HIGH-ENERGY SOLAR GAMMA-RAY OBSERVATIONS

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1. Introduction

In the last solar maximum, gamma-rays associated with solar flares were observed with GRANAT, GAMMA-1, CGRO and YOHKOH. The gamma-ray energies ranged from 100 keV to a few GeV. We obtained several new findings of gamma-ray emission on the Sun: (1) Gamma-ray production in the corona, (2) GeV gamma-ray production in very long duration flares, (3) Electron-rich flares, (4) Gamma-ray lines and solar atmospheric abundances and (5) Possible location of gamma-ray emission. We present the observations of these new findings and discuss high energy phenomena relating to particle acceleration and gamma-ray production during solar flares.

2. Observations

2.1. CORONAL SOURCE OF GAMMA-RAYS

Since gamma-rays are produced from the thick-target interactions at the chromosphere, it has been thought to be difficult to observe gamma-rays from a limb flare and a behind the limb flare because of strong attenuation effect. The GRANAT observation provided first evidence for gamma-ray emission in the corona from a behind the limb flare on June 1, 1991 (Barat *et al.*, 1994). This flare was the most energetic event which produced detectable electron bremsstrahlung and nuclear deexcitation lines. The observed gamma-ray spectrum is shown in Fig.1. We see a compound of Ne, Mg, Si and Fe lines, C and O lines. The neutron capture line at 2.22 MeV was not evident.

The spectral analysis indicated that the energy spectrum of accelerated ions steepened with time (power-law index changed from 2 to 5) and accelerated heavy ions were enhanced with time.

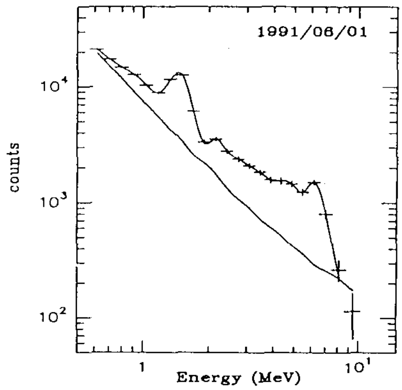

Figure 1. The energy spectrum of the coronal gamma-ray flare on June 1, 1991.

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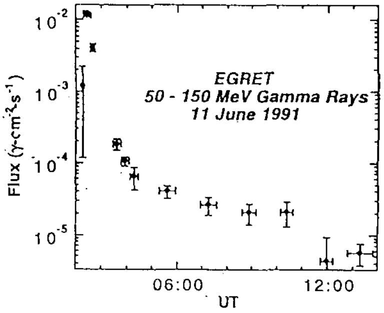

Figure 2. Time profiles of 50 - 150 MeV gamma-rays from the 1991 June 11 flare.

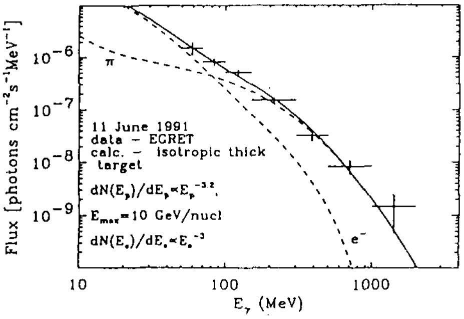

Figure 3. The gamma-ray spectrum of the 1991 June 11 flare.

2.2. HIGH-ENERGY GAMMA-RAYS FROM VERY LONG DURATION FLARES

CGRO and GAMMA-1 observed MeV to GeV gamma-rays from very large flares on June 11 and 15 flares (Kanbach *et al.*, 1993; Akimov *et al.*, 1991). The time profile of 50 - 150 MeV gamma-rays and energy spectrum from the June 11 flare is shown in Fig.2 and 3, respectively. The gamma-ray spectrum is given in Fig.3. The CGRO gamma-ray spectrum extended to about 2 GeV and consists of nuclear gamma-ray lines, electron bremsstrahlung and pion-decay gamma-rays. Pion-decay gamma-rays are dominant at high energies. It implies that more than a few GeV protons were efficiently accelerated in the flares. Moreover, high energy gamma-rays were emitted for about 8 hours. In order to explain the long-term gamma-ray emission, two scenarios were proposed. One is that particles are accelerated in an impulsive phase and subsequently trapped at the Sun (Mandzhavidze *et al.*, 1996) and the other is that particles are accelertaed continuously over the duration of the gamma-ray emission (Akimov *et al.*, 1993; Kocharov *et al.*, 1993). Mandzhavidze *et al.* analyzed the time profiles of gamma-rays from pion-decay, neutron capture and C deexcitation and of radio emission at 17 GHz from the June 11 flare. They found that there were three phases of gamma-ray emission and suggested that ions were accelerated episodically and subsequently trapped in the low density coronal portions of the flaring loops between the acceleration episodes, but produced gamma-rays in the denser subcoronal interaction regions. On the other hand, Akimov *et al.* and Kocharov *et al.* found similarities of combined pion-decay and nuclear line gamma-ray time profiles and microwave time profile. They concluded that continuous acceleration took place after the impulsive phase and acceleration may be associated with a long post eruptive energy release after coronal mass ejection (CME).

2.3. ELECTRON-RICH FLARES

SMM, GRANAT and YOHKOH observed unusual intense bremsstrahlung spectra with no detectable gamma-ray lines (Rieger and Marschhauser, 1990; Yoshimori *et al.*, 1992). It implies that electrons were preferentially accelerated in comparison with protons. This type of flare is named an "electrion-rich" event. Although most gamma-ray flares show the gamma-ray lines superposed on the bremsstrahlung continuum spectrum, a few electron-rich flares have been reported so far. These flares have a short duration and impulsive characteristic. An electron-rich flare was observed with SMM on March 6, 1989. The energy spectrum shows the intense electron bremsstrahlung continuum without detectable gamma-ray lines and extends to 10 MeV, as shown in Fig.4. This type of flare is suggestive of the sudden appearance of a transient potential drop as large as 100 MV which accelerates more electrons than ions.

