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A STATISTICAL STUDY OF RHESSI FLARES

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Abstract. A statistical analysis of RHESSI X-ray flares in the 12–25 keV band during the period from February 2002 to June 2005 is presented. We found that a power-law with an index of 1.80 ± 0.02 can fit well the frequency distribution of the peak count rates. This power-law does not change significantly with time. However, the frequency distribution of the flare durations cannot be fitted well by a single power-law. There is a weak correlation between the peak count rates and the characteristic times like rise times, decay times, or durations. But the correlation between the rise times and decay times seems to be strong. We discuss the results obtained and compare them with previous works. The frequency distribution of rise times for the sub-group events with a similar magnitude of peak count rates is also shown. In particular, we propose a new parameter R_a, the growth factor of the count rate, defined as the peak count rate divided by the rise time, to reflect the characteristics of the rising phases of flares. The distribution of R_a is shown and discussed.

1. Introduction

Solar flares are one of the most powerful phenomena on the Sun. The flare soft X-rays (SXR) usually result from thermal radiation, while the hard X-rays (HXR) originate from electron-ion bremsstrahlung radiation produced by energetic electrons. Statistical analysis of flare X-rays is therefore important for understanding the mechanism of the energy release process, the flare system behavior, the relation between thermal and nonthermal radiation, the coronal heating problem, and flare predictions.

Crosby, Aschwanden, and Dennis (1993) and Aschwanden, Dennis, and Benz (1998) have pointed out that the frequency distributions of most flare-associated activities such as radio bursts, soft X-rays, hard X-rays, interplanetary type III bursts, and interplanetary particle events can be represented by a power-law of

$$dN = Ax^{-\alpha}dx$$

above a certain threshold (often attributed to the sensitivity of the observations), where dN denotes the number of events recorded with the parameter x in the interval $[x, x + dx]$, A and α are constants, which can be determined from a fit to the data. Hudson (1991) showed that for an indicator x of event energy, if $\alpha < 2$, large events dominate the total power of the distribution and nanoflares cannot contribute much. Otherwise, if $\alpha \geq 2$, the more numerous small-scale events may provide enough energy for coronal heating. However, the energy is not an observable quantity and most of the research is based on the distributions of peak flux or peak count rate.

There have been many statistical works both in HXR and SXR. Over 30 years ago, Drake (1971) first analyzed the SXR flares measured in the 2–12 Å range from Explorer 33 and 35 and found $\alpha = 1.75 \pm 0.10$ for the peak flux distribution. Dennis (1985) and Crosby *et al.* (1998) summarized α for the distributions of different flare-related parameters stating that it varies from 1.4 to 2.4. The early statistical results are consistent with the two main statistical flare models: the stochastic relaxation model (Rosner and Vaiana, 1978) and the avalanche model (Lu and Hamilton, 1991; Lu *et al.*, 1993). However, the absence of a correlation between the strength of a flare and the elapsed time since the previous event supports the avalanche model (Crosby *et al.*, 1998; Wheatland, 2000b). The power-law distributions indicate that the flare system acts like a self-organized critical (SOC, also known as 'avalanche concept') system, and the power-law index should not change over the solar cycle according to the avalanche model, in which a solar flare is considered as an avalanche of many small reconnection events (Lu and Hamilton, 1991). Some authors provided supportive evidence from observations (Dennis, 1985; Veronig *et al.*, 2002), while others obtained contrary results (Bai, 1993; Bai, 2006).

The recent statistical studies in HXR and SXR were based on the data from ISEE-3/ICE, WATCH/GRANAT, and GOES. Bromund, McTiernan, and Kane (1995) analyzed the data above 30 keV observed from 1978 to 1986 by ISEE-3/ICE, and obtained $\alpha = 1.86 \pm 0.01$ for the peak photon flux distribution and $\alpha = 2.40 \pm 0.04$ for the duration distribution. In the soft X-ray wave band, Lee, Petrosian, and McTiernan (1995) found $\alpha = 1.86 \pm 0.10$ for the frequency distribution of peak flux of GOES flares that correspond to hard X-ray flares and found that the slopes for the soft X-ray peak flux and the hard X-ray fluence distribution are different. They concluded that other heating mechanisms than accelerated electrons are necessary to explain the observations. Feldman, Doschek, and Klimchuk (1997) obtained $\alpha = 1.88 \pm 0.21$ for the peak flux distribution of GOES flares from 1993 to 1995. Veronig *et al.* (2002) analyzed over 50 000 GOES flares observed between 1976 and 2000 and found that both the frequency distribution of peak fluxes and durations could be fitted by a single power-law of $\alpha = 2.11 \pm 0.13$ and 2.93 ± 0.12, respectively.

