Energetics of Nonthermal Electrons and Protons in Intense Solar Flares

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Abstract

We analyze Yohkoh gamma-ray energy spectra of X-class solar flares on October 27, 1991 (X6.1), November 6, 1997 (X9.4), July 14, 2000 (X5.7) and November 24, 2000 (X2.3) to study the energy content of nonthermal electrons and protons. The accelerated electron and proton spectra are derived from a spectral analysis of the continuum and lines above 1 MeV. The energy content in >1 MeV and >10 MeV protons are estimated to be 6x10^{28}- 4x10^{30} and 2.5x10^{28}-5x10^{29} ergs, respectively. We study the flare to flare variation in the energy contents of > 1 MeV electrons and >10 MeV protons. Ratios of > 1 MeV electrons to >10 MeV proton energy contents vary within an order of magnitude.

1. Introduction

The gamma-ray spectral analysis provides diagnostics for particle acceleration in solar flares. Energy content of nonthermal electrons and protons are derived from the gamma-ray spectral analysis and are important for discussion of an equal share of nonthermal energy between electrons and protons. In this paper we present gamma-ray spectra of four X-class solar flares obsereved with Yohkoh and estimate the energy contents of electrons and protons. The particle acceleration process is discussed from the gamma-ray spectral observations.

2. Observations

Yohkoh observed intense gamma-ray flares on October 27, 1991 (X6.1), November 6, 1997 (X9.4), July 14, 2000 (X5.7) and November 24, 2000 (X2.3) (Yoshimori et al., 1994, 2000, 2002). Their backgtround-subtracted gamma-ray count spectra (time-integrated over the duration of gamma-ray flares) are shown in Fig. 1, 2, 3 and 4. In order to make a spectral fitting, we use a convolution method in which a trial incident gamma-ray spectrum is assumed to be a composite of the continuum and gamma-ray lines (both narrow and and broad lines), is convolved with the instrumental response function, and the resulting gamma-ray count spectrum is tested to determine whether it is compatible with the observed spectrum. Since the Yohkoh counting statistics is poor and the energy resolution

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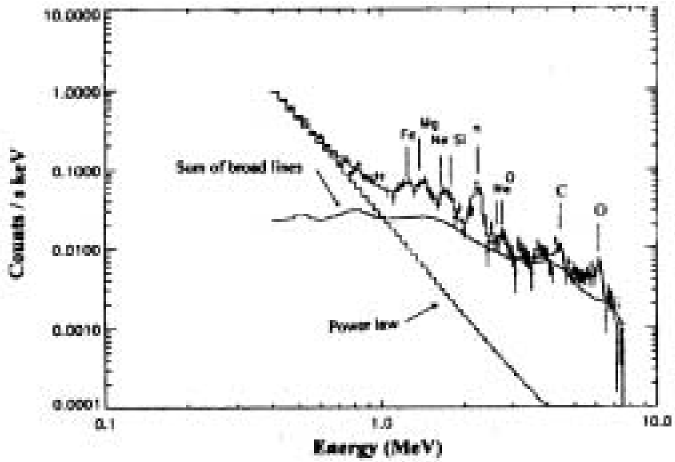

Fig. 1. Gamma-ray count spectrum of the 1991 Oct. 27 flare.

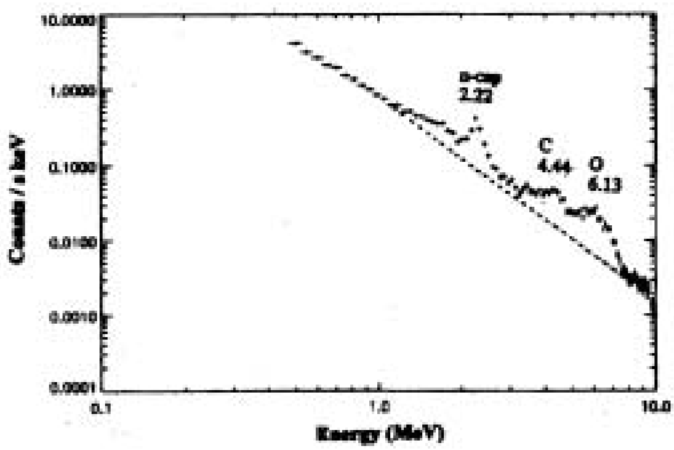

Fig. 2. Gamma-ray count spectrum of the 1997 Nov. 6 flare.

of the spectrometer is low, we fix the parameters of center energies and line widths and sequently vary only the values of line intensities until the chi-square value is minimized.

