Two Types of Gamma-Ray Flares

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Abstract

Yohkoh observed two types of γ-ray flares on Nov. 6, 1997 and Aug. 18, 1998. The 1997 Nov. 6 flare showed strong narrow γ-ray lines superposed on the bremsstrahlung continuum, suggesting both protons and electrons were efficiently accelerated. A ratio of low-FIP (Mg, Si and Fe) to high-FIP (C, N, O and Ne) line fluxes was enhanced by a factor of 3 in the decay phase of the flare compared to those in the rise and peak phases. A flux ratio of O to Ne lines and a fluence ratio of neutron capture to C lines indicated that the proton spectrum was essentially constant throughout the flare and its power law spectral index was 4.3±0.3. The photospheric ^{3}He/H abundance ratio was estimated to be $(1.5\pm0.5)\times10^{-5}$ from the time profile of the neutron capture line at 2.22 MeV. It is consistent with that obtained from the 1991 June 4 flare. On the other hand, the 1998 Aug. 18 flare exhibited hard bremsstrahlung continuum without γ-ray lin es, suggesting that electrons were preferentially accelerated to high energies (electron-dominated flare). The continuum spectrum varied with time. The power law spectral indices in the rise, peak and decay phases were 2.11, 1.85 and 2.25, respectively. The continuum spectrum extended to 20 MeV but significantly steepened above 20 MeV, implying that electrons were not accelerated above a few tens of MeV.

Key words: Solar flares – Gamma-rays – Particle acceleration

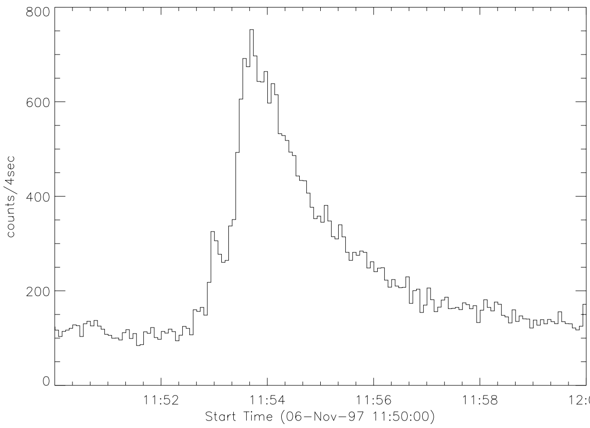
1. Introduction

The SMM (Rieger and Marschhäuser, 1990; Share and Murphy, 1995) and Yohkoh (Yoshimori et al., 1995) observed two types of γ-ray flares, γ-ray line flare and bremsstrahlung continuum flare. Most of the γ-ray flares accelerate protons and heavy ions which produce γ-ray lines through various nuclear reactions with ambient nuclei. On the other hand, there is a different type of γ-ray flare which emits strong bremsstrahlung continuum without γ-ray lines. This type of flare is named an electron-dominated flare in which electrons are preferentially accelerated. The number of the electron-dominated flares is smaller than that of the γ-ray line flares.

Recently the OSSE experiment of the Compton Gamma-Ray Observatory showed the possibility that the ambient abundances at a γ-ray emission site varied with time within a long-duration flare on June 4, 1991. In order to advance the understanding of the temporal variation, we need more observational data of γ-ray lines. Yohkoh observed an intense γ-ray line flare on Nov. 6, 1997 and obtained a new additional result which supports the temporal change in the ambient abundances. In this paper possible explanations for the temporal variation is discussed. The accelerated proton spectrum is derived from a flux ratio of O to Ne lines and a fluence ratio of 2.22 MeV line to C line. The temporal variation in the proton spectrum is examined here. The observation of time profile of the neutron capture line has been used to obtain the ^{3}He abundance in the photosphere where it has not been obtained by any other method. The photospheric ^{3}He/H abundance ratio is determined from this method and compared with the previous one. Yohkoh recorded an intensive and short-duration electron-dominated flare on Aug. 18, 1998. The electron acceleration process is discussed from the temporal variation in the γ-ray continuum spectrum.

