SPECTRAL VARIATIONS OF FLARE HARD X-RAYS

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ABSTRACT

We report on a set of eight solar hard X-ray bursts corresponding to M-class flares and well-observed with the RHESSI and HXRS instruments. We find, as previously reported, that the impulsive phases of these events invariably show the soft-hard-soft spectral pattern (SHS) in which the power-law spectral index anticorrelates with the flux. The RHESSI data have higher spectral resolution but give the same result. The SHS pattern occurs in the spectral domain above the typical break energy of double power-law fits as well as below. Some of the events also show other patterns, including the soft-hard-harder evolution seen in eruptive events. We discuss the physical interpretation of the spectral behavior.

Key words: flares; X-rays; corona.

1. INTRODUCTION

High-energy particle acceleration characterizes the time development and energetics of a solar flare. Central to the development of a flare is its *impulsive phase*, characterized by rapid fluctuations of hard X-ray emission attributed to the non-thermal bremsstrahlung of quasi-relativistic non-thermal electrons (Kane, 1969). The earliest observations with balloon-borne hard X-ray spectrometers revealed a "soft-hard-soft" (hereinafter "SHS") pattern of spectral evolution (Parks & Winckler, 1969) in the largest events. The spectral hardness correlates directly with the hard X-ray flux, say at 30 keV. If we fit the spectrum to a power law in photon number, $J(h\nu) = J_{30} \times (h\nu/30\ keV)^{-\gamma}$, then we find an anticorrelation between J_{30} and γ. Clear examples of major events showing the SHS pattern appear in Benz (1977), Brown & Loran (1985), and Dennis (1985); recently Fletcher & Hudson (2002) have pointed out that this pattern systematically extends to GOES M-class flares as well. Because the SHS correlation occurs symmetrically during rise and decay, it strongly implies a lack of long-term trapping of the impulsive-phase electrons. Thus the SHS spectral variation originates intrinsically in the acceleration process, rather than in the effects of subsequent propagation.

With the launching of the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) in February 2002 we have new tools with which to study basic processes in the impulsive phase of a flare (Lin, 2002). In particular the spectral resolution in the hard X-ray range is of order one keV. The RHESSI detector also has the advantage of using a mechanical shutter system to increase the dynamic range. At the same time the HXRS instrument on board the MTI spacecraft (Fárník et al., 2001), launched in 2001, provides data from a classical scintillation-counter spectrometer for some of the same flare events. Although the spectral resolution of HXRS is relatively low, its time resolution (0.2 s) is relatively high in comparison with the RHESSI spin period of about 4 s.[1] In this paper we present a comparison of the two data sets and use them to probe the time dependence of the soft-hard-soft morphology.

In this short paper we restrict ourselves to the spectral evolution of flare hard X-ray sources, independent of their spatial properties. Now of course the new RHESSI data will enable us to extend the imaging studies done with the *Yohkoh* HXT instrument with improved resolution. Sakao et al. (1998) discovered spatial/spectral correlations with HXT, for example, and Fletcher & Hudson (2002) have extended this to smaller flares with RHESSI.

2. SOFT-HARD-SOFT

Figure 1 shows a remarkably clear example of SHS behavior, using HXRS data, from a flare of September 24, 2001. Note that this is an X-class flare. We have identified a sample of eight events commonly observed by RHESSI and HXRS, as listed in Table 1 and use this to confirm that the SHS pattern occurs also in weaker events (the sample consists of M-class flares plus one C9.7). For this sam-

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[1] The RHESSI time resolution will eventually become much better as software becomes available.

