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HARD X-RAY SPECTRAL EVOLUTION AND PRODUCTION OF SOLAR ENERGETIC PARTICLE EVENTS DURING THE JANUARY 2005 X-CLASS FLARES

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ABSTRACT

High-resolution hard X-ray observations provided by the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) are used to study the spectral evolution of ~50–200 keV nonthermal electron bremsstrahlung emissions of five X-class flares observed during the January 2005 solar storm events. Four of these flares show progressive spectral hardening during at least some hard X-ray peaks, while only one event shows the otherwise more commonly observed soft-hard-soft behavior. Imaging observations reveal that ~50–100 keV nonthermal electron bremsstrahlung emissions originate from footpoints of flare loops at all times, including during times of progressive spectral hardening, indicating that the spectral hardening component is produced by precipitating electrons, and not by electrons trapped in the corona. The four flares with progressive spectral hardening are all related to solar energetic particle (SEP) events, while the only X-class flare with soft-hard-soft behavior is not. This finding is consistent with earlier studies, suggesting that electron acceleration and transport in flares is somehow linked to the production of SEPs escaping into interplanetary space.

Subject headings: Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

The Sun exhibits very efficient particle acceleration during coronal mass ejections (CME) and solar flares, as revealed by in situ particle measurements and remote-sensing X-ray and γ-ray observations. Solar energetic particles (SEPs) with access to open field lines can escape into interplanetary space, where they can be observed with in situ particle detectors, making it possible to sample particles accelerated at the Sun. Particles traveling on field lines connected back to the Sun eventually lose their energy by collisions, producing X-ray and γ-ray emission as the density rapidly increases in the transition region and below. Energetic ions produce γ-ray emissions by nuclear interactions, while energetic electrons lose their energy by collisions, producing hard X-ray (HXR) bremsstrahlung emission. Both emissions are most often seen from footpoints of flare loops (Hoyng et al. 1981; Hurford et al. 2006), but occasionally also from the corona (Frost & Dennis 1971; Masuda et al. 1994; Tomczak 2001; Krucker & Lin 2008). The spectral hardness of nonthermal HXR emissions is often found to directly correlate with the X-ray flux at the corresponding energy (Parks & Winckler 1969; Fletcher & Hudson 2002; Grigis & Benz 2004), with an initially soft (steep) spectrum prior to a flux peak, which becomes harder (flatter) as the flux increases, and softens again during the flux decay, a pattern commonly referred to as soft-hard-soft (SHS) behavior. SHS behavior is thought to be a result of the electron acceleration mechanism in solar flares (e.g., Grigis & Benz 2006), although other possible causes include propagation effects of electrons traveling along flare loops and return currents caused by self-induced electric fields (Zharkova & Gordovskyy 2006). It has also been observed that certain flares exhibit a HXR spectrum that progressively hardens throughout flux peaks (Frost & Dennis 1971; Cliver et al. 1986). This spectral evolution, referred to as soft-hard-harder (SHH), is more frequently found in flares with a gradual rather than an impulsive time profile and occurs much less commonly than the above-mentioned SHS behavior; it could be due to trapping of energetic electrons, with high-energy electrons being trapped the longest.

Kiplinger (1995) found that the occurrence of flares that demonstrate a SHH spectral evolution is closely associated with the observance of high-energy interplanetary proton events. While the physical association between progressively hardening solar flares and SEPs is not clear, the Kiplinger study obtained a 96% success rate in predicting large proton events with the following selection criteria. (1) Predict a large proton event (>10 particles $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ at >10 MeV) if the related flare shows spectral hardening during HXR peaks with FWHM duration >70 s or if hardening is only observed during the HXR decay. (2) Do not predict a proton event if the *Geostationary Operational Environmental Satellites* (*GOES*) soft X-ray (SXR) peak flux is below *GOES* class X1 or if the event is located east of E40. This association between spectral hardening and SEP production suggests a connection between the HXR producing electrons in the flare in closed flare loops and escaping energetic protons on open field lines. This is rather puzzling, especially if the CME shock front is indeed the main proton accelerator.

