PROPERTIES OF ENERGETIC PARTICLES STUDIED FROM GAMMA-RAY OBSERVATIONS

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Abstract

We study properties of accelerated particles during solar flares using Yohkoh gamma-ray observations. We derive proton and electron energy spectra, total numbers of interacting particles on the sun, electron to proton ratios and directivity of accelerated ions. We compare them with the results of Ramaty *et al.* and discuss the particle acceleration process.

1. Introduction

Several gamma-ray flares were observed by Yohkoh in October to December 1991 (Yoshimori 1993; Yoshimori *et al.* 1992a, 1992b, 1994; Kawabata *et al.* 1994). The numbers and spectra of relativistic electrons interacting at the sun can be determined from the gamma-ray continuum observations, whereas the numbers and spectra of energetic protons can be determined from the gamma-ray line observations. We investigate the influence of the abundance variations on the determination of spectra. In the present calculations, we use an isotropic thick-target interaction model (Ramaty *et al.* 1993).

The angular distribution of the interacting ions can be studied using gamma-ray line shapes of Be line at 429 keV and Li line at 478 keV (Murphy *et al.* 1990). These lines result from He-He interactions at the sun. The angular distribution of accelerated ions is influenced by scattering due to plasma turbulence in a magnetic loop. The line shapes resulting from various assumed angular distribution was calculated (Murphy *et al.* 1991). We compare the observed line shapes with the calculated ones.

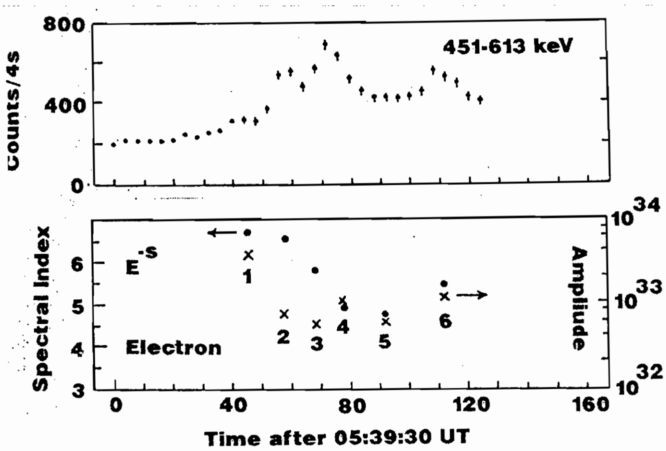

Fig. 1. Counting rate time profile of 415 - 613 keV band and temporal evolution of electron power law index and spectral coefficient for the 1991 October 27 flare.

2. Energy Spectra and Total Numbers of Accelerated Particles

We assume that the electron spectrum is a power law in energies below 100 MeV. The resulting 0.3 - 1 MeV bremsstrahlung photon spectrum can also be given by a power law. The photon spectral index and the differential bremsstrahlung emission (photons / MeV) at 0.5 MeV are calculated by Ramaty *et al.* (1993) as a function of the electron spectral index. Using the Ramaty *et al*'s result, we can derive the energy spectra and total numbers of accelerated electrons.

To determine the energy spectra (10 - 100 MeV) of the interactiong protons at the sun, we used a ratio of 2.22 MeV to C and O nuclear line fluences (Hua and Lingenfelter 1987, Yoshimori 1990). Here we used a ratio of 2.22 MeV to C and O nuclear deexcitation line fluences (Hua and Lingenfelter 1987). This method, however, depends on abundances of both the gamma-ray production site and accelerated ions. We assume two abundance models, composition 1 and composition 2, which are the same abundances as those assumed by Ramaty *et al* (1993). For composition 1, the photospheric composition is used for both the gamma-ray production site and the accelerated ions, and for composoition 2, the composition derived from the 1981 Apr. 27 flare is used for both. Composition 2 shows the characteristics that the accelerated particles are rich in heavy elements and the gamma-ray production site has similar Mg, Si and Fe abundances to the corona, if normalized to O. The limb darkening of the 2.22 MeV line has been known (Wang and Ramaty 1973), but we need not take account it because all of the Yohkoh gamma-ray flares occurred on a disk. Our calculation is carried out for proton spectrum of power law.

We show a counting rate time profile in the 415 - 613 keV band and a temporal evolution of the electron spectral index s and spectral coefficient A (spectrum is represented by AE^{-s}) for the 1991 October 27 flare in Fig.1. We see a spectral hardening around the maximum time of counting rate.

We can derive the proton spectra using the dependence of ratio of 2.22 MeV to 4 - 7 MeV nuclear line fluences on power law index (Ramaty *et al.* 1993). We show the proton spectrum for the 1991 October 27 flare in Fig.2. We give two proton spectra for composition 1 and composition 2 to investigate the influence of abundance variations on the determination of spectra. As shown in Fig.2, the proton flux is larger for composition 1 than for composition 2. It implies that the abundance variations strong affect the proton flux, but the power law index does not much depend on the abundances.

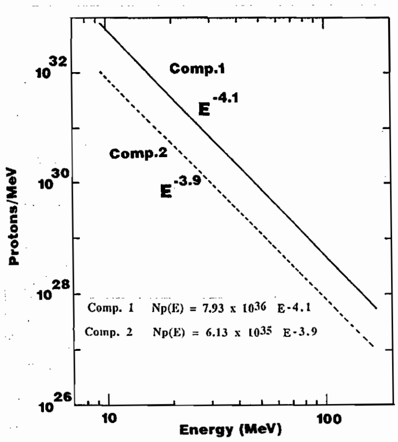

Fig. 2. Proton spectra for composition 1 and composition 2 for the 1991 October 27 flare.

The ratio of interacting electron (0.5 MeV) to proton (10 MeV) fluxes ranges from 1000 to 3000 for composition 1 and from 6000 to 18000 for composition 2. Interplanetary particle observations show that the ratio is generally larger (smaller) than 100 for impuslive (gradual) flares (Kallenrode *et al.* 1992). We see that Yohkoh gamma-ray flares show a trend of the ratio >100, regardless whether the flares is classified as impulsive or gradual.

3. Directivity of Accelerated Ions

A spectral feature of the Be and Li deexcitation lines at 429 and 478 keV resulting from He-He interactions on the sun depends on the angular disrtribution of the interacting He nuclei (Murphy *et al.* 1990). The line feature at 420 keV was observed during the 1991 November 15 flare (Yoshimori *et al.* 1993). The background-subtracted count spectrum, integrated over 4 s at the flare maximum time, is shown in Fig.3. Murphy *et al.*(1992) calculated the photon spectrum for several assumed angular distributions, where both magnetic mirroring and MHD pitch-angle scattering were taken account. Here we assume typical three angular distributions: strong pitch-angle scattering, no pitch-angle scattering and isotropic distribution. The calculated count spectra of Be and Li lines are given by the dotted curve for the three angular distributions in Fig. 3(a), 3(b) and 3(c). The observation supports strong pitch-angle scattering. This implies that the bulk of accelerated He nuclei strongly scatter with plasma turbulence in a flare magnetic loop and interact in the loss cone, leading to the distribution which peaks in the downward direction.

4. Conclusions

Dependence of the proton flux and spectral index on abundances indicates that the abundance variations affect the proton flux, but doex not much affect the power law index. Several flares have been reported for which power law indices and total numbers of both the interacting and interplanetary particles are available (Ramaty *et al.* 