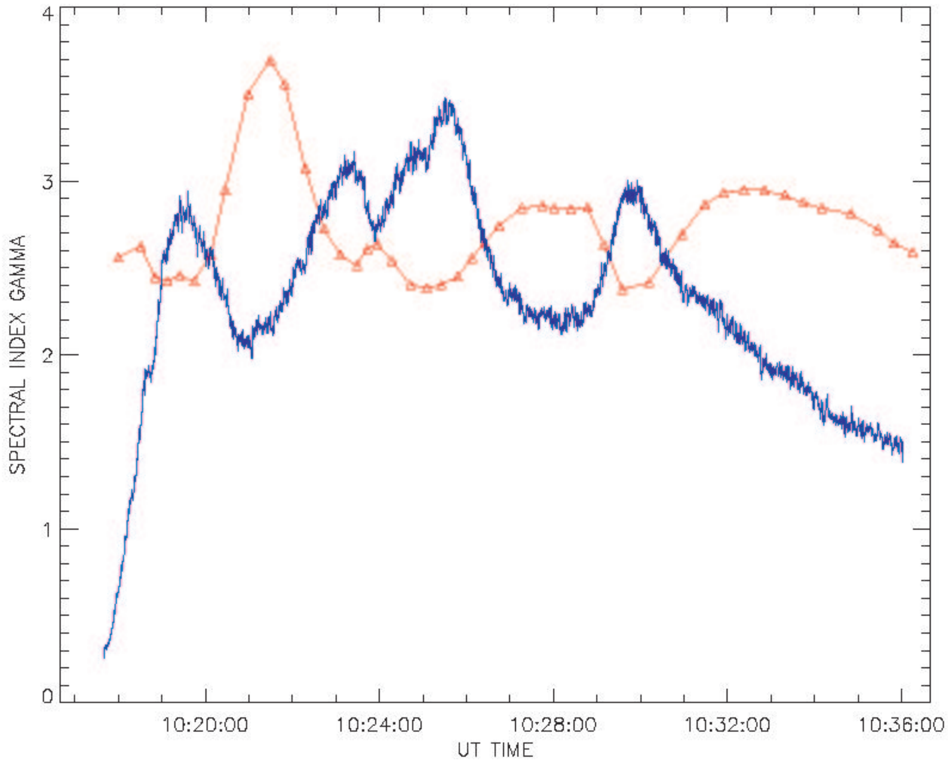

Figure 1. Example of soft-hard-soft spectral (SHS) evolution as observed by the HXRS instrument for an X-class flare of September 24, 2001 (Fárník et al., 2002). Note the almost perfect mirror symmetry between the flux variation (dark; arbitrary units) and the spectral slope (light; left axis).

ple of events we can use either the high-resolution Ge spectra from RHESSI or the scintillation-counter data from HXRS. The low resolution of a scintillation counter suggests the possibility that a relatively subtle effect, such as SHS in a smaller flare, might result as an artefact of "contamination" of the hard X-ray fluxes by low-energy X-rays of thermal origin. To check this we show a comparison in Figure 2 between the HXRS 29-42 keV band and this exact energy range in the RHESSI data. Note that the RHESSI data consist of individual photon counts labeled by their pulse heights, so they can be rebinned arbitrarily in this manner. By suitable weighting, in fact, one could approximate the exact detector response matrix in HXRS or any other hard X-ray data set to be compared.

Table 1. Event list

Date	Start	Peak	End	Class
20-FEB-02	09:46	09:59	10:04	M4.3
20-FEB-02	16:18	16:26	16:29	C9.7
20-FEB-02	21:00	21:07	21:09	M2.4
14-MAR-02	01:38	01:50	02:02	M5.7
17-MAR-02	10:11	10:19	10:24	M1.3
17-MAR-02	19:24	19:31	19:34	M4.0
10-APR-02	12:23	12:31	12:40	M8.2
10-APR-02	18:48	19:07	19:15	M1.6

