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On the Lower Energy Cutoff of Nonthermal Electrons in Solar Flares

Wei-Qun Gan *, You-Ping Li and Jin Chang

Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008
National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012

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Abstract A quantitative method to determine the lower energy cutoff (E_c) of power-law electron beams is established. We apply this method to the 54 hard X-ray events observed with BATSE/Compton Gamma Ray Observatory (CGRO). The results show that about 75% of the observed broken double power-law spectra of hard X-rays can be explained by a lower energy cutoff in the power-law electron beams. The values of E_c, varying among the flares, are all greater than the usually accepted 20 keV! On average, E_c is about 69 keV. So high a lower energy cutoff of nonthermal electrons implies that nonthermal electrons might not be as important in powering solar flares as was previously thought. Further significance of this finding is discussed.

Key words: Sun: hard X-rays – Sun: gamma-rays – Sun: flares – Sun: particles

1 INTRODUCTION

The lower energy cutoff of nonthermal electron beams is an important quantity. Not only is it related to the acceleration mechanism, but it also determines the total number of accelerated electrons and the energy they carry. The power-law of electron beams cannot extend to lower energies indefinitely, for if it did, it would imply an indefinitely large number of electrons. A lower energy cutoff (E_c), therefore, must exist, to keep the number of electrons within a reasonable range. For quite a long time, it seems to be known that a sudden cutoff at the lower energy end of nonthermal electrons may result in the flattening towards the lower energy of hard X-ray spectra (e.g., Dennis 1988). The fact that the broken energy of hard X-ray spectrum (ϵ_b) is smaller than E_c seems to be also known (e.g., Nitta, Dennis, & Kiplinger 1990). But, to our knowledge, we have not seen any detailed quantitative studies, especially on how to determine the lower energy cutoff from the observations. Usually, one assumes the E_c to be 20 keV or 25 keV in practice. Such an assumption constitutes a main ingredient of the so-called standard picture of solar flare: first the flare accelerates electrons; the accelerated electrons, producing hard X-rays when penetrating into the deeper layers, release most of their energy and heat up

* E-mail: wqgan@pmo.ac.cn

the atmosphere, resulting in a series of phenomena consequent on solar flares, like chromospheric evaporation and Hα emission. The key of this picture is that the total energy carried by the electrons is substantial in powering a solar flare. However, the total energy carried by electrons depends closely on the E_c. Gan, Chang & Li (2001), based on theoretical calculations of hard X-ray spectra, proposed a quantitative method, with which one can easily get E_c from the hard X-ray spectral observations. In this paper, we briefly introduce that method while paying more attention to its applications. The conclusions of this paper will greatly complement those obtained previously by Gan et al. (2001).

2 METHOD

We consider two cases of describing the power-law electron spectrum. Case 1 has a sharp cutoff at the lower energy end

$$F(E_0) = \begin{cases} AE_0^{-\delta} & E_0 > E_c, \\ 0 & E_0 \leq E_c, \end{cases} \tag{1}$$

and case 2, which we call a saturation form

$$F(E_0) = \begin{cases} AE_0^{-\delta} & E_0 > E_c, \\ AE_c^{-\delta} & E_0 \leq E_c. \end{cases} \tag{2}$$

Although these two distributions are rather idealised, they may be representative to some degree, and the actual distribution of electrons below E_c may probably be intermediate between the two. Gan et al. (2001), by using the thick-target bremsstrahlung formula (Brown 1971; Tandberg-Hansen & Emslie 1988), studied the hard X-ray spectra resulting from a power-law distribution of electrons with a lower energy cutoff in the form of either (1) or (2). They found that for photon energy ϵ greater than E_c, the hard X-ray spectrum presents a usual power-law form with a spectral index δ-1. But for ϵ smaller than E_c, the hard X-ray spectrum flattens towards the lower energies. The degree of the flattening depends on the electron power-law index δ. If we use a double power-law to simulate the calculated hard X-ray spectrum

$$I(\epsilon) = \begin{cases} a\,\epsilon^{-\gamma_1} & \epsilon < \epsilon_b, \\ b\,\epsilon^{-\gamma_2} & \epsilon \geq \epsilon_b, \end{cases} \tag{3}$$

we may establish a theoretical relationship between γ_1 and γ_2 (as shown in Fig. 1) as well as one between ϵ_b and γ_2 (Gan et al. 2001). The significance of these relationships is that if the observed hard X-ray spectrum can be simulated with a broken-down double power-law, and the two power-law spectral indices satisfy the relationship shown in Figure 1, it implies that the observed hard X-rays can be explained by a power-law spectrum of electrons with a lower energy cutoff; then from the relationship between ϵ_b and γ_2 (Gan et al. 2001), one can further get the E_c. Therefore, we have established a quantitative method to deduce the E_c directly from the hard X-ray observations.

