Solar Gamma-Ray Flares in the 23rd Solar Maximum

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Abstract

Yohkoh observed six γ-ray flares between November 1997 and March 1999. We discuss spectral characteristics of two different type of flares on 6 November, 1997 and 18 August, 1998. The November 6 flare is a γ-ray line event, while the August 18 flare is an electron-dominated event. We discuss particle acceleration processes in the two types of flare on the basis of the temporal variations in the γ-ray spectra .

1 Introduction:

The accelerated particle composition and energetics and ambient abundances were studied from γ-ray spectroscopy of the 1991 June 4 solar flare (Murphy *et al.*, 1997). Yohkoh observed six γ-ray flares producing high energy photons of energies above 1 MeV between November 1997 and March 1999. The Yohkoh γ-ray flare list is shown in Table 1. In particular, the 1997 November 6 flare emitted strong γ-ray lines and the spectrum extended to a few tens of MeV (Yoshimori *et al.*, 1999a,b), while the 1998 August 18 flare exhibited hard continuum extending 20 MeV without apparent γ-ray lines (Yoshimori *et al.*, 1999c). We discuss a ratio of accelerated ions and protons, time dependent spectra of accelerated protons and electrons and total energy contained in accelerated electrons from the observed γ-ray data.

Date	Time (UT)	GOES / Hα	Location	NOAA
1997-Nov-06	11:52	X9.4 / 2B	S18 W63	8100
1998-Aug-18	22:15	X4.9 / 1B	N33 E87	8307
1998-Nov-22	06:37	X3.7 / 1N	S27 W82	8384
1998-Nov-22	16:19	X2.5 / 2N	S30 W89	8384
1998-Nov-28	05:40	X3.3 / 3N	N17 E32	8395
1998-Dec-18	17:18	M8.0 / 2N	N19 E65	8415

Table 1   Yohkoh γ-ray flare list

2 1997 November 6 Flare:

The γ-ray time profiles and energy spectra of the 1997 November 6 flare are given by Yoshimori *et al.* (1999a,b). This flare exhibited narrow and broad γ-ray lines. The ratio of broad to narrow line fluxes gives a measure of the relative abundance of accelerated heavy ions to accelerated protons. However, the measured variation in the ratio should represent a lower limit to the actual variation because the broad line component contains unresolved narrow lines produced by protons. Broad lines are seen around 1.5-1.6, 4 and 6 MeV, which result from accelerated Ne+Mg, C and O, respectively, (Murphy *et al.*, 1990). The time dependence of the observed   ratio of broad to narrow line fluxes is shown in Fig.1. The ratio exhibited a time variation, ranging from 2 to 5. It increased

spectrum (the 2.22 MeV line flux is much larger than the prompt line fluxes). In order to perform the Gan's method, we need several parameters: yields of neutrons and prompt lines, conversion factors from neutron to 2.22 MeV line and decay constant of 2.22 MeV line emission. The first two parameters are taken from Hua and Lingenfelter (1987) and Murphy and Ramaty (1984) and the third one is given by Yoshimori et al. (1999c).

We assumed a power law proton spectrum. The time dependence of the power law spectral index is shown in Fig.3. The spectral index ranges from 3.0 to 3.5 in 0-200 s (11:52:36 - 11:55:

Fig.3 Time dependence of the proton power law spectral index.

56 UT) but the error in the spectral index is larger after 200 s (11:55:56 UT). Using the Ramaty et al's calculation (1996) to derive the flare-averaged proton spectral index from the ratio of 2.22 MeV to C line (4.44 MeV) fluences and assuming that the ratio of ambient Ne to O abundances is 0.25, we obtain the power law index of 3.5±0.3 for the ratio of accelerated He to proton fluxes $\alpha/p=0.1$ and 3.9±0.3 for $\alpha/p=0.5$. These values are consistent with that obtained from the Gan's method.

The flare-averaged continuum spectrum is fitted by a single power law function of index of 2.59 ±0.02. The fluence of >1 MeV γ-rays (integration time is 200 s) is (1966±231) photons/cm^2. We derive the corresponding accelerated electron spectrum from the measured bremsstrahlung continuum using the Ramaty et al.'s calculations (Ramaty et al., 1993). The power law index of the electron spectrum is calculated to be 3.88±0.02 and the total energy contained in >1 MeV electrons is estimated to be (2.59±0.29)x10^{28} ergs.

The C+O line flux decays exponentially with time. The decay constant is 33±3 s before 158 s (11:55:14 UT) but changes into 126±76 s after that (See Fig.3(b) in SH1.2.03). It suggests the possibility that a different proton acceleration process starts or protons trapped in the corona for long time produce γ-ray lines after 158 s.