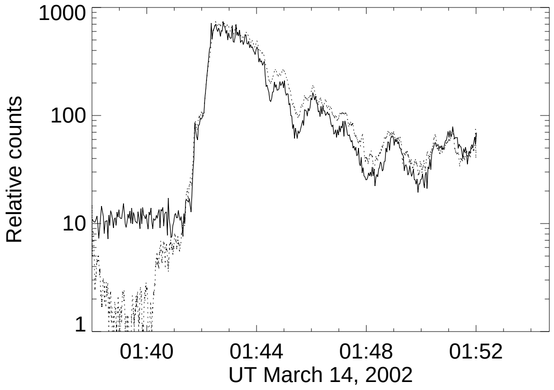

Figure 2. Comparison of RHESSI and HXRS counts, with an ad hoc normalization after background corrections, for the HXRS 29-42 keV spectral band. Note that RHESSI data (the heavier line) have excellent spectral resolution and can be rebinned for any desired energy range. Over a wide range of counting rate the two rates agree closely.

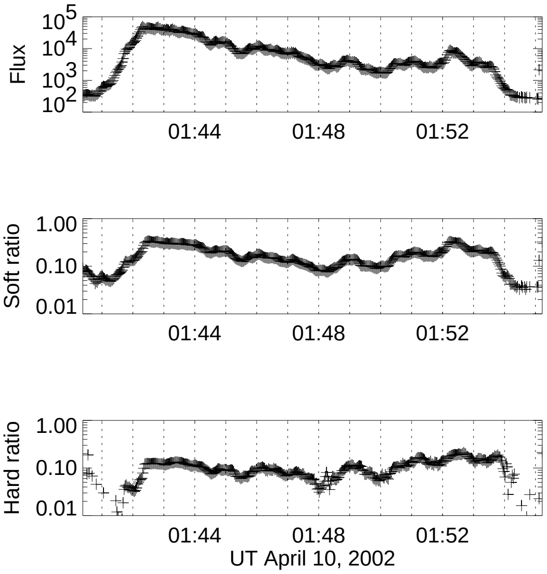

Figure 3. Illustration of the soft-hard-soft (SHS) pattern for the event of Figure 2. Upper panel, the RHESSI 30-50 keV light curve, based on 2-s integrations; middle panel, the spectral hardness in the 20-50 keV range; lower panel, the spectral hardness in the 30-70 keV range. Both spectral ranges show a clear correlation with the flux variations on shorter (seconds to minutes) time scales. Note that the hardness ratios shown here have an inverse correlation from that of the spectral index shown in Figure 1.

For each event in Table 1 we have made standard plots of the type shown in Figure 3. These invariably show the SHS effect on time scales of seconds to minutes, although there are noticeable deviations in some events for longer time scales. We expect this in view of the known differences in spectral patterns for major events (see Cliver et al., 1986), and tentatively conclude that such non-SHS physical processes may also occur in M-class flares. We note that other similar events reported by Fletcher & Hudson (2002) also show ubiquitous SHS patterns but again with some deviations on longer time scales. Because background corrections to the hard X-ray spectra can be expected to pose more of a problem on longer time scales, we do not rule out the possibility that some of the observed discrepancies from SHS may be artefacts.

In the example of Figure 3 we have shown two hardness ratios based on 20-30, 30-50, and 50-70 keV energy bands (note that this is a different presentation from the "mirror" plot of Figure 1, since the spectral index anticorrelates with hardness). The presence of the SHS pattern over a wider spectral range suggests that it occurs both above and below a spectral break (if any) of the type studied by Lin & Schwartz (1987).