This paper aims to verify whether the relationship between the five X-class flares and SEP events that occurred during January 2005 is consistent with the Kiplinger study, using *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) observations (Lin et al. 2002). Furthermore, *RHESSI*'s imaging capability (with spatial resolution down to 2.3″) makes it possible to compare the location of nonthermal X-ray emissions relative to thermal emissions, providing clues to the possible physical mechanisms involved in SEP related flares. The high spectral resolution of *RHESSI* (~1 keV) allows us to cleanly separate the thermal continuum from the nonthermal component of the spectrum and to follow the evolution of the nonthermal spectral index throughout the flare. However, the additional imaging information provides the most interesting new diagnostic tool that was not available for the original study by Kiplinger.

2. OBSERVATIONS AND DATA ANALYSIS

During the time span of 2005 January 14–21, six large flares with *GOES* class above M8.5 occurred in the same active region, AR 10720. Of those six flares, four are clearly associated with a temporally correlated increase in *GOES* $>$ 10 MeV proton time profiles, and one flare (January 15, 00:30 UT) clearly shows no related enhancement (Fig. 1). For the January 19 flare, the pre-event

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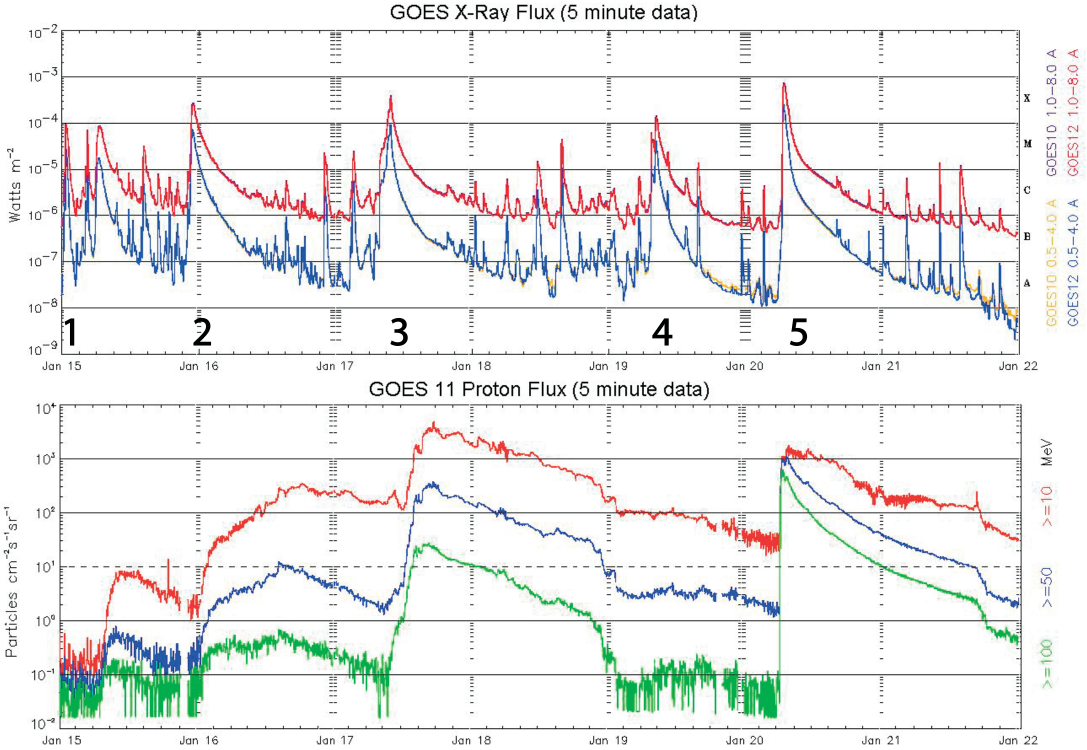

FIG. 1.—Overview plots of the *GOES* SXR and energetic proton observations. The five X-class flares discussed in this paper are marked with numbers.

