The spatial distribution of the hard X-ray spectral index and the local magnetic reconnection rate

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Abstract

The rare phenomenon of ribbon-like hard X-ray (HXR) sources up to 100 keV found in the 2005 May 13 M8.0 flare observed with the Reuven Ramaty High Energy Solar Spectroscopic Imager provides detailed information on the spatial distribution of flare HXR emission. In this Letter, we further investigate the characteristics of HXR emission in this event using imaging spectroscopy, from which we obtain spatially resolved HXR spectral maps during the flare impulsive phase. As a result we found, along a flare ribbon, an anticorrelation relationship between the local HXR flux and the local HXR spectral index. We suggest that this can be regarded as a spatial analog of the well-known temporal soft-hard-soft spectral evolution pattern of the integrated HXR flux. We also found an anticorrelation between the HXR spectral index and the local electric field along the ribbon, which suggests electron acceleration by the electric field during flares.

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

1. INTRODUCTION

It has long been recognized that hard X-ray (HXR) emission is a powerful diagnostic of accelerated energetic electrons produced by flares. The HXR spectrum emitted by nonthermal electrons often appears as a power-law distribution in photon energy, which implies a characteristic in the energy distribution of the electron flux bombarding the target under the bremsstrahlung emission mechanism. Temporal evolution of the electron energy distribution is highly important for identifying the dominant acceleration process.

As is known from the early results of the traditional scintillation-counter spectrometers, the HXR spectral index generally follows a soft-hard-soft (SHS) spectral pattern in the rise-maximum-decay phase of flares (Parks & Winckler 1969; Benz 1977; Brown & Lorain 1985; Dennis 1985). It was further corroborated by the results of Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002), which can measure HXR spectra with much higher resolution. Hudson & Farní (2002) illustrated the consistency of the SHS pattern derived using higher energy resolution RHESSI data (of order 1 keV) with that obtained with the HXRS scintillation-counter spectra. A systematic study by Grigis & Benz (2004) using RHESSI revealed that the SHS pattern appears even in subpeaks of HXR with durations of 1 minute to shorter than 8 s. With RHESSI’s capability of imaging spectroscopy, the study of SHS has been extended to spatially resolved HXR sources. Emslie et al. (2003) and Battaglia & Benz (2006) examined spectral evolution of both coronal and footpoint HXR sources in the course of flares and found that they commonly show the SHS behavior. On the basis of the results, they suggested that SHS can be an intrinsic feature of electron acceleration in the flare impulsive phase.

The SHS can also be regarded as a relation between the HXR spectral index and flux because the hardest spectrum usually appears in the period of maximum flux (Grigis & Benz 2006). As a possible extension of this relation to spatial characteristics, we may consider a spatial analog of the SHS pattern in which a stronger HXR region has a harder spectrum. Such an idea has been proposed in a couple of studies. For instance, Masuda et al. (2001) determined spectral index maps of an extended HXR event using Yohkoh data to find spectral hardening toward the ribbon edge where the most intense energy release is expected. Hudson et al. (2004) proposed that the regions of weaker HXR emission would correspond to softer HXR spectra, in an attempt to explain the footpoint-like HXR morphology in contrast with extensive ribbon structure seen at Hα and UV wavelengths. However, a more thorough examination will be needed to see whether the relation between the HXR flux and the spectral index in time can simply be transformed to such a spatial analog. This is one of the goals of this Letter that we intend to achieve using RHESSI imaging spectroscopy.

In addition to spectral evolution, the HXR flare ribbon motion can also manifest the progression of flare energy release due to magnetic reconnection. This was enabled after Forbes & Priest (1984) derived a relationship between the ribbon expansion velocity \(u\) and the electric field \(E\) in the reconnecting current sheet (RCS) in the form of \(E = uB\), where \(B\) is the local vertical magnetic field strength in the footpoint. It is important to have an indirect measurement of the electric field, because direct acceleration of electrons by the electric field is a candidate mechanism for creating high-energy electrons in flares (Litvinenko 1996). Some studies showed that there is a temporal correlation between the HXR flux and the electric field derived this way (e.g., Qiu et al. 2002). It is then of further interest whether there is not only a temporal but also a spatial correlation between the HXR spectral index and the electric field in the RCS. Recently, Wood & Neukirch (2005) presented a particle simulation with prescribed electric and magnetic fields, which shows a hardening of the electron energy spectrum with increasing electric field. Such a model prediction can be compared with the above mentioned measurements of the HXR spectrum and the electric field.