Besides, Wheatland, Sturrock, and McTiernan (1998) and Wheatland and Litvinenko (2002) studied the flare waiting-time distribution (WTD). Wheatland (2000a) also found that the distribution of flare peak count rates from the same active region is also a single power-law.

However, for the deka-keV energy band, much less statistical research has been done. By analyzing 10–30 keV data of 1537 flares observed from 1990 to 1992 by WATCH/GRANAT, Crosby *et al.* (1998) found $\alpha = 1.58 \pm 0.02$ for the frequency distribution of the peak count rates and that α was smaller for the short duration sub-group events than that for the long duration sub-group events. The frequency distribution of flare durations they obtained cannot be fitted well by a single power-law. These results seem to support the avalanche model (Crosby *et al.*, 1998). Furthermore, Crosby *et al.* (1998) found that the radiation around 10 keV contains not only thermal radiation but also a hotter component or a nonthermal population. Lin, Feffer, and Schwartz (2001) found nonthermal electrons down to 8 keV. We also found some flares in which the 12–25 keV band has a nonthermal property. Therefore, the deka-keV energy band, which is one of the least studied energy ranges for solar purposes (Crosby *et al.*, 1998), contains information of both thermal and nonthermal radiation.

Why then is the distribution of durations in deka-keV different from that in other energy bands? Is it an instrumental effect or a real phenomenon? Does the power-law index change with the phase of solar cycle? So far, we have not seen any detailed statistical study based on the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) data. Here, we present a statistical analysis in 12–25 keV, the first using RHESSI data, including the frequency distributions of peak count rates and for different years, durations, as well as correlation diagnostics among different flare parameters. Also, we propose a new parameter R_a (the growth factors of count rates that is the peak count rate divided by the rise time) to reflect the different process during the rising phases of flares. The results are shown and discussed in Section 3, and the summary is given in Section 4.

2. Data Selection and Reduction

RHESSI was launched on February 5, 2002. It provides the first high-resolution hard X-ray imaging spectroscopy, the first high-resolution gamma-ray line spectroscopy, and the first imaging above 100 keV including the first imaging of γ-ray lines. The spatial resolution is as fine as $\sim$2.3 arcsec with a full-Sun field of view, and the spectral resolution is $\sim$1–10 keV FWHM over the energy range from soft X-rays (3 keV) to gamma-rays (17 MeV) (Lin *et al.*, 2002). By 2005, more than 16 000 events have been recorded in the RHESSI Flare list, which provides the possibility for a detailed statistical study.

The flare list data in the RHESSI homepage are deduced from the 12 to 25 keV energy band, including the start time, end time, peak time, and peak count rate. The definition of a flare occurrence is that the count rate must be above 3σ of background level. The flare parameters we use in this paper are taken directly from the RHESSI flare list. All the results in this paper are based on 12–25 keV data.

Since RHESSI uses attenuators to reduce the count rate to keep the detectors from being saturated when intense flares occur (Smith *et al.*, 2002), the direct comparison of the peak count rates among flares with different state of attenuators has no meaning. Thus, the peak count rates of all the flares should be corrected to the same state. Considering that to dispose each flare is too time consuming, we use a simple method to convert the peak count rates to the same state with no attenuators (att0). From the data in the RHESSI flare list, we obtained the observed peak count rates, then multiplied them by their corresponding conversion coefficient (1, att10, att30) according to the state (att0, att1, att3) at the peak time. Empirically, the average conversion coefficient is 8.2 for state att1 to att0 and 70.6 for att3 to att0.

The data collected covers the period from February 2002 to June 2005. For selection criteria, we first removed nonsolar events and selected events with no SAA and no particles. We require the time structure to be complete. Some events recorded in the flare list have two or even more main peaks that may belong to different flares. Some others have flat and long-duration main peaks. The peak time for these events may have no actual meaning in our study. Therefore, we removed these events and the events with peak count rates smaller than $16\,\mathrm{c\,s^{-1}\,detector^{-1}}$.