3 APPLICATIONS

In order to compare the observations with the curves in Figure 1, we consider BATSE/CGRO hard X-ray events. Gan et al. (2001) studied 14 suitable hard X-ray events among the observations covering from 2000 March 1 to 2000 April 30. Here we scanned the events observed from

1998 January to 2000 May and got 54 suitable hard X-ray events. The so-called suitable sample should have a perfect single-peak in its light curve, in order to exclude (hopefully) possible effects of multisources on the spectrum. That is, in our samples, there is only a single source or a single acceleration region playing a role in the flare. In such samples, the hard X-ray spectrum would properly reflect the spectrum of a beam of nonthermal electrons. Another criterion for the selection is that the count rate be moderate, not larger than $5\times10^4\,\mathrm{s}^{-1}$, where the pile-up effect may appear, and not too small to cover enough energy channels. Still another criterion for the selection is that the peaks in different energy channels be simultaneous, in order to exclude any effect of transportation. With these preconditions, the hard X-ray spectrum of selected samples are expected to correctly reflect the spectrum of a beam of accelerated electrons. We use the standard spectral analysis software in SSW to simulate the observed hard X-ray spectra. Table 1 lists the 54 flares and their fitted parameters with the two power-law spectra. For each flare, we fitted the spectrum only at the time of peak flux. In Figure 1 the fitted data are plotted in comparison with the theoretical curves. From the figure we can see that quite a number of observed broken-down hard X-ray spectra are close to either curve 1 or curve 2, implying that this kind of hard X-ray spectra can be explained by a power-law electrons with a lower energy cutoff.

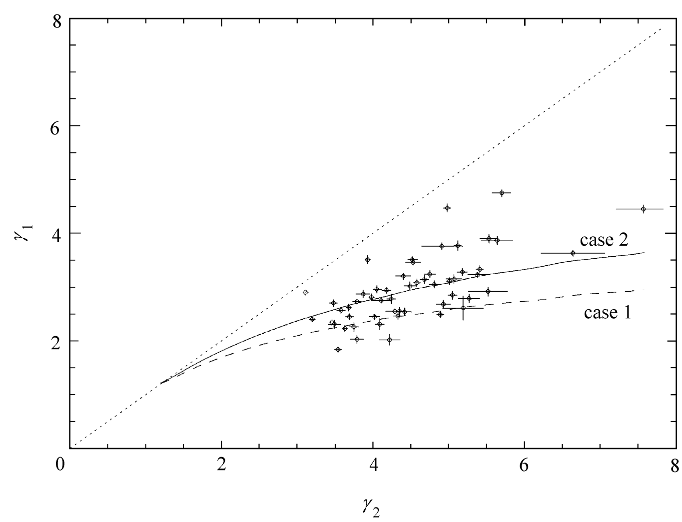

Fig. 1 Fitted double power-law indices (γ_1 vs. γ_s) for the calculated hard X-ray spectra emitted by a beam of power-law electrons with a sharp lower energy cutoff (case 1, dashed line) and with a saturation flux below a cutoff (case 2, solid line). The points with error bars are the fitted double power-law indices for the observed hard X-ray spectra of the 54 BATSE/CGRO events. The dotted line represents a single power-law.

4 DISCUSSION

The 54 hard X-ray events in Table 1 all have broken-down spectra, although there are 3∼4 events which present an almost single power-law spectrum. What we should emphasize is that we have never taken the spectrum into account in the selection of our samples. This leads to a conclusion that the broken-down spectrum is universal as regards the hard X-ray spectrum at its peak time.

But from Figure 1, we see that not every observed points are close to the curves. After deleting the events which deviate more than 10% from the curves, we have about 40 events whose hard X-ray spectra can be explained by the electron spectrum either in the form of Equation (1) or Equation (2). That is, in a total of 54 samples, about 75% events can be explained by a power-law electron beam with a lower energy cutoff. This result demonstrates that nature favours the broken-down hard X-ray spectrum.