In this Letter, we investigate spatial distribution of the HXR spectrum and the electric field during the 2005 May 13 M8.0 flare. This is a particular event (Liu et al. 2007b) in which the HXR sources are so extended as to be suitable for the imaging spectroscopy and is thus adequate for studying the possible spatial relationship between the spectral index and the electric field.
spectral maps that provided the spectral index information in ribbon-like HXR event, in which Masuda et al. (2001) obtained such an attempt was also made for the only other reported index on the basis of the spectrum in each pixel. Previously, sources. We thus choose to measure the local HXR spectral explore the spatial variation of the spectral index inside the source is so compact as to be barely resolved. In our case, however, we study extended HXR sources, and our goal is to initially isolated sources (e.g., Emslie et al. 2003; Battaglia & such a way to determine the flux spectra integrated over spa-
spectroscopic result. For this moderate event, however, we still suffer from the trade-off between choosing finer energy/time bins and making better count statistics that is essential for imaging spectroscopy. We also found that natural weighting produces a more physically reason-
able single power law may not be good enough in all pixels. We ariwise as low as in the 9–12 keV band. We emphasize that the ribbon-like HXR sources are an intrinsic feature in this event, as evidenced by its fidelity to the UV ribbon emissions (Liu et al. 2007a; Dennis et al. 2007).

The emission at high energies (≥25 keV) is mainly from sources located in each side of the magnetic polarity inversion line (PIL) presumably from the footpoints of the flaring loops. A footpoint-to-ribbon transformation of the HXR morphology can be clearly seen across the peak of the HXRs at 16:42:04 UT. At lower energies, sources above the PIL become evident, and they could come from the tops of the loops joining the HXR footpoints and ribbons, while the footpoint emissions are still visible, as low as in the 9–12 keV band. We emphasize that the ribbon-like HXR sources are an intrinsic feature in this event, as evidenced by its fidelity to the UV ribbon emissions (Liu et al. 2007a; Dennis et al. 2007).

2. IMAGING SPECTROSCOPY

*RHESSI* imaging spectroscopy has thus far been made in such a way to determine the flux spectra integrated over spa-
tially isolated sources (e.g., Emslie et al. 2003; Battaglia & Benz 2006). This technique gives a viable result when the source is so compact as to be barely resolved. In our case, however, we study extended HXR sources, and our goal is to explore the spatial variation of the spectral index inside the sources. We thus choose to measure the local HXR spectral index on the basis of the spectrum in each pixel. Previously, such an attempt was also made for the only other reported ribbon-like HXR event, in which Masuda et al. (2001) obtained spectral maps that provided the spectral index information in each pixel, from the count ratio between the *Yohkoh* M2 and H bands. With *RHESSI*’s higher temporal and energy resolution as well as improved dynamic range, we expect a better imaging spectroscopic result. For this moderate event, however, we still suffer from the trade-off between choosing finer energy/time bins and making better images by accumulating for wider energy/time bins.