3 1998 August 18 Flare:

Two time profiles of γ-ray counting rate in 4-7 and 10-17 MeV are shown in Fig.4. This flare showed a strong single spike with a duration of 1 min. The γ-ray count spectrum in 22:15:37-22:16:10 UT is given in Fig.5. It exhibited strong continuum extending to 20 MeV without apparent lines, suggesting electrons were preferentially accelerated to high energies within a short time. The power law function was used for a spectral fitting procedure. The index is 2.11±0.07 in 22:14:58 - 22:15:26 UT, 1.85±0.02 in 22:15:26 - 22:15:58 UT and 2.25±0.02 in 22:15:58 - 22:16:10 UT. The spectrum slightly hardens at the peak phase. The flare-averaged index is 2.07±0.02. The fluence of >1 MeV γ-rays (integration time is 72 s) is (1412±182) photons/cm^2. The corresponding accelerated electron spectrum is calculated to be the power law function of index of 3.35±0.02 and the total energy contained in >1 MeV electrons is estimated to be (7.36±0.94)x10^{27} ergs. This flare has
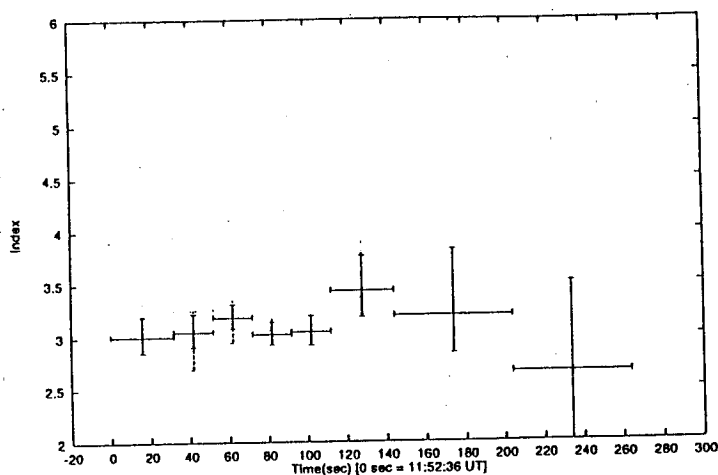
with time, reached the maximum at the peak phase of the flare and decreased in the late phase. The SMM observations of 19 flares showed considerable flare to flare variations of the ratio, ranging from 2 to 7 (weighted mean of 3.2±0.2) (Share and Murphy, 1995). The OSSE/CGRO observed a very long-duration flare on 4 June, 1991. The ratio observed from this flare was 3.40±0.1 for the first orbit and 2.19±0.09 for the second orbit, suggesting that the accelerated heavy ion to proton ratio decreased as the flare progressed (Murphy et al., 1997). The present Yohkoh ratio does not conflict with those measured from the other flares and indicates a similar temporal variation to that for the 1991 June 4 flare.

Fig.1   Time dependence of the observed ratio of broad to narrow line fluxes.

The ratio of bremsstrahlung continuum and high-FIP narrow line fluxes represents the number ratio of accelerated electrons and protons. The temporal variation of the ratio of bremsstrahlung continuum above 1 MeV to narrow high-FIP (C+N+O+Ne) line fluxes is shown in Fig.2. It exhibites that the ratio is nearly constant in 0-140 s (11:52:36 - 11: 54:56 UT) though it is slightly smaller at the rise phase, suggesting that both electrons and protons were simultaneously accelerated. However, the ratio decreases significantly in the late

Fig.2   Temporal variation of the ratio of >1 MeV bremsstrahlung continuum to narrow C+N+O+Ne line fluxes.

phase after 140 s (11:54:56 UT). This result implies that nuclear reactions producing deexcitation lines lasted for a longer time as compared with the electron bremsstrahlung. This time dependence is similar to that reported from the 1991 June 4 flare (Murphy et al., 1997).

