

OBSERVATIONS OF SOLAR FLARE GAMMA-RAYS AND PROTONS

M. YOSHIMORI and H. WATANABE
Department of Physics, Rikkyo University,
Toshima-ku, Tokyo 171, JAPAN.

ABSTRACT

Solar flare gamma-rays (4 - 7 MeV) and protons (8 - 500 MeV) were simultaneously observed from six flares on 1 Apr., 4 Apr., 27 Apr. 13 May 1981, 1 Feb. and 6 June, 1982 by the Hinotori and GMS satellites. The relationship between 4 - 7 MeV gamma-ray fluences and peak 16 - 34 MeV proton fluxes for these flares are analyzed. It does not reveal an apparent correlation between these two parameters. The present result implies that the protons producing gamma-rays and the protons observed near the Earth do not always belong to the same population.

1. Introduction

The particle acceleration mechanism in solar flares has been studied through observations of radiowaves, X-rays, gamma-rays, neutrons and flare particles. The energetic photon observations provide a clue on the particle acceleration through interaction processes in the flare region. On the other hand, the particle observations provide the clue through propagation effects in the corona and interplanetary space. Hence, we need simultaneous observations of the photons and the particles to understand deeply the particle acceleration mechanism and the photon emission processes in solar flares. To study the acceleration of nuclei, it is important to investigate the relationship between the particles producing gamma-ray lines and the particles observed near the Earth. This investigation provide diagnostics for the following question: Are these two kinds of accelerated particles the same population? In addition, it provides the clue on the interaction model (thin-target or thick-target interaction model), together with observations of fragments such as deuterons, tritons and He-3 nuclei.

The gamma-ray observations were successfully performed during the solar maximum period from 1981 Feb. to 1982 June by the Hinotori satellite (Yoshimori et al., 1983). The Hinotori satellite observed 8 gamma-ray line flares during the above period. On the other hand, the GMS (Geostationary Meteorological Satellite) observed 23 solar proton events during the same period. Several observations of solar particles associated with gamma-ray line flares have been reported so far by the ISEE-3 (Pesses et al., 1981) and the IMP-8 (McGuire et al., 1981) satellites. These observations indicated that the solar proton fluxes were not always correlated with the gamma-ray line fluxes. Furthermore, Cliver et al. (1983) showed a lack of correlation between the peak 10 MeV proton fluxes and the 4 - 8 MeV gamma-ray excesses for western hemisphere flares.

In this paper, we analyze the relationship between flare-associated gamma-ray lines and interplanetary proton events observed from Apr., 1981 to June, 1982. The gamma-ray data are from the gamma-ray spectrometer on board the Hinotori satellite. The proton data are from the solid state Si detector on board the GMS.

2. Gamma-Ray and Proton Observations

The flares in which gamma-rays and protons were simultaneously observed are listed in Table 1. The flare date, maximum time, location, $H\alpha$ importance and GOES X-ray class are presented there. The detailed characteristics of these flares were described by Yoshimori (1984).

The time histories of gamma-ray count rate in the 4.0 - 6.7 MeV band were observed for the 1 Apr., 4 Apr., 27 Apr., 13 May, 1981, 1 Feb. and 6 June, 1982 flares. The 4.0 - 6.7 MeV gamma-rays are mostly dominated by prompt nuclear deexcitation lines of C-12 at 4.44 MeV and of O-16 at 6.13 MeV (Yoshimori, 1984). A few additional gamma-ray lines were reported for these flares. Of these flares the Feb. 1, 1982 flare did not reveal an apparent gamma-ray emission. The corresponding time histories of proton fluxes in the 8 - 500 MeV bands were observed.

The 1 Apr., 1981 flare showed the gradual time history with a long duration of 26 min. The 4.0 - 6.7 MeV gamma-ray fluence and the peak 16 - 34 MeV proton flux were (20 ± 4) photons / cm^2 and (2.5 ± 0.3) protons / cm^2 s sr, respectively. This flare is considered to be magnetically well-connected to the Earth; this flare occurred within the so-called preferred connection helio-longitude range. Protons with high energies of 200 - 500 MeV also were observed (Yoshimori, 1985). These 200 - 500 MeV protons revealed a fast rise and fall time history.

The 4 Apr., 1981 flare showed the impulsive time history with a short duration of 80 s. The 4.0 - 6.7 MeV gamma-ray fluence and the peak 16 - 34 MeV proton flux were (25 ± 5) photons / cm^2 and (3.4 ± 0.4) protons / cm^2 s sr, respectively. This flare is also considered to be magnetically well-connected to the Earth.

The 27 Apr., 1981 flare showed the gradual time history with long duration of 25 min, but the Hinotori satellite was eclipsed by the Earth at 0815 UT. This flare revealed the intensive gamma-ray line emission (Chupp, 1982, 1983; Yoshimori et al. 1983). However, this flare did not reveal the apparent proton increase in the 8 - 500 MeV band, in spite of the magnetically well-connected flare. Further, three large proton events which occurred in the same sunspot were reported on 24, 26 and 28 Apr., 1981. These results may imply that protons accelerated in the 27 Apr. flare could not escape into interplanetary space. The 4.0 - 6.7 MeV gamma-ray fluence is (30 ± 5) photons / cm^2 , and the upper limit of the peak 16 - 34 MeV proton flux is 3 protons / cm^2 s sr.

The 13 May, 1981 flare showed the gradual time history with long duration of 18 min. This flare revealed a small increase of gamma-ray emission, but did not reveal the increase of proton flux. The absence of the apparent increase of proton flux may be due to the bad propagation condition in interplanetary space; this flare did not occur within the preferred connection helio-longitude range. The 4.0 - 6.7 MeV gamma-ray fluence is (50 ± 9) photons / cm^2 , and the upper limit of the peak 16 - 34 MeV proton flux is 2 protons / cm^2 s sr.