Most often, *RHESSI* imaging is made using the CLEAN algorithm with grids 3–9. Recently, Dennis et al. (2007) showed that adding grids 1 and 2 (the finest grids) can enhance the image quality depending on the source structure, and the ribbon-like HXR sources in this event is such a suitable case. We found that use of all grids not only improves the imaging quality compared with using grids 3–9 but also gives better count statistics that is essential for imaging spectroscopy. We also found that natural weighting produces a more physically reason-

We first make 128 × 128 pixels images with a pixel size of 1" for the five 1 minute intervals that cover the rise and decay phases of HXR (a–e as in Liu et al. 2007a, Fig. 1). Figure 1 shows the images in four energy bands from 9 to 100 keV.
Fig. 3.—Spatial distribution of HXR spectral index (black) in comparison with those of HXR flux in the 25–100 keV range (gray, upper panels) and electric field (gray, lower panels) in the five 1 minute time intervals, shown as functions of the ribbon distance. Depicted as the black line in Fig. 2, the index of the ribbon distance runs from 0 in the northern end to 99 in the southern end. The existence of break points in the profiles of spectral index indicates bad fittings at those locations.

Fig. 4.—Scatter plot of spectral index ($\gamma$) and HXR flux ($\log F$, upper panel), and spectral index and electric field ($\log E$, lower panel), measured at each indexed location along the ribbon for all the time intervals. Data points and best fits in linear-log space (solid lines) by minimizing the $\chi^2$ error statistic for different time intervals are represented with different colors.

We repeat the fitting procedure and obtain nearly identical spectral features.

3. RESULTS

Comparison of Figure 1 and Figure 2 reveals several characteristics. First, there are three major footpoint-like HXR emitting sources with hard spectra near the HXR peak at $\sim$16:42:04 UT, when the spectral index reaches a minimum value of $\sim$2.2. The averaged value of spectral index over the fittable pixels in the field of view is $\sim$3.3 at this time, which agrees with that derived using the OSPEX package for integrated X-ray emission. Earlier and later in the event, the overall spectrum of the flare region as well as those of the main HXR sources are seen to be much softer, with higher index values. This temporal evolution of the SHS pattern is thus what typically has been observed before (Battaglia & Benz 2006). Second, the main HXR sources show a spatial distribution of spectral index from the center with smaller value (harder spectrum) to the outer regions with larger value (steeper spectrum), which is most prominent near the HXR peak (see panel 16:41:34–16:42:34 UT). When the HXR sources evolve to a ribbon morphology later in the event (e.g., panel 16:43:34–16:44:34 UT), there are still kernels with harder spectra discernible, although the whole system has a much steeper spectrum compared with the flare peak.

As our major interest lies in how the physical quantities vary spatially, we make the comparison between the HXR spectral index and flux along the ribbon axis. Specifically, we measure the variation of spectral index along the eastern flare ribbon, where there is a clear footpoint-to-ribbon evolution of HXR morphology (cf. Fig. 1; also see Liu et al. 2007a). We trace out the spectral index and the flux in the 25–100 keV range using the same indexes of ribbon distance as defined by (specified in Fig. 2 as black line at each time interval) Jing et al. (2007) and present the results in the upper panels of Figure 3. It is obvious in each time interval that the HXR spectral index exhibits a strong spatial anticorrelation with the HXR flux ($\log F$), with absolute values of the correlation coefficient $\approx 0.8$. In the lower panels of Figure 3, we compare the spatial evolution of the HXR spectral index with that of the electric field ($\log E$) in the RCS, which was previously derived by tracing the Hα ribbon motion and incorporating the longitudinal magnetic field measurement (Jing et al. 2007). It can be seen that there also exists a prominent anticorrelation relationship between these two quantities, with absolute values of the correlation coefficient $\approx 0.65$.

Figure 4 shows the results in Figure 3 as scatter plots. The relationships between the spectral index and flux and the spectral index and the electric field are shown in the upper and lower panels, respectively. First, we can see without ambiguity that at a specific time, the source position with a weaker HXR emission (lower HXR flux) corresponds to steeper X-ray spectra and presumably to softer electron precipitation spectra. We therefore suggest that this anticorrelation between the HXR spectral index and flux is a spatial analog of the well-known temporal SHS pattern of HXR emission. Second, the anticor-
relation relationship between the spectral index and the electric field clearly points to a softer HXR spectrum in the case of a weaker electric field, consistent with the trend predicted by numerical simulation (Wood & Neukirch 2005). This result thus appears to support the hypothesis that direct acceleration by the electric field in the RCS may play an important role in producing energetic electrons in flares.