In the process of sample selections, we noticed a lot of events with a very short duration and low count rate, most of which have no corresponding obvious GOES SXR enhancement. Some of these events last for even less than 20 s. We kept most of these events except those whose time structures were not clear. We think that these short-time events may be related to microflares and nanoflares.

Finally, we collected a sample of 2759 events. Among these events, there are only 131 events that have obvious enhancement above 25 keV. We referred to these events as F_{25} flares in following sections. Most of these F_{25} flares should be nonthermal flares. Though some flares with no emission above 25 keV may be thermal, they do not influence our results.

3. Statistical Results and Discussion

3.1. The Frequency Distribution of the Peak Count Rates

After Veronig *et al.* (2002) we obtained α from the linear fitting with a constant bin size in log–log space. We assumed that the uncertainties are the same. Figure 1 shows the frequency distribution of the peak count rates of all flares, with a best fitting power-law of $\alpha = 1.87 \pm 0.04$ over 3 orders of magnitude of the peak count rates. The fitting range is determined from Figure 1. Following Bai (1993), we also used the maximum-likelihood method, which does not involve binning of the data, and found $\alpha = 1.80 \pm 0.02$ for the best fitting, with the threshold $400.0\,\mathrm{c\,s^{-1}}$.

This result is consistent with most previous results, such as $\alpha = 1.8 \pm 0.1$ based on the data of HXRBS/SMM by Pearce, Rowe, and Yeung (1993); $\alpha = 1.86 \pm 0.01$ based on the data of ISEE-3/ICE by Bromund, McTiernan, and Kane (1995); $\alpha = 1.86 \pm 0.10$ based on the data of GOES flares that have a corresponding hard X-ray emission (Lee, Petrosian, and McTiernan, 1995); $\alpha = 1.88 \pm 0.21$ based on the data of GOES 1993–1995 flares by Feldman, Doschek, and Klimchuk (1997). Some other authors obtained either smaller or bigger values of α, as shown in the introduction. The α we found is larger than that from Crosby *et al.* (1998) by

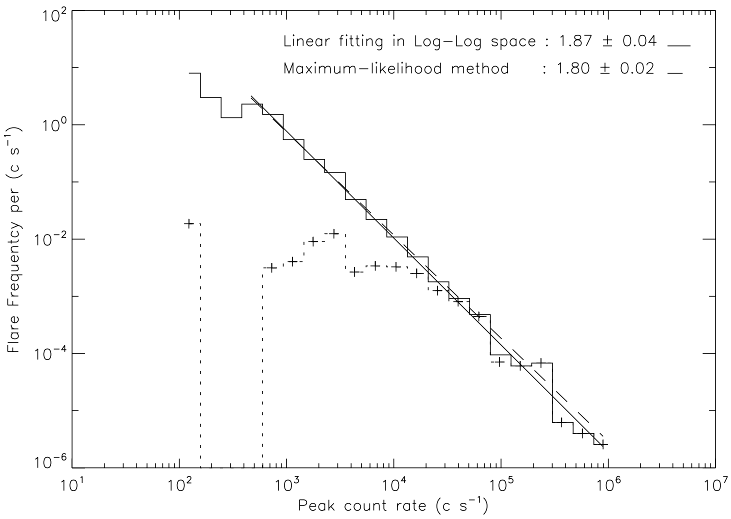

Figure 1. The frequency distribution of the RHESSI flare peak count rates (*full line*). The *dotted line* is the frequency distribution of F_{25} flares.

0.14. A possible reason may be that our selection criteria resulted in the lack of long-duration flares, some of which have large peak count rates.

The dotted line in Figure 1 is the frequency distribution of F_{25} flares. It is clear that the number of F_{25} flares dominate the distribution above 10^4 c s^{-1}. In general, the emission above 25 keV is of nonthermal origin. The two distributions suggest that the large peak count rates in 12–25 keV of intense flares may be due to emission from nonthermal bremsstrahlung or/and effective heating resulting from nonthermal electrons. Thus, the higher end of the distribution may reflect contributions from mainly nonthermal flares.

Differing from previous results, the distribution at the lower end of the peak count rates does not drop so much in comparison to the extension of the power-law. We think that this is due to the different detection capability from the previous detectors. As described in Section 2, we kept most of the flares with low peak count rates and short durations. If the capability of detection were further enhanced, the number of this part would be even greater.