The energy spectrum of accelerated protons can be derived from the ratios of γ-ray line fluxes. Here the thick-target interaction model, impulsive-flare abundances and a downward isotropic angular distribution for accelerated ions are assumed (Ramaty et al., 1996). Their production cross sections with different energy depencencies are sensitive to the proton spectral index. There are two methods for derivation of the proton spectrum: (1) the ratio of the neutron capture line at 2.22 MeV to O line at 6.13 MeV fluences and (2) the ratio of O line to Ne line (1.63 MeV) fluxes. The first method is used with flare-integrated data to provide an average index for the whole flare, while the second method gives an instantaneous measure. Recently Gan (1998) developed a new method to calculate the time variation of proton spectrum from time-differentiation of the 2.22 MeV line flux. Here we use the Gan's method because this method gives an more accurate power law index of the proton
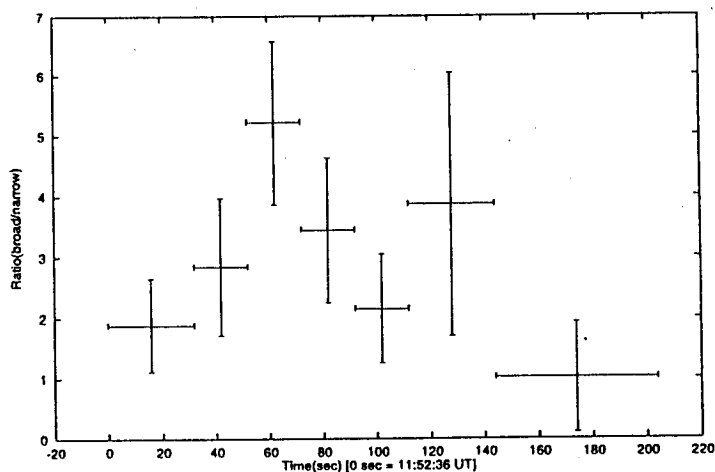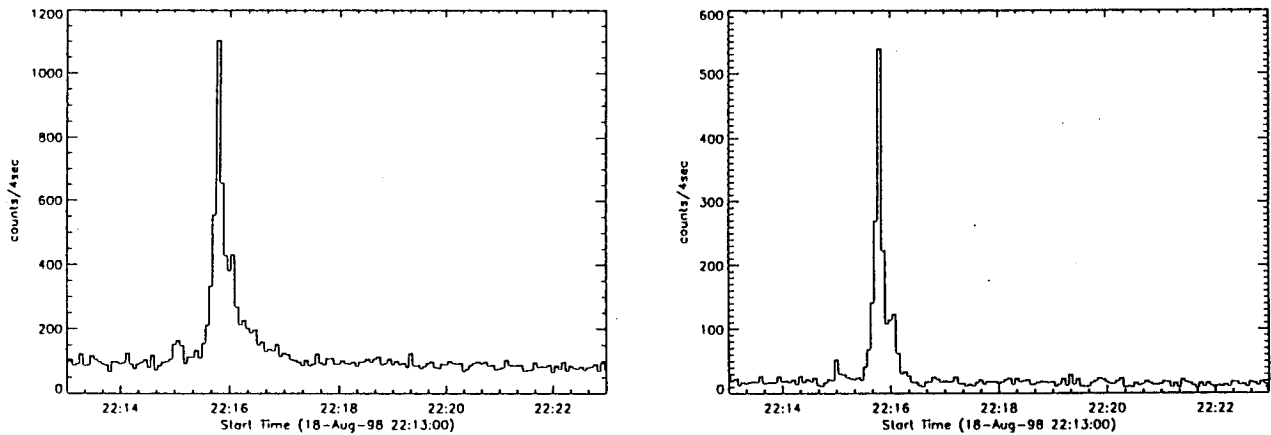
Fig.4   Time profiles of γ-ray counting rate. (a) 4-7 MeV and (b) 10-17 MeV.

characteristics of short duration (impulsive), considerably hard spectrum and no delay of γ-ray emission with respect to hard X-ray emission. This type of flare is named the electron-dominated event (Rieger and Marschhäuser, 1990). In order to explain the electron acceleration in the electron-dominated event, a mechanism which has capabilities of prompt switch-on and switch-off. Acceleration by DC electric fields seems to be a possible mechanism.
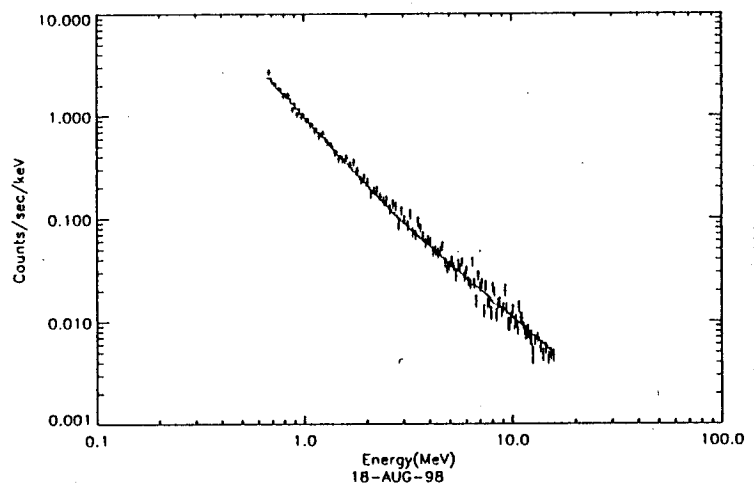

Fig.5   Flare-averaged γ-ray count spectrum in 22:15:37-22:16:10 UT.

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