TABLE 1

FLARES AND SEP PRODUCTION IN JANUARY 2005

SXR Peak Time (2005)	*GOES* Class	Flare Location	>10 MeV Proton Peak Flux	Spectral Evolution	Kiplinger's Prediction
Jan 15 00:43	X1.2	N14, E08	<0.1	SHS	no
Jan 15 06:38	M8.6	N16, E04	~8	. . .	. . .
Jan 15 23:02	X2.6	N15, W05	~30	first SHS, then SHH	yes
Jan 17 09:52	X3.8	N15, W25	~4000	first SHS, then SHH	yes
Jan 19 08:22	X1.3	N15, W51	~10	SHS, decay SHH	yes
Jan 20 07:01	X7.1	N14, W61	~1500	SHH	yes

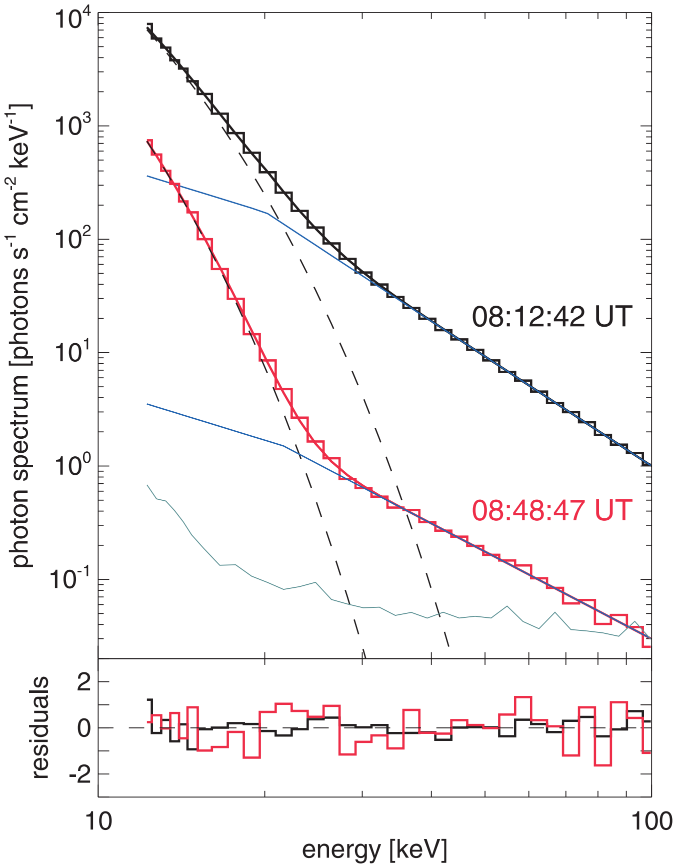

FIG. 2.—Example of spectral fitting for the 2005 January 19 flare: two spectra, one during the first HXR peak (08:12:42 UT) and the other much later (08:48:47 UT), are shown in black and red, respectively. The black (dashed) and blue curves are thermal and broken power law fits, respectively, and the thin gray curve represents the background emission. The bottom panel shows the residuals of the spectral fits normalized by the standard deviation. The later emission is much fainter, but has a flatter (harder) spectrum (with power law index $\gamma \sim 2.6 \pm 0.1$) than the emission during the first HXR peak ($\gamma \sim 3.2 \pm 0.1$).

GOES proton flux is still enhanced from the previous SEP event, especially at 10 MeV, making it difficult to determine the existence of a new injection. The >10 MeV proton flux shows a small increase ($\sim$10 cm^{-2} s^{-1} sr^{-1}) after the January 19 flare onset that could be the related SEP event. In situ ion observations at lower energy from the Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on the *Advanced Composition Explorer* (*ACE*; Stone et al. 1998) clearly show a new increase in $\sim$0.1–1 MeV nucleon^{-1} ions. Therefore, the January 19 flare likely produces an SEP event as well. *RHESSI* has good coverage for the five X-class flares, but missed the M8.6 flare (January 15, 5:54 UT) event. Hence, the sample of events available to study the spectral evolution are four flares with SEP events, and one without (Table 1).