Figure 2 shows the frequency distribution of the peak count rates of flares in 2002, 2003, and 2004. The α obtained with the maximum-likelihood method with the threshold 400.0 c s^{-1} for the three years (1.80 ± 0.02, 1.82 ± 0.06, 1.80 ± 0.07, respectively) does not show a remarkable change, although the total number of flares in each year differs greatly. This is consistent with the statistical results from Veronig *et al*. (2002), Dennis (1985), Nita *et al.* (2002), and the predictions of avalanche flare models.

However, the slight change of α has been noticed by Bai (1993), who found that the size distribution is steeper during the maximum years of solar cycle 21 (1980

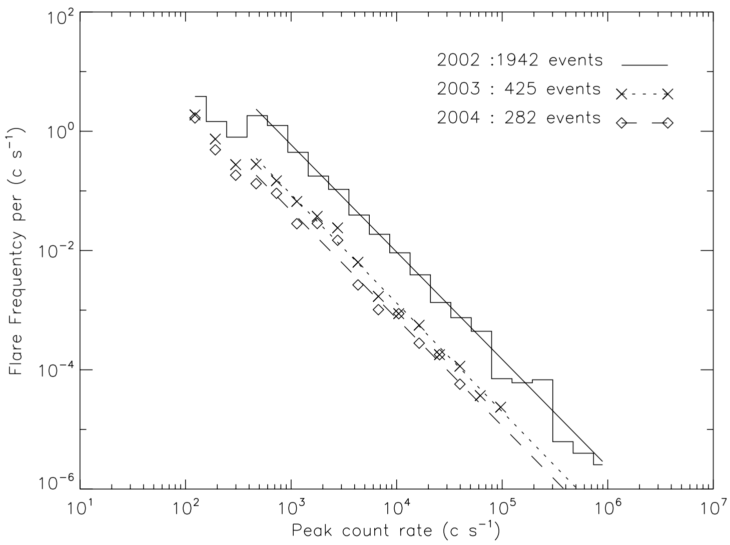

Figure 2. The frequency distribution of the peak count rates of flares in the years 2002, 2003, and 2004.

and 1981) than during the declining phase (1982–1984). Our result is different from the result of Bai (2006), who found the distribution of flare sizes measured in GOES classes for 2003 and 2004 was much harder than those for the maximum years and all preceding years. If the index does change, it means other underlying cause than energy release in magnetic configurations in self-organized critical states (Bai, 1993). More data and improved analysis is expected in the future.

It is evident from Figure 2 that the number of flares with low peak count rates is below the power-law in 2002, while close to the power-law in 2003 and 2004. A possible reason may be that the background X-ray radiation in 2002 is higher than in the other two years, increasing the difficulty of detection of flares with low count rates.

3.2. The frequency distribution of the durations

The frequency distribution of RHESSI flare durations, which can not be fitted well with a single power-law, is shown in Figure 3. This is consistent with the statistical result by Crosby *et al.* (1998), who suggested that this distribution may indicate a limit to the duration of a flare, above which the dynamic evolution of the system is no longer governed by a self-organized behavior. However, our selection criterion may be another reason resulting in this distribution, since long-duration events are easily excluded due to the incomplete time coverage by the satellite nights, particles, and SAA. Therefore, even if the real distribution is a power-law, this selective effect would lead to deviation from a power-law.

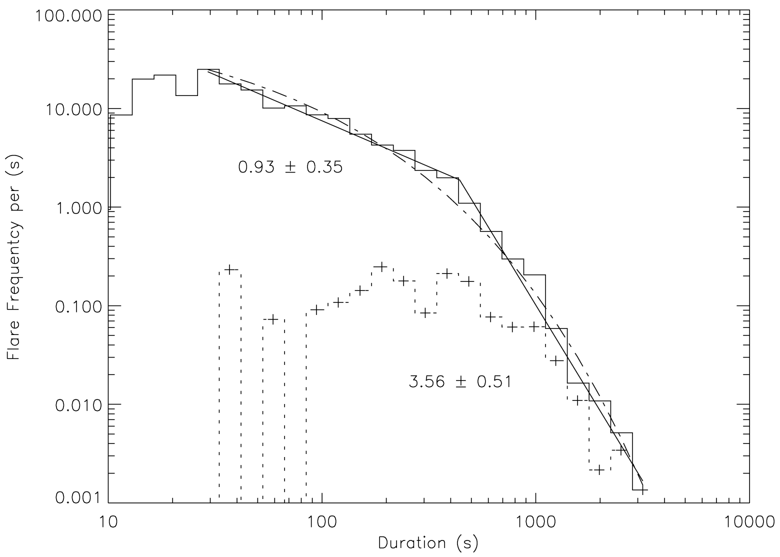

Figure 3. The frequency distribution of the RHESSI flare durations, with a fitting by either two power-laws or an exponential function (*dash-dotted line*). The *dotted line* indicates the frequency distribution of the F_{25} flare durations. The break point is at 440.6 ± 142.5 s.

