows are most easily visible in the maximum to late phases of the soft X-ray time profile of the flare, although downflow features are sometimes visible in the rise phase as well. *This seems inconsistent with the standard model, if we assume reconnection occurs when the downflows are seen, since the most intense energy release occurs during the rise phase. Selection effects may also affect the visibility of the flow field.*

6) Both bright and dark flow tracers occur. *Dark outflows seem inconsistent with the idea of heating by the reconnection process itself.*

Are the discrepancies noted significant (i.e., not due to selection effects), and if so can natural extensions of the standard model explain them? If discrepancies do exist, this might simply point to a lack of development of the standard model, i.e. the observations may simply have outstripped the predictive capability of the current theory. We will leave these questions and the necessary CSHKP repair work to the theorists!

Now what are the implications of the extended non-thermal emission for the formation of these structures? The energetics of the rise phase of an eruptive flare is generally not explained by the CSHKP model, and the presence of intense non-thermal radiation implies directly that MHD may not be a reliable theoretical framework here. We do not have any suggested explanation for the fact that slow LDEs appear preferentially to favor the appearance of the spiky arcade events in which we can detect the downflows (4/16 in the sample of Hudson and McKenzie, 2000). This association may be illusory, because we have not made a rigorous study of the biases inherent in the event selection.

4. Conclusions

We have described gradual flares that exhibit extended non-thermal effects, consistent with the Neupert effect, and large-scale coronal flows strongly suggestive of the standard model (CSHKP) for the late phase of an eruptive solar flare or CME. The greater sensitivity of the current hard and soft X-ray instruments on board *Yohkoh* in particular have made these observations possible; in particular the ability to determine a two-dimensional flow field from movie sequences of soft X-ray images is a powerful innovation. The observations highlight weaknesses in the standard theory which may or may not be fixable. We would like to emphasize here that the standard theory has little to say about the "impulsive" phase of a flare, which appears to be distinctly non-MHD in character even in slow LDE events—such gradual events look thermal, but are not.

The results on slow LDEs confirm the inherent non-thermality of the flare energy release in the impulsive phase. The non-thermality, in terms of energetics, does not depend upon flare magnitude or flare time scale to first order. This is the basic implication of the Neupert effect, which applies equally to these slow LDE events, even though they seem less violent—we speculate that more sensitive hard X-ray observations (perhaps those from HESSI) will reveal strong non-thermal effects even in quiet-Sun arcade events underlying CMEs.

Acknowledgments. This work was supported under NASA contract NAS 8–37334. *Yohkoh* is a mission of the Institute of Space and Astronautical Sciences (Japan), with participation from the U. S. and U. K. We thank the BATSE team for making solar hard X-ray data readily available for studies such as this.

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