Standard *RHESSI* spectral analysis techniques are used to fit a thermal model and a single or double broken power law function to the pile-up corrected count spectra (Fig. 2). To search for SHS and SHH behavior, the power-law indices at highest energy are used, generally starting around 50 keV, except for the January 17 and 20 flares with start values between $\sim$75 and $\sim$100 keV. Since all these flares have rather high count rates, the pile-up correction (Smith et al. 2002) does not always work perfectly, and produces significant residuals in the fits. However, this mostly affects the energy range between 30 and 40 keV, and does not affect the power-law fit above 50 keV.

The temporal evolution of the HXR flux and spectral power law index γ are presented in Figure 3 and summarized in Table 1

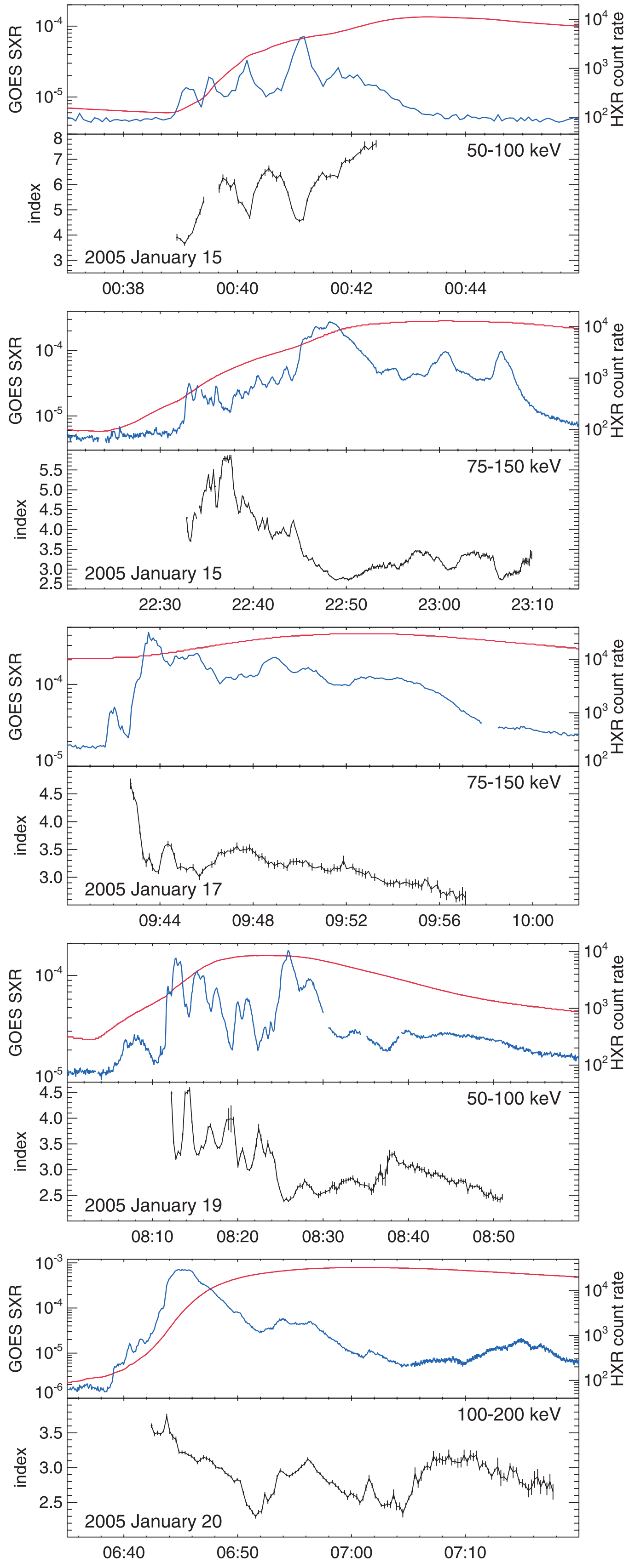

FIG. 3.—HXR spectral evolution for the five presented flares. For each flare, the *GOES* SXR (*red*; low-energy channel) and *RHESSI* 50–100 keV HXR (*blue*) time profiles are shown in the top panels, with the temporal evolution of the power-law indices in the energy range given in the top right corner of each plot presented below.