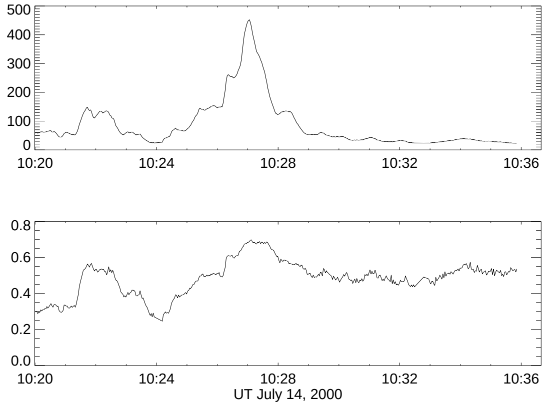

Figure 4. Example of soft-hard-harder spectral evolution in the well-known event of July 14, 2000, as observed by the Yohkoh HXT instrument. The upper panel shows the 53-93 keV counting rate, and the lower panel the ratio of 53-93 keV to 33-53 keV. From the design of this instrument (Kosugi et al. 1991) this ratio roughly equals unity for a power-law slope $\gamma = 2$. Note that the hardness ratio shown here has the inverse correlation from that shown in Figure 1.

3. SOFT-HARD-HARDER

According to the discussion above, the SHS pattern appears to be an essential feature of the impulsive-phase electron acceleration, normally observed in the 10-100 keV range. The departures from this pattern reveals other physics linked to processes in the solar corona. We illustrate this with *Yohkoh* HXT observations of the well-known flare of July 14, 2000. Figure 4 shows the presence of SHS in the impulsive peaks, but also a gradual tendency for hardening with time, with the count-rate ratio increasing from about 0.3 to almost 0.6 during the 15-minute interval. This SHH pattern occurs preferentially in long-duration events (Cliver et al., 1986), consistent with its interpretation as a slowly-developing coronal non-thermal process associated with eruption. Kiplinger (1995) argues that this pattern correlates well with solar proton events.

Note that the SHH pattern can also probably be seen in the September 24, 2001 event illustrated with HXRS data in Figure 1; the final decrease of counting rate at the end of the event corresponds to a decreasing value of γ. Although we might expect SHH behavior in this event, because of its eruptive nature (Fárník et al., 2002), we must use caution because of the critical effects of background subtraction. Indeed, the comparison event shown in Figure 3 itself shows a hint of SHH, especially in the harder region (30-70 keV range). Thus each of the three events illustrated in this paper, making use of three different instruments, shows some evidence for departures from strict SHS spectral variation.

4. CONCLUSIONS

This paper had two main objectives: first, to illustrate the consistency of the HXRS scintillation-counter spectra with the higher-resolution data from RHESSI. This we have done only approximately but see no systematic discrepancies that might result, for example, from the lack of spectral resolution in the HXRS spectral measurements. The RHESSI data will certainly supersede the earlier results in terms of the precision of spectral measurement, and inferences about the electron spectrum, but in the meanwhile we can safely make use the experience gained with scintillation-counter spectrometers to understand broad-band spectral patterns.

A second major objective here was to demonstrate the prevalence of the SHS spectral pattern. Based upon our sample of events and on the earlier data, we argue that this pattern forms an essential characteristic of the impulsive-phase energy release in a solar flare. Various models exist for particle acceleration in the impulsive phase, but so far as we are aware the only explicit theoretical demonstration of the SHS behavior in a model consistent with a thick-target interpretation was in the discussion of stochastic acceleration by Benz (1977), which assumes that the acceleration takes place in a wave-filled volume. Brown & Loran (1985) improve this work and apply it to other flare events. In this model the flux and spectral slope scale inversely with the product of the assumed region size and wave energy density. It would seem reasonable that other acceleration mechanisms would predict SHS behavior, but one could also imagine ones for which this would not be natural. Betatron acceleration (Brown & Hoyng, 1975) or an adiabatic process (Maetzler et al., 1978) could mimic this effect under the proper conditions but no longer represent viable models for a thick-target interpretation.

The HXRS data will be a valuable supplement to the RHESSI observations because of the inevitable gaps in coverage due to orbital eclipse periods. We intend therefore to continue the detailed cross-calibration work of the two instruments, making use of the flexibility RHESSI's high resolution offers for this purpose.

ACKNOWLEDGMENTS

This work was supported by NAS 5-98033 from NASA (Hudson) and by grant No. 205/02/0980 from the Grant Agency of the Czech Republic (Fárník).

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