The 6 June, 1982 flare showed the impulsive and multi-peak time history with duration of 6 min. The proton flux revealed the very gradual increase and the peak reached on 9 June. In addition, protons with energies above 68 MeV were not observed with statistical significance. It implies that protons could not be accelerated to energies above 70 MeV during the flare. The 4.0 - 6.7 MeV gamma-ray fluence and the peak 16 - 34 MeV proton flux are (35 ± 6) photons / cm^2 and (6.0 ± 0.7) protons / cm^2 s sr, respectively.

An unusual event was the 1 Feb., 1982 flare, in which intensive proton flux was observed, but gamma-ray line emission was not significant. The 16 - 34 MeV peak proton flux is (80 ± 9) protons / $\text{cm}^2 \text{ s sr}$, and the upper limit of 4.0 - 6.7 MeV gamma-ray fluence is 13 photons / cm^2 . This flare shows an opposite trend to the 27 Apr., 1981 flare, although this flare is also considered to be magnetically well-connected to the Earth.

3. Discussion

As shown in the previous section, the Hinotori and GMS data do not always reveal the apparent correlation between the gamma-ray line fluences and the peak 16 - 34 MeV proton fluxes. The scatter diagram of the 4.0 - 6.7 MeV fluence versus the peak 16 - 34 MeV proton fluxes is shown in Fig. 1 to see the correlation between these two parameters. The most of the 4.0 - 6.7 MeV gamma-rays consist of the C-12 line at 4.44 MeV and of the O-16 line at 6.13 MeV. The 16 - 34 MeV protons should contribute greatly to the production of these prompt gamma-ray lines. As shown in Fig. 1, there is no compelling evidence for the correlation for both eastern and western hemisphere flares. It is easily understood that there is not good correlation for the eastern hemisphere flares of 13 May, 1981 and 6 June, 1982. It is because the bad propagation condition in interplanetary space. Furthermore, the correlation is neither always found for the western hemisphere flares, which occurred within the preferred connection helio-longitude range. The present result is consistent with the Cliver et al.'s result (1983). These results seem to suggest that the protons producing the gamma-ray lines in the flare site and the protons observed near the Earth do not always belong to the same population.

Two gamma-ray line production models (thick- and thin target interaction models) have been proposed (Ramaty et al., 1975). If the gamma-ray lines are produced from the thin-target interaction, the gamma-ray line fluence should be nearly proportional to the 16 - 34 MeV proton flux. On the other hand, the thick-target model should predict that there is not always apparent correlation, because the gamma-ray lines are produced by the accelerated nuclei streaming down to the denser chromosphere and photosphere. The thick-target model is also supported from the absence of spallation products such as deuterons, tritons and He-3 nuclei (McGuire et al., 1977; Mewaldt et al., 1983). In the thick-target model, the spallation products that accompany the production of gamma-ray lines, are slowed down in the denser solar atmosphere and hence are not expected to be observed in interplanetary space.

The scattering diagram suggests that the directivity of accelerated nuclei in the flare site varies from flare to flare. The directivity may depend on the configuration of magnetic field of the flare region. If the directivity is isotropic, both gamma-ray lines and accelerated nuclei should be observed. However, if most of the accelerated nuclei stream down to the chromosphere, only gamma-ray lines will be observed. For example, the 27 Apr., 1981 flare showed the significant gamma-ray line fluences, but did not show the apparent solar proton flux. No increase of solar protons associated with this flare was interpreted in terms of some particle confinement mechanism (Sakurai, 1983). This confinement mechanism asserts that most of accelerated nuclei were trapped for long time in the acceleration region and were little released into interplanetary space. On the contrary, if most of the accelerated nuclei move upward, only solar particles will be observed. For example, the 1 Feb., 1982

flare showed the appreciable solar proton flux, but did not show gamma-ray line emission. Another similar result was reported from the 9 Dec., 1981 flare (Cliver et al., 1983). These two flare data may indicate that the upward moving protons are so dominant that gamma-ray lines are not observed. Much more data of solar gamma-rays and protons are needed to establish the detailed relation between the gamma-ray line fluences and the peak solar proton fluxes.

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Table 1

No.	Date	Maximum Time (UT)	Location	H _α / GOES
1.	1 Apr., 1981	0154	S43 W52	2B/X2.3
2.	4 Apr., 1981	0502	S44 W85	3B/X1.9
3.	27 Apr., 1981	0813	N15 W90	--/X5.5
4.	13 May, 1981	0418	N11 E58	3B/X1.5
5.	1 Feb., 1982	1402	S14 W09	3B/X2.6
6.	6 June, 1982	1633	S09 E25	3B/X12

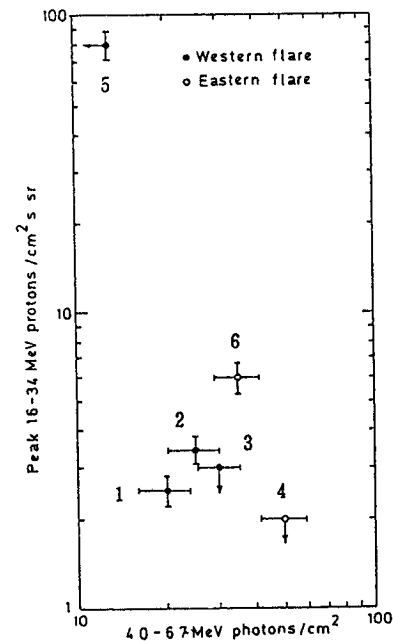


Fig. 1 Numbers attached to data correspond to flare numbers in Table 1.