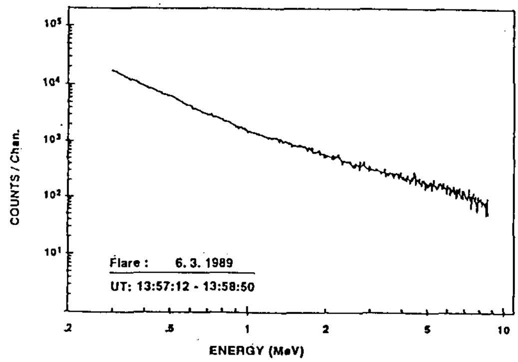

Figure 4. The energy spectrum of electron-rich flare on March 6, 1989.

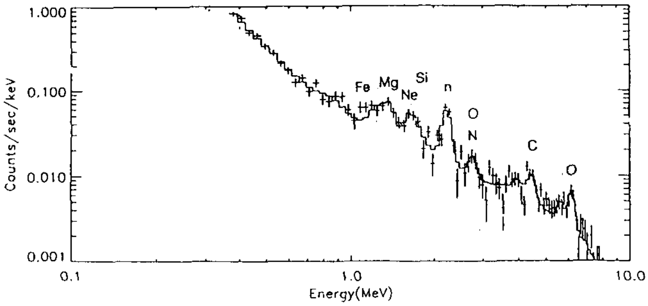

Figure 5. The gamma-ray spectrum of the 1991 October 27 flare.

2.4. GAMMA-RAY LINES AND SOLAR ATMOSPHERIC ABUNDANCES

Gamma-ray lines were reported with the SMM (Murphy *et al.*, 1990) and Hinotori (Yoshimori, 1990) observations in 1980 - 1982. A number of gamma-ray lines were observed in a flare of April 27, 1981 and the abundances of solar atmospheric elements were discussed. In the last solar maximum (1989 - 1992), GRANAT (Vilmer, 1994), CGRO (Murphy *et al.*, 1994) and YOHKOH (Yoshimori *et al.*, 1994) recorded several gamma-ray lines from large solar flares. As an example, the gamma-ray spectrum observed with YOHKOH on October 27, 1991 is shown in Fig.5. Further, Share and Murphy (1995) investigated flare-to-flare variations in the gamma-ray line fluxes from 19 gamma-ray flares observed with SMM and derived the abundances of solar atmospheric elements. Ramaty *et al.* (1996) found that (1) Ratio of low FIP (first ionization potential) element to high FIP element (Mg/O, Si/O and Fe/O) is enhanced relative to the photospheric abundances. It implies that gamma-rays are produced above the photosphere, (2) Ratio of C to O is 0.35 - 0.44 which is almost independent on flare, (3) Ratio of Ne to O is about 0.25. It is higher than the coronal value (about 0.15), suggesting that the gamma-rays are produced in a subcoronal region.

The flux of Ne line at 1.63 MeV provides information on the ion spectrum at low energies because the threhold energy of proton which produces the Ne deexcitation line is 1.5 MeV. The strong Ne line were reported in several flares, suggesting the energy content in accelerated ions is 10^{32} ergs (Ramaty *et al.*, 1995; Share *et al.*, 1996). It is comparable to the energy content of 10 keV electrons which is nearly equal to be the total energy of solar flare.

2.5. POSSIBLE LOCATION OF GAMMA-RAY PRODUCTION

Location of gamma-ray production site can be deduced from observations of limb flares. For the limb flares, the neutron capture line is strongly absorbed, while the nuclear deexcitation lines are not much absorbed. It suggests that the gamma-ray emission region should have a small size. YOHKOH observed a hard X-ray image, its time variation and C and O line emission time profile (Yoshimori *et al.*, 1996). The hard X-ray image revealed two strong sources which are thought to correspond to both footpoints of a flaring loop. These two hard X-ray sources showed different hard X-ray time profiles. The hard X-ray time profile of one source is similar to the gamma-ray time profile but that of the other source is quite different from the gamma-ray time profile. Based on the similarity in one of the two hard X-ray sources and gamma-ray emission, gamma-rays were probably producerd at the first point source.

3. Particle Accleration in Gamma-Ray Flares

Gamma-rays and neutrons are produced from the interactions of accelerated ions with the chromosphere (thick-target model). Most gamma-rays flares are impulsive events but several gradual events produce gamma-rays. Although the impulsive events show enhancements in electron-to-proton ratio, ^{3}He to ^{4}He ratio and heavy ions, these gamma-ray-producing gradual events also reveal similar abundance characteristics. The gamma-ray spectral analysis indicates that the gamma-ray-producing ions have a common origin with ions escaping to interplanetary space. It suggests that gamma-ray producing ions are accelerated by similar mechanism, independent of the flare type, impulsive or gradual (Cliver, 1996).

Temerin and Roth (1992), Miller and Vinas (1993) and Miller and Reames (1996) proposed that particle acceleration in impulsive flares is due to gyroresonant interactions with plasma waves. They explained that the ^{3}He and heavy ion enhancements result from plasma wave turbulence which could be generated by nonrelativistic electron beams. Further, Miller discussed the possibility of preferential acceleration of heavy ions due to the cascading of Alfven waves. This model does not request preacceleration. Meyer (1996) suggested the preferential acceleration of heavy ions and Temerin and Roth (1996) discussed the possibility of selective acceleration of ^{3}He and heavy ions by electromagnetic ion cyclotron waves.

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