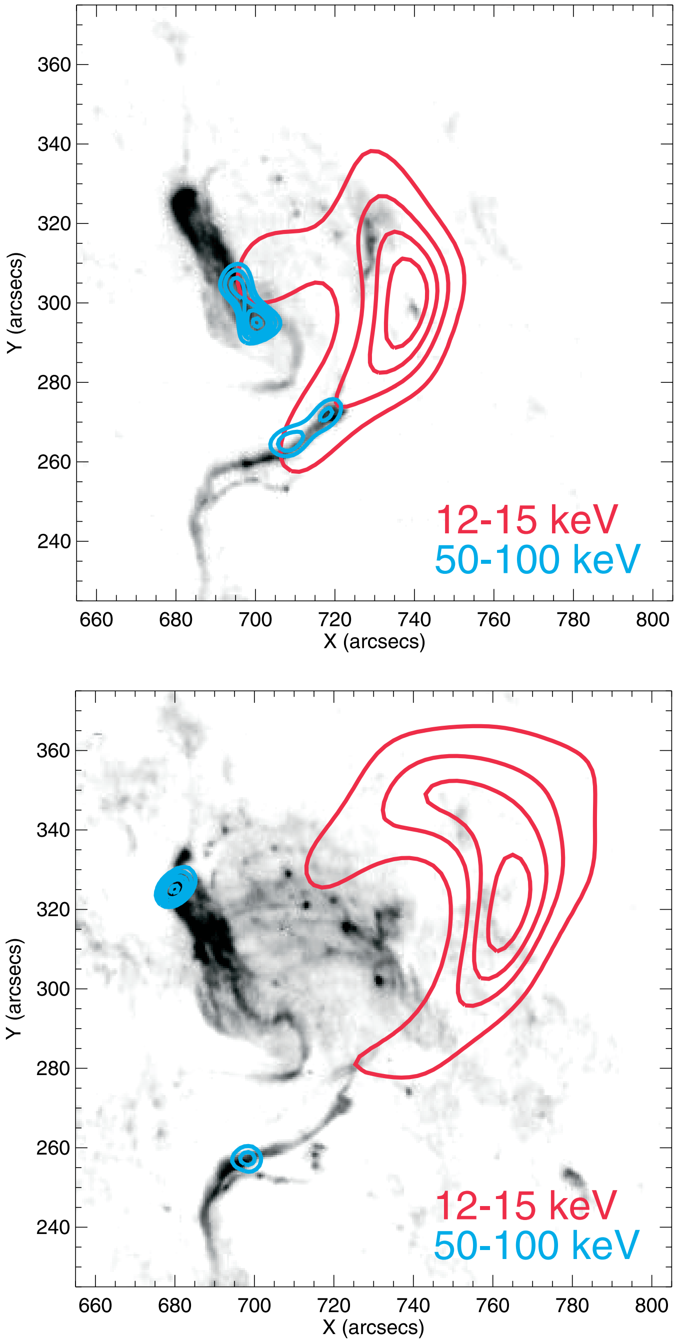

FIG. 4.—HXR imaging results of the 2005 January 19 flare taken during the first HXR peaks (08:11:40–08:13:41 UT; *top*) with SHS behavior and later during the progressively hardening phase (08:43:10–08:45:40 UT; *bottom*). Both figures show HXR contours in the thermal (*red*; contours are 20%, 40%, 60%, and 80%) and nonthermal (*blue*; contours are 7.5%, 15%, 30%, 50%, 70%, and 90%) range superposed on *TRACE* 1600 Å images taken at 08:25:30 UT (first image available for this flare) and 08:45:03 UT. For both spectral behaviors, SHS and SHH, nonthermal HXR emissions in the 50–100 keV range are observed from footpoints. Due to the limited dynamic range of the HXR observations, the legs of the thermal loop connecting the HXR footpoints with the corona are not visible in the image at the bottom.