We calculate the accelerated electron spectrum from the observed continuum on the assumption of thick-target model (Ramaty et al., 1993). The accelerated proton spectrum is derived as follows: First we assume that the proton spectrum is approximated by a single power-law and determine the power-law index from the measured fluence ratio of the neutron-capture line to C and O deexcitation lines (Ramaty and Murphy, 1987). A total number of protons accelerated above 10 MeV is estimated from a comparison of the measured fluences of C and O lines with the theoretical ones. Moreover, the proton energy content depends on a ratio of accelerated He to proton. Here we assume the ratio of 0.5

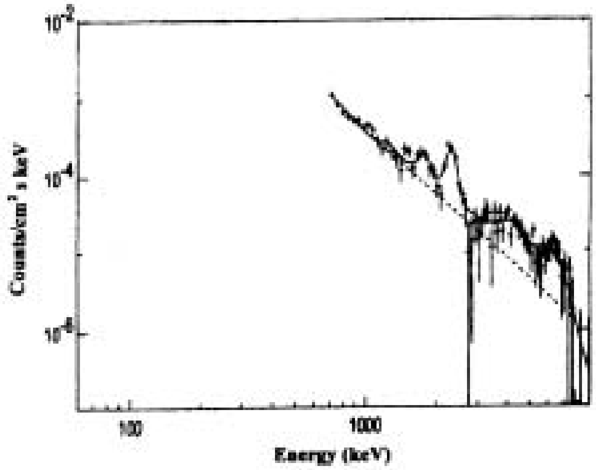

Fig. 3. Gamma-ray count spectrum of the 2000 July 14 flare.

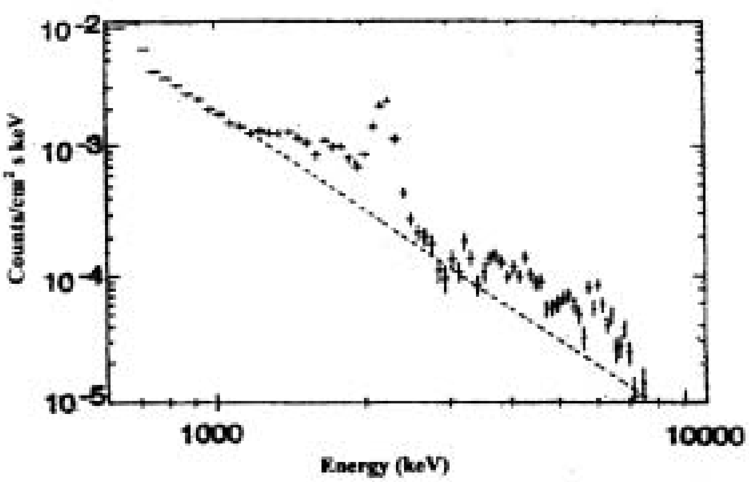

Fig. 4. Gamma-ray count spectrum of the 2000 Nov. 24 flare.

(Murphy et al., 1997). Thus we obtain the approximate energy content of >1 MeV electrons (We(>1MeV)) and >10 MeV protons (Wp(>10MeV)). The estimated energy contents are shown in Table 1 along with the electron and proton power-law spectral indices (Se for electrons and Sp for protons) .

3. Discussion

The present result shows that We(>1MeV) and Wp(>10MeV) much vary from flare to flare. We can not unambiguously state that nonthermal energy is eqially shared between >1 MeV electrons and >10 MeV protons. The ratio of We to Wp, however, varies within an order of magnitude in the limited energy ranges mentioned above. We need to study the energy participation between electrons

Table 1. Estimated >1MeV Electron and >10 MeV Proton Energy Contents.

Flare Date	We(>1MeV)	Se	Wp(>10MeV)	Sp	We/Wp
'91 Oct.27	$(6.1\pm2.6)\text{x}10^{28}$	5.1 ± 0.4	$(2.0\pm1.3)\text{x}10^{28}$	4.1 ± 0.7	3.1 ± 2.4
'97 Nov.6	$(4.4\pm2.5)\text{x}10^{30}$	3.9 ± 0.6	$(4.8\pm2.6)\text{x}10^{29}$	3.0 ± 0.5	9.2 ± 7.2
'00 Jul.14	$(2.6\pm1.7)\text{x}10^{29}$	2.7 ± 0.4	$(5.8\pm2.8)\text{x}10^{28}$	3.1 ± 0.6	4.5 ± 3.7
'00 Nov.24	$(1.0\pm0.6)\text{x}10^{30}$	2.8 ± 0.3	$(1.5\pm1.0)\text{x}10^{29}$	3.3 ± 0.6	6.7 ± 6.0

and protons over the wide energy range. In particular, a low energy-proton tail would contain considerable energy. In order to do it, we have to analyze the Ne line at 1.64 MeV because the threshold energy for excitation of Ne is about 3 MeV. Ramaty et al. (1988) calculated a total number of accelerated protons and their energy content from the gamma-ray and neutron observations. For the proton energy spectrum predicted by stochastic acceleration, the total number of protons and energy content are independent of the injection energy, while the injection energy has to be specified for shock acceleration. The stochastic model gives the energy content of accelerated protons for about 10^{30} ergs for the intense flare on June 3, 1982. The shock acceleration model gives about 10^{30} ergs (Ramaty and Murphy, 1987).The electron energy content in large solar flares was estimated from the high-energy continuum spectrum (Vestrand et al., 1987; Ramaty et al., 1993). It ranges from about 10^{29} to about 10^{30} ergs above 100 keV.

4. References

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