4. SUMMARY AND DISCUSSION

Exploiting RHESSI’s capability of imaging spectroscopy, we have determined the spectral index of the local photon spectrum in the unusually extended HXR source observed in the 2005 May 13 M8.0 flare. We then find a spatial anticorrelation relationship between both the local HXR flux and the electric field corresponding to the local HXR spectral index at several time intervals. We discuss the present results in comparison with similar works on solar HXR imaging spectroscopy.

The present approach is closest to that of Masuda et al. (2001), who used Yohkoh images at two energy bands to find a spectral index change across flare ribbons. In their result, the HXR spectrum at the outer edge of the ribbon is found to be harder than in other regions of the ribbon, and the hardness of the spectrum gradually changes across the ribbon width. This is consistent with the physical picture that the ribbon edge is connected to the most recently reconnected field lines and thus shows the most energetic electrons. The present study shows a similar result with more spatial details. It clearly shows the hardest HXR sources lying along the edge of flare ribbon in UV (cf. our Fig. 2 and Fig. 2 of Liu et al. 2007a) and a smooth transition of spectral index across the HXR sources. In particular, we find that the HXR spectral index exhibits a strong spatial anticorrelation with the HXR flux in all time intervals during the flare impulsive phase. We call this spatial SHS behavior in analogy with the well-known temporal SHS pattern of integrated HXR flux. The spatial SHS may also be an essential feature of solar flare electron acceleration and may help to explain the confined nature of HXR sources compared with extended Hα and UV ribbons (cf. Hudson et al. 2004).

We must note that the spatial SHS implies a more strict relationship between the HXR flux and the spectral index than that found in the previous RHESSI studies on the temporal SHS behavior in individual sources (Emslie et al. 2003; Battaglia & Benz 2006). In the latter results, each isolated source exhibits the temporal SHS pattern independent of each other, and thus the normalization of the flux–spectral index relation ($F$–$\delta$ relation) may differ from one source to another. On the other hand, our spatial SHS implies that the same normalization of the $F$–$\delta$ relation should hold in all regions. A major difference between those works and ours is that our spatial SHS refers to correlations among local subregions within one footpoint side of the magnetic arcade, whereas Emslie et al. (2003) and Battaglia & Benz (2006) compared spectra integrated over individual footpoint sources. We suspect that almost all local regions in this event were subject to a common acceleration and transport process to share the same $F$–$\delta$ relation. For this reason, we do not believe that our result is in conflict with the previous results.

An entirely new result in this study is the spatial anticorrelation between the HXR spectral index and the electric field in the RCS. This property was found because we could measure both the spectral index and the electric field as functions of position within an extended HXR ribbon. As a comparison, we note that the numerical simulation for the direct electric field acceleration of electrons predicted electron energy distribution with power-law indexes $\delta = 4.0, 2.6,$ and $1.5$ for electric field strengths $E = 0.1, 1.0,$ and $10 \text{ V cm}^{-1},$ respectively (Wood & Neukirch 2005). We are not sure how to convert this electron power-law index $\delta$ into the observed photon spectral index $\gamma$, because further assumptions need to be made about the nature of the numerical solutions and the radiation. Within the scope of this Letter, we note that there is a qualitative agreement between our observational result (Fig. 4) and the model result (Wood & Neukirch 2005), in that both indicate a hardening of electron energy distribution with increasing electric field strength. It appears that the present result suggests the dominance of direct electric field acceleration of flare electrons. It does not, however, exclude other possibilities. As discussed by Hudson & Färnık (2002), an explicit theoretical demonstration of the SHS behavior under the framework of the thick-target model can be made with the stochastic acceleration mechanism discussed by Benz (1977). As an alternative, it is still possible that the efficient electron acceleration is confined in the regions of strong HXR flux and the weaker HXR flux regions nearby result from some propagation effect. A more systematic survey of the relationship between these two physical quantities, both temporally and spatially, will be needed in order to ascertain such an association under the context of electron acceleration mechanism.

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