using visual inspection for SHS and SHH behavior. The January 15 (00:30 UT) event, the only X-class flare in January 2005 that did not produce an SEP event, clearly shows SHS behavior as the HXR flux and γ are anticorrelated (Fig. 3, *top*). After 00:42:30 UT, the spectra are clearly soft/steep, with $\gamma > 7$, but pile-up effects makes the data analysis difficult, and therefore no data points are shown. The other event that only shows a single behavior is the flare of January 20, with a clear SHH behavior seen in every peak (Fig. 3, *bottom*). The other three flares show first SHS and then SHH. For both the January 15 (22:30 UT) and January 17 flares, SHS is only seen in the first few peaks, but most of the later peaks (after 22:44 UT and 09:47 UT, respectively) are clearly SHH (the last two HXR peaks in the Jaunary 15 [22:30 UT] flare show hard/flat spectra, but their spectral evolution is neither clearly SHS nor clearly SHH). The January 19 flare shows SHS behavior for all the main HXR peak, and only shows progressive hardening starting at 08:38 UT ($\sim$26 minutes after the SXR peak), which lasts for more than 10 minutes. Hence, all events with SEP production also show progressive spectral hardening at least during part of the event, while the event without SEP shows SHS behavior, and therefore Kiplinger's predictions hold.

RHESSI not only provides excellent spectral resolution, but also gives simultaneous imaging capability. HXR imaging for all five flares reveals that the emissions in the $\sim$50–100 keV come from footpoints of flare loops at all times, including during times of progressive hardening. Figure 4 shows imaging during the peak and the progressive hardening phase of the January 19 flare, as a typical example of the imaging results. Since the HXR footpoints are moving in time, the shape of the HXR footpoints is elongated in the 2 minute averaged images shown in Figure 4. During the SHS behavior, the motion is along the flare ribbons, as observed in some flares (Krucker et al. 2003; Grigis & Benz 2005), but not perpendicular to the ribbons, as expected in simple reconnection models. At the time of the progressive hardening, the footpoint motion is much slower and rather perpendicular to the ribbons. In any case, during both time intervals, HXR emissions clearly come from footpoints and not from the corona.

3. DISCUSSION AND SUMMARY

Spectral analysis of five X-class flares observed in January 2005 by *RHESSI* clearly reinforce the relationship between progressive hardening seen in the flare HXR emissions and the SEP production first noted by Kiplinger (1995). The nature of their association, however, is unknown, and it is not clear how the spectral hardening of flare-accelerated electrons in closed magnetic field structures is related to high-energy protons that are able to escape the Sun.

RHESSI images made during the progressive hardening phase of the flares indicate that hard X-ray emissions originate from the footpoints rather than the corona (Fig. 4). This was previously noted by Qiu et al. (2004) using *Yohkoh*/HXT observations of a flare with progressive hardening. Hence, if coronal trapping is responsible for the gradual hardening, the observed HXR emissions are not produced by electrons in the corona, but by electrons leaving the trap and precipitating to the footpoints. Therefore, the trapping time in the corona must be shorter than the collisional loss time, at least at energies ($<$100 keV) considered here.

Imaging in the γ-ray range of the January 20 flare (S. Krucker et al., in preparation), however, reveals that relativistic electrons with energies above $\sim$1 MeV seem to be trapped long enough to produce electron bremsstrahlung in the γ-ray range in the corona.

This paper provides first results of some of the most prominent *RHESSI* events with progressive spectral hardening. A statistical study containing all SEP events with good *RHESSI* coverage is planned, including a quantitative analysis of the spectral fit results. Furthermore, future combined observations with *STEREO* will reveal the relative position of HXR footpoints and the CME.

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