2. Observation

A γ-ray line flare (X9/2B, W80) was observed at 21:52 UT on Nov. 6, 1997. The neutron capture line, C, O, Ne, Mg, Si and Fe lines and high energy γ-rays up to a few tens of MeV were detected (Yoshimori et al., 1999). Two counting rate time profiles of 2.22 MeV neutron capture line and 4–7 MeV band (lines + continuum) are shown in figure 1. The decay time of the 2.22 MeV line (135±7 s) is longer than that of 4–7 MeV band (35±3 s). The



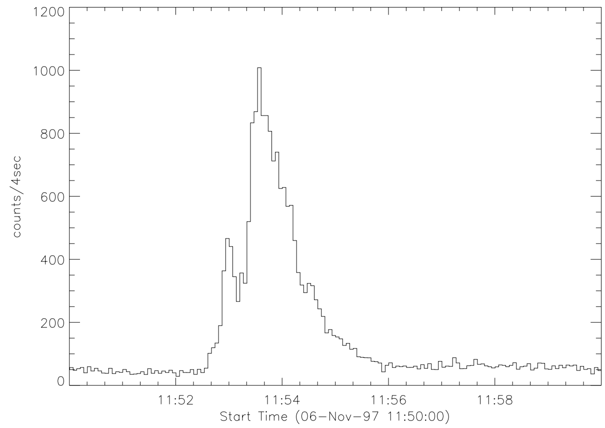


Fig. 1 Time profiles of γ-ray counting rate of the 2.22 MeV neutron capture line (left) and 4–7 MeV band (lines + continuum) (right) for the 1997 November 6 flare. The decay times are 135±7 and 35±3 s for the 2.22 MeV line and 4-7 MeV band.

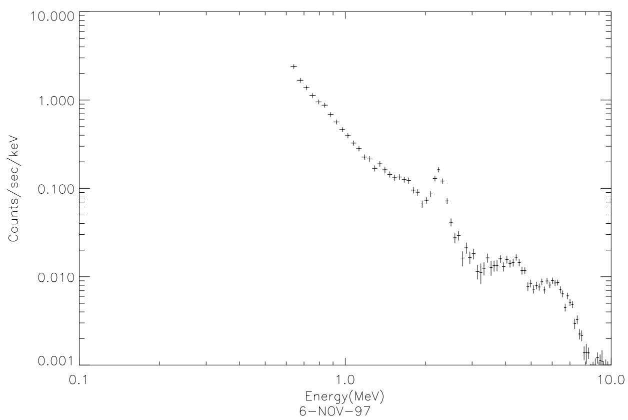


Fig. 2 Flare-averaged γ-ray count spectrum of the 1997 Nov. 6 flare (11:52:28-12:02:12 UT.)

flare-averaged γ-ray count spectrum in 11:52:36–11:56:12 UT is shown in figure 2. In our spectral fitting procedure a trial incident spectrum consisting of a single power law, nine narrow Gaussian lines and five broad Gaussian lines is constructed and convolved with a numerical model of the instrumental response. The resulting predicted counts are compared, channel by channel, with the observed count spectral data. A χ^2 minimization algorithm was used to fit the data. In order to constrain the fits, we have fixed the line center energies and widths of narrow and broad lines at their theoretical values (Murphy et al., 1990). Free parameters in the fit are the amplitudes of the γ-ray lines, and the amplitude and spectral index of single power law. The relative narrow line fluence (fluence of O line at 6.13 MeV, 78±7 photons/cm^2, is normalized to 1.00) is 0.51±0.18 for Fe line at 1.24 MeV, 0.74±0.16 for Mg line at 1.37 MeV, 1.34±0.15 for Ne line at 1.64 MeV, 0.41±0.13 for Si line at 1.78 MeV, 1.13±0.15 for C line at 4.44 MeV, 1.00±0.10 for O line at 6.12 MeV and 0.51±0.08 for N+O line at 7 MeV. These values are in agreement with the average ones of the 19 SMM γ-ray line flares (Share and Murphy, 1995). We search for temporal variation of relative fluxes of the lines. Here we group elements in the flare plasma with respect to first ionization potential (FIP). Mg, Si and Fe are the elements with low-FIP (<10eV), while C, N, O and Ne are those with high-FIP (>10eV). The line flux ratios of (Si+Fe)/Mg=2.1±0.6 and Ne/(C+N+O)=0.50±0.14 were almost constant throughout the flare, but the (Mg+Si+Fe)/(C+N+O) line ratio varied with time. It was 0.6±0.1 in the rise and peak phases but enhanced by a factor of 3 in the decay phase.