The cases of the deviating points in Figure 1 should be separately studied. For the points which are close to a single power-law, the E_c may be smaller than 40 keV, correspondingly the ϵ_b may be at around or smaller than 30 keV. This energy range is beyond the capability of the BATSE/CGRO. This explanation is also suitable for the other points obviously above the curve 2. If this explanation is correct, then the usually taken value of E_c=20∼25 keV applies to at most 20% of the whole sample. We therefore draw another conclusion that the E_c=20∼25 keV is not favoured at all. A more elaborate conclusion should be based on the observations with a higher energy resolution at the lower energies.

There are three points which lie obviously below the curve 1. This phenomenon is hard to understand, since in principle Equation (1) sets a lower limit for hard X-ray emissions below E_c. One possible explanation is that a double power-law is not suitable to simulate the hard X-ray spectrum of this kind of events. The electron spectrum may not be a power-law. Anyway, this kind of events account for only 5% of the total sample.

Most of hard X-ray spectra can be explained by a power-law electron beam with a lower energy cutoff. The double power-law broken energy ϵ_b and the deduced E_c are listed in Table 1. We see from the table that E_c, varying from 47 to 145 keV, is on average 69 keV. Figure 2 shows the number distribution of the E_c. Below 40 keV, as we discussed above, while representatives exist, the proportion is small. Between 47 keV and 60 keV, the proportion is more than 50%. A high value of E_c means that the total energy carried by the electrons will significantly decrease. Taking the averaged E_c and averaged spectral index as an example, the total energy carried by nonthermal electrons is about two orders of magnitude lower than that derived by taking E_c=20 keV. This result is in conflict with the so-called standard solar flare picture as mentioned before. The key is that the original energy balance is broken if a high E_c exists.

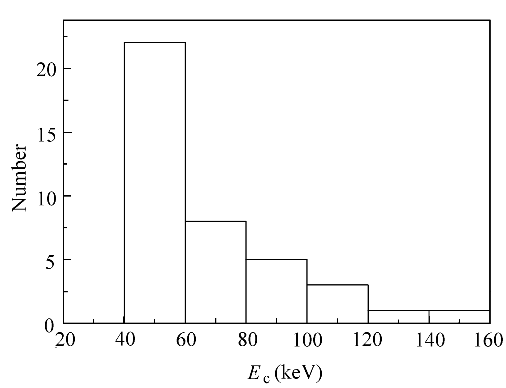

Fig. 2 The frequency distribution of E_c

Table 1 54 BATSE/CGRO Events and Their Derived Parameters

No.	Date	Time (UT)	γ_1	γ_2	ϵ_b(keV)	E_c (keV)
1	1998–02–22	16:42:05	2.45	3.69	37.4	49.6
2	1998–05–06	04:55:12	2.85	5.05	40.3	52.1
3	1998–05–07	05:32:38	2.57	3.58	70.3	97.7
4	1998–06–28	11:41:08	2.49	4.89	59.1	72.9
5	1998–09–05	06:25:33	3.46	4.53	64.8	
6	1998–11–06	09:09:55	1.84	3.54	64.2	
7	1998–11–09	04:21:40	3.76	4.91	77.9	
8	1998–11–10	06:52:27	3.51	4.52	67.2	
9	1998–11–21	20:53:39	2.68	4.93	41.4	52.2
10	1998–11–30	10:15:47	3.51	3.93	49.7	
11	1998–12–10	23:45:38	2.78	4.24	46.4	63.1
12	1998–12–13	05:15:14	2.62	3.68	39.5	54.9
13	1998–12–18	12:51:14	2.31	4.09	56.4	70.8
14	1999–01–17	23:25:18	2.96	4.05	38.9	54.1
15	1999–01–22	07:03:53	2.61	5.19	38.9	47.7
16	1999–01–22	23:08:01	2.79	5.27	42.6	53.6
17	1999–01–23	13:47:28	2.03	3.79	42.9	
18	1999–02–12	22:03:05	3.63	6.64	60.6	79.4
19	1999–03–06	20:14:08	2.92	5.52	70.4	89.5
20	1999–03–16	02:50:07	3.90	5.53	67.3	
21	1999–04–28	20:31:00	2.75	4.11	37.5	51.3
22	1999–05–03	23:10:19	2.90	3.11	68.9	
23	1999–06–20	08:36:27	3.33	5.41	38.3	51.4
24	1999–07–23	11:32:13	2.31	3.49	48.7	63.4
25	1999–07–30	22:58:08	3.23	5.38	93.0	125.0
26	1999–08–02	05:31:29	3.77	5.12	42.9	
27	1999–08–02	09:15:57	2.73	3.79	73.6	103.3
28	1999–08–06	01:37:02	2.87	3.87	40.7	56.9
29	1999–08–20	03:27:29	2.70	3.48	37.4	52.9
30	1999–08–21	22:13:07	2.81	3.98	41.4	57.7
31	1999–10–25	02:23:17	3.24	4.75	39.4	53.8
32	1999–11–09	06:12:57	2.26	3.75	43.2	54.7
33	1999–11–09	09:37:12	3.02	4.49	40.8	56.0
34	1999–11–14	14:55:06	3.20	4.40	71.8	98.9
35	1999–11–16	09:53:09	2.54	4.42	38.7	49.0
36	1999–11–21	18:15:19	4.47	4.98	56.3	
37	1999–11–26	13:41:55	2.45	4.02	82.0	104.9
38	1999–12–03	19:51:24	2.23	3.63	38.6	48.9
39	1999–12–17	09:33:37	4.75	5.70	70.8	
40	2000–02–21	00:42:36	3.28	5.18	40.8	55.0
41	2000–03–01	20:27:44	3.08	4.58	40.5	55.6
42	2000–03–05	06:50:37	3.87	5.64	57.1	
43	2000–03–05	16:08:07	2.94	4.18	69.1	96.6
44	2000–03–06	23:01:41	3.05	4.81	63.1	86.1
45	2000–03–08	00:24:51	2.40	3.20	74.2	106.0
46	2000–03–10	11:01:45	4.45	7.57	50.2	
47	2000–03–11	00:15:54	3.11	5.01	39.8	53.9
48	2000–03–13	05:03:20	2.55	4.29	113.1	145.0
49	2000–03–15	05:40:55	3.14	4.68	51.0	69.9
50	2000–03–19	12:44:24	2.35	3.46	36.9	48.8
51	2000–03–20	01:44:09	2.02	4.22	39.2	
52	2000–03–20	10:03:41	2.55	4.35	51.6	65.9
53	2000–04–27	19:40:39	2.46	4.33	39.4	49.3
54	2000–04–28	05:24:54	3.15	5.07	52.3	70.7