Considering that the duration distributions of the SXR or HXR flares detected by some other instruments can be fitted with a single power-law, (for example, $\alpha = 2.40$, 2.17, 2.93 for ISEE-3/ICE (Bromund, McTiernan, and Kane, 1995), HXRBS/SMM (Crosby, Aschwanden, and Dennis, 1993), and GOES (Veronig *et al.*, 2002), respectively) and that the α deduced from SXR seems to be different from that from HXR, we think that both thermal and nonthermal components in 12–25 keV provide an alterative explanation for the nonsingle power-law of the duration distribution obtained here. The difference between the distribution of durations for 12–25 keV and that for other bands in X-rays is a physical phenomenon.

3.3. Correlation among flare parameters

We define rise time as the time interval between the start time and the peak time, decay time as the time interval between the peak time and the end time, and duration as sum of the rise time and the decay time. Then the relation between the characteristic times and the peak count rates is shown in Figure 4. The logarithmic slopes and correlation coefficients are 0.32 and 0.41; 0.29 and 0.37; 0.35 and 0.40, respectively. These correlation coefficients are lower than 0.61, 0.50, and 0.62 deduced from WATCH/GRANAT data by Crosby *et al.* (1998) and higher than those deduced from GOES data (about 0.25) by Veronig *et al.* (2002). Our result indicates a low correlation between the characteristic times and the peak count rate.

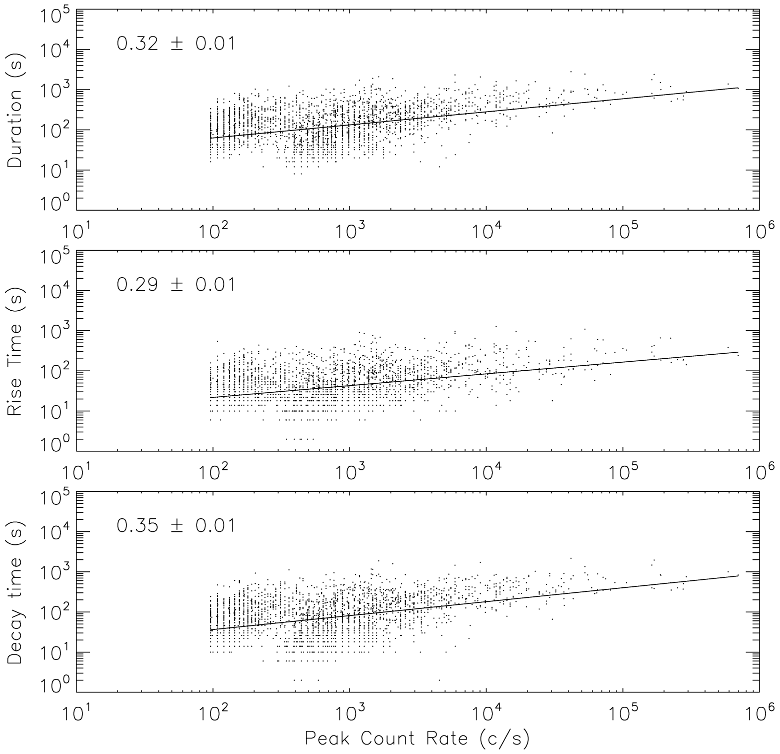

Figure 4. Scatter plots of the duration, rise time, and decay time as a function of the peak count rates. The fitted slopes in log–log space are 0.32, 0.29, 0.35 and correlation coefficients 0.41, 0.37, 0.40, respectively.

Figure 5 shows the scatter plots between the decay time and the rise time. The correlation coefficient is 0.76. The crosses in the figure indicate the flares with peak count rate larger than 60 000 c s^{-1}, and the triangles indicate the flares with peak count rate less than 180 c s^{-1}. From Figure 5, we see that large flares and small flares may have similar time structure (time parameters) in 12–25 keV.