A different type of γ-ray flare (X4.8/1B, N33E87) was observed at 22:15 UT on Aug.18, 1998. Two time profiles of γ-ray counting rate at 4–7 and 10–17 MeV are shown in figure 3. They showed a strong single spike with a duration

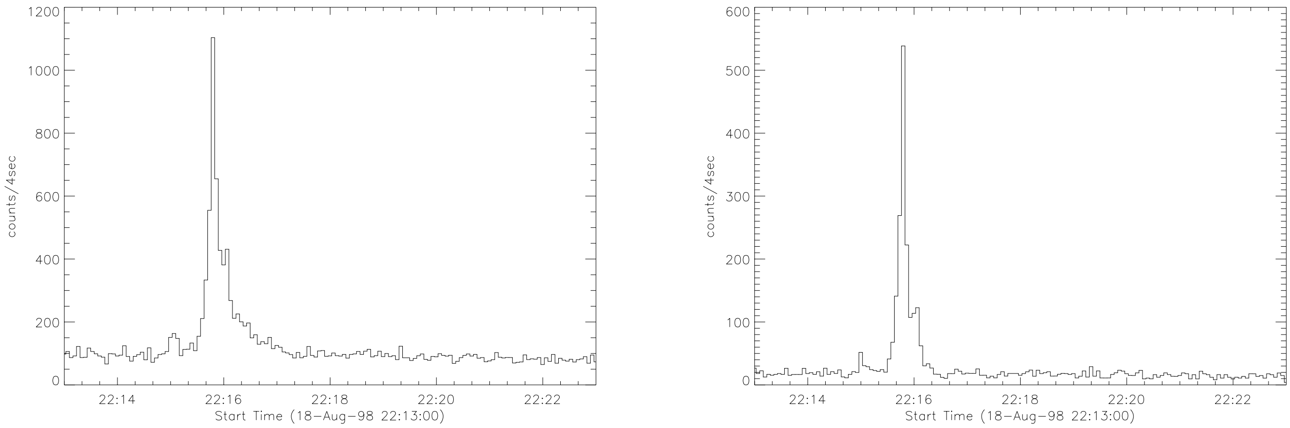


Fig. 3 Time profiles of γ-ray counting rate in 4–7(left) and 10–17(right) MeV bands for the 1998 Aug. 18 flare.

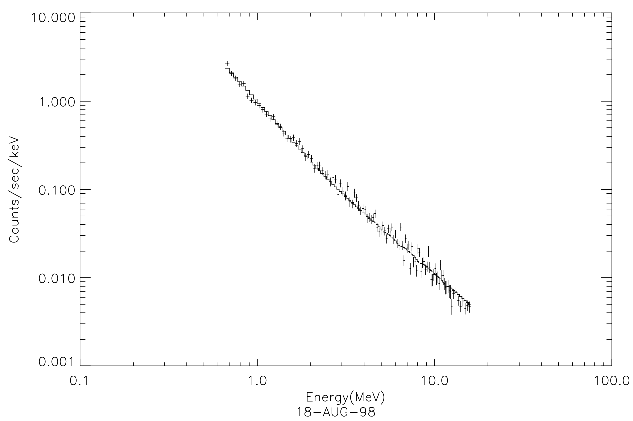


Fig. 4 Flare-averaged γ-ray cont spectrum of the 1998 Aug. 18 flare (22:15:37-22:16:10 UT).

of 1 min. The γ-ray counting rate spectrum in 22:15:37–22:16:10 UT is given in figure 4. Although it exhibited strong bremsstrahlung continuum extending to >10 MeV, no strong γ-ray lines were detected, suggesting electrons were preferentially accelerated to high energies within a short time (electron-dominated flare). The single power law was used for a spectral fitting procedure for this flare. The flare-averaged γ-ray spectrum is fitted by a single power law of index of 2.09$\pm$0.01, as shown in figure 4. However, the spectrum index varied with time. The spectral index is 2.11$\pm$0.07 in 22:14:58–22.15:26 UT, 1.85$\pm$0.02 in 22:15:26–22:15:58 UT and 2.25$\pm$0.02 in 22:15:58–22:16:10 UT. It showed a general trend, that is, the spectrum is soft at the rise time, hardens at the peak time and becomes soft at the decay time.