In fact, the dominant role of electrons in powering a solar flare has been suspected from different directions (e.g., Gan 1998). Ramaty et al. (1995), through analyzing the nuclear lines of ^{20}Ne and ^{16}O, argued that the power-law proton spectrum should extend to 1 MeV. If so, the total energy carried by protons would be comparable to, or even greater than that carried by electrons above 20 keV. Gan (1999) analyzed with another method a major solar flare observed with SMM and found that the E_c is around 76 keV. Miller et al. (1997) stated a serious problem: the total number of electrons derived from hard X-ray observations is much larger than that contained in the whole region occupied by the flare. Obviously, with a high value of E_c, this problem would be naturally removed, since the total number of electrons will be at least two orders of magnitude lower than that derived by taking E_c=20 keV. The high E_c is also beneficial for removing or weakening the well-known contradiction between the hard X-ray observations and microwave observations on the total number of accelerated electrons. As far as energy shortage is concerned, besides a possible role of energetic protons, direct thermal energy release may be another source of compensation (e.g., Holman & Benka 1992). Thermal conduction may transport the energy from the release site to the top of the chromosphere, where chromospheric evaporation may occur (e.g., Gan et al. 1991) and Hα emission may also be expected (e.g., Gan et al. 1993a, b). The electrons with a high energy can penetrate into the deep layer, resulting in hard X-ray emissions as well as instant Hα emissions, although the total energy carried by electrons is much less than is previously thought.

5 CONCLUSIONS

Based on studies of the 54 hard X-ray events observed with BATSE/CGRO, we arrive at following conclusions:

1. The peak hard X-ray spectra, without any exception in our sample, all present a broken-down form;
2. About 75% broken-down hard X-ray spectra can be explained by a power-law electron beam with a lower energy cutoff;
3. The lower energy cutoff of nonthermal electrons, varying from 47 to 145 keV in our sample, is on average 69 keV, much greater than the usually accepted 20 keV;
4. So high a lower energy cutoff means that the total energy carried by nonthermal electrons is much less than that required in the so-called standard scenario of solar flare. But the great decrease of the total number of accelerated electrons seems to be favourable in explaining the numerous contradictories related to the standard picture.

It would be proper that further studies are based on observations with a high energy resolution. Meanwhile, the high E_c brings us a series of new topics, like the other related observational effects and the acceleration mechanisms. We expect that a series of follow-up work will be done, to improve or rebuild the standard picture of solar flare.

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