3.4. The frequency distribution of parameters in the rising phase

We furthermore selected two sub-groups of events with different magnitudes of peak count rates to compare the distributions of rise times. Figure 6 shows the frequency distributions of the rise times for the two groups. It is clear that the rise times are distributed over 2 orders of magnitude for each group. For flares in each group, the different rise times may reflect the different time scales and processes in the rising phases. However, for flares in different groups (i.e., flares with different sizes), the rise time may not be a good parameter to reflect the different process in the rising phases, since flares with different sizes may have a similar rise time (as

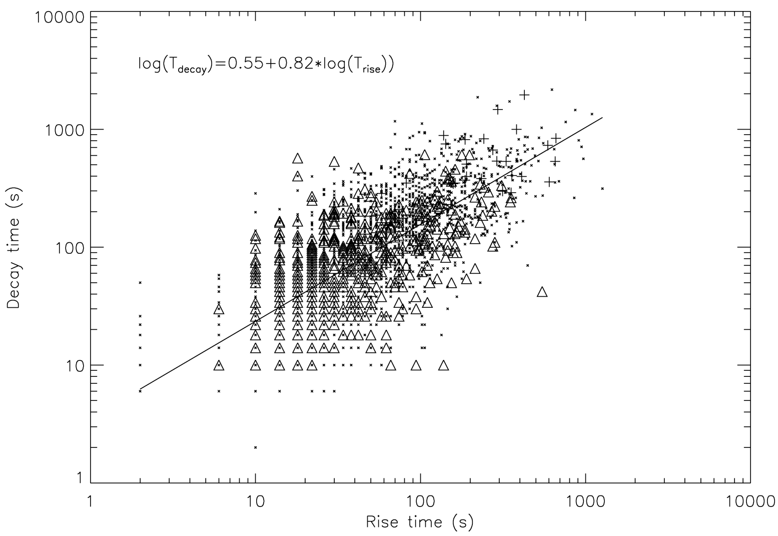

Figure 5. Scatter plots between the decay time and the rise time with a linearly fitted slope of 0.82. The logarithmic correlation coefficient is 0.76. The *crosses* indicate the flares with peak count rate larger than 60 000 c s^{-1}, the *triangles* indicate the flares with peak count rate less than 180 c s^{-1}, and the $\times$ symbols indicate intermediate flares.

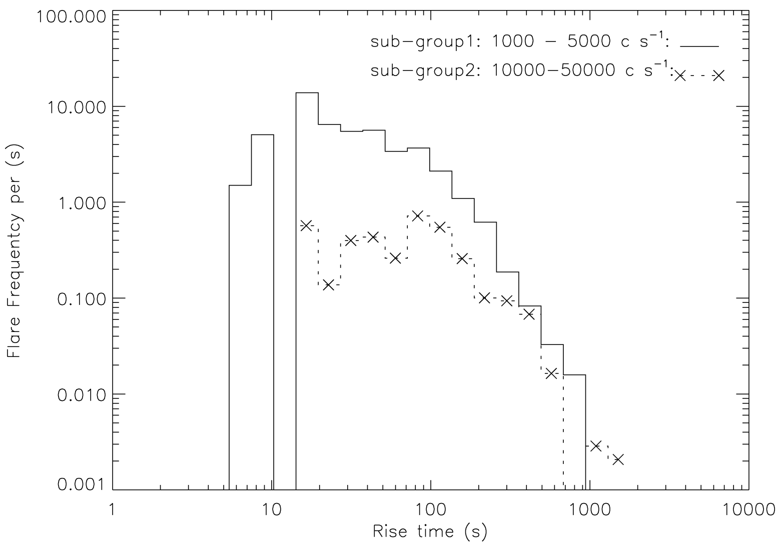

Figure 6. The frequency distributions of the rise times for the sub-group events with a similar magnitude of peak count rates.

shown in Figures 5 and 6). Here we propose a new parameter to reflect the different process during the rising phases of all flares.