3. Discussion

The Yohkoh observation of the short-duration flare on Nov. 6, 1997 indicated (1) the line fluxes from elements with similar FIP correlated well with one another throughout the flare and (2) the low-FIP to high-FIP line ratio was enhanced by a factor of 3 in the decay phase. The present Yohkoh result suggests the possibility of a temporal change in the composition of the γ-ray production site. It also confirmed the previous result from a long-duration flare (June 4, 1991) in which the enhancement of the ratio was a factor of 2.5 (Murphy et al., 1997). The coronal abundance ratio of low-FIP to high-FIP elements is enhanced by a factor of 4 compared to the photospheric one (Grevesse and Anders, 1988). Possible explanations for the temporal variation of line ratio are (1) the efficient transport of low-FIP elements to the γ-ray production site and (2) the change in γ-ray emission site with time. The second one may take place if magnetic mirror points move upward to the corona. The movement of the mirror points could be conjectured from the temporal change in X-ray images. Yohkoh hard X-ray image data revealed that a distance between two foot-point sources was gradually increased in the decay phase (Sato, 1998). However, it is now difficult to discuss how the change in hard X-ray images is related to the enhancement of the low-FIP to high-FIP line ratio in the decay phase.

There are two spectral index-determining methods for accelerated protons. The proton spectrum is derived from a flux ratio of O (6.13 MeV) to Ne (1.63 MeV) lines and a fluence ratio of neutron capture line (2.22 MeV) to C line (4.44 MeV) (Ramaty et al., 1996; Share and Murphy, 1995). The first method is particularly useful for deriving the low energy proton spectrum at 5–20 MeV. On the other hand, the second one provides spectral information on 10–100 MeV protons. The proton spectrum is approximated by a power law function. The spectral index depends on the ambient Ne to O abundance ratio (Ne/O) and the accelerated He to proton flux ratio (α/p). Here we assumed Ne/O is 0.25 (Ramaty et al., 1996). The observed O to Ne line ratio is 0.75$\pm$0.10 throughout the flare, indicating the proton spectral index is 3.8$\pm$0.2 for α/p=0.1 and 4.2$\pm$0.2 for α/p=0.5. Next we derive the proton spectrum from the second method. The proton spectral index is 4.1$\pm$0.1 for α/p=0.1 and 4.4$\pm$0.1 for α/p=0.5. The assumption of α/p=0.5 provides better agreement between the two index-determining methods because the differences in the indices are 0.64 and 1.36 σ for α/p=0.5 and 0.1, respectively. The average proton spectral index for the 19 SMM γ-ray flares is 4.3 for α/p=0.5 (Share and Murphy, 1995) , indicating that the Yohkoh proton spectrum for the 1997 Nov. 6 flare appears to be typical of γ-ray flares. The total number of protons accelerated to >30 MeV in the 1997 Nov. 6 flare is estimated to be $(2.5\pm0.7)\times10^{32}$.

The decay time of the 2.22 MeV line emission depends on three processes: (1) radiative neutron capture leading the 2.22 MeV line, (2) nonradiative neutron capture of ^{3}He(n,p)^{3}H and (3) neutron decay. Since the 1997 Nov. 6 flare is impulsive, we use a simplified approach (Prince et al.,1981) to obtain the photospheric ^{3}He/H ratio. The 2.22 MeV line flux from an instantaneous production of neutrons is assumed to fall exponentially in time with a time constant which is determined by time constants for the three processes mentioned above. We assume that the 2.22 MeV lines are produced at the photosphere (hydrogen number density is assumed to be 10^{17} cm^{-3}) . Substituting the observed time constant of 2.22 MeV line flux (100$\pm$5 s) for the Prince et al.'s formula, we determined that the photospheric ^{3}He/H ratio is $(2.5\pm0.5)\times10^{-5}$ which is consistent with that obtained from the 1991 June 4 flare (Murphy et al., 1997).

A very small number of electron-dominated flares were observed with SMM (Rieger and Marschhäuser, 1990). Most of these flares were of short duration and did not show a delay between hard X-rays and high energy γ-rays. The impulsivity and weak signature of high energy protons calls for an acceleration mechanism which has capabilities of prompt switch-on and switch-off. Acceleration by DC electric fields seems to be a possible mechanism for the electron-dominated flare.

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