By simply dividing the peak count rate by rise time, we obtain the growth factor of count rates R_a for each flare. If we assume that the 12–25 keV contains only thermal

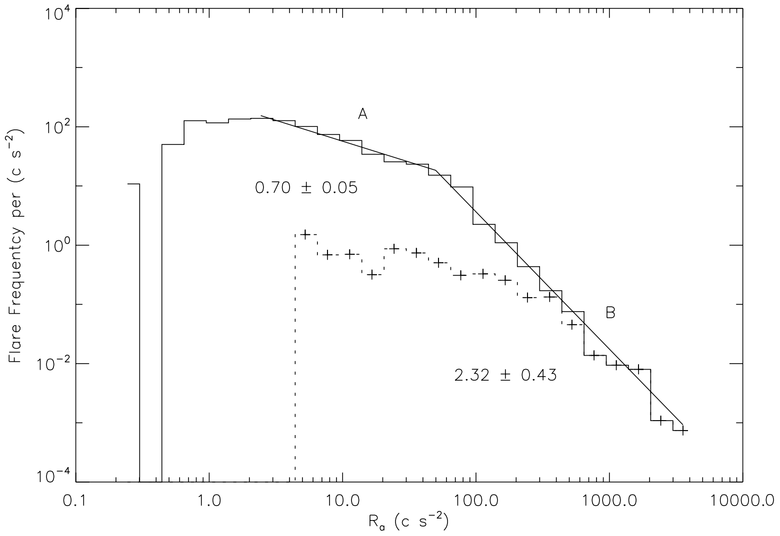

Figure 7. The frequency distribution of R_a with two power-law fits. The *dotted line* shows the distribution of R_a for the F_{25} flares.

radiation, then R_a would indicate an average nonthermal emission rate, according to the Neupert effect. Then as a parameter of a self-organized critical system, R_a might be expected to present a single power-law distribution like the distributions of HXR peak count rate and peak flux. However, Figure 7 shows clearly two power-law distributions of R_a above a certain threshold. The break point is at $49.8 \pm 8.0\,\mathrm{c\,s^{-2}}$. It may suggest that nonthermal radiation also exists in 12–25 keV. As R_a increases, the F_{25} flares dominate the distribution of R_a (part B). Of the total 131 F_{25} flares, about 78% are in part B of Figure 7. Therefore, based on the discussions in Section 3.1, we think that the large value of R_a, which may be the result of the bremsstrahlung radiation from electrons and the thermal radiation from plasma heated by the electrons, corresponds mostly to nonthermal flares, i.e., part B is dominated by nonthermal flares. In contrast, part A might be dominated by thermal flares.

Flares with same value of R_a may have the same heating process, despite their different sizes and rise times. The distribution at about 1.0 and below $1.0\,\mathrm{c\,s^{-2}}$ may be related to a very slow energy release process. The parameter R_a seems to be a better parameter than rise time to reflect the different processes during the rising phases of flares. Further study of the distribution of R_a using SXR and HXR data would be an interesting work.

4. Summary

Using 12–25 keV data observed with RHESSI from February 2002 to June 2005, we made a statistical study of the distributions of flare parameters and of the relations between parameters. The frequency distribution of the peak count rates can be well fitted by a single power-law with $\alpha = 1.80 \pm 0.02$. The frequency distribution of the duration cannot be fitted by a single power-law. A weak correlation of about 0.4 is found between the peak count rates and the characteristic times (rise time, decay time, and duration), but the correlation between rise time and decay time is higher, up to about 0.76.

We did not find any significant change of the power-law index of the frequency distribution of the peak count rates for different years. The difference between the distribution of durations for 12–25 keV and that for other bands in X-rays is a physical phenomenon. The fact that 12–25 keV contains both thermal and nonthermal components should be the reason.

Furthermore, we found that the rise times for the sub-group events with a similar magnitude of peak count rates are in a wide range of over 2 orders of magnitude. By simply dividing the peak count rate by rise time, we propose a new parameter R_a that is better than rise time to reflect the different processes during the rising phases of flares. The distribution of R_a clearly shows two power-laws. The indices of the two power-laws are 0.70 ± 0.05 and 2.32 ± 0.43, respectively, and the break point of R_a is $49.8 \pm 8.0\,\mathrm{c\,s^{-2}}$. The higher end of the distribution is dominated by nonthermal flares.

In the process of sample selection, we found lots of short-duration flares with low peak count rates. As shown in Figure 1, some of them even have enhanced radiation above 25 keV. These events may be associated with miroflares and nanoflares. However, we found that most of the sample events have no radiation enhancement above 25 keV. On the basis of the statistical results in this paper, further studies are expected to make full use of the imaging capability of RHESSI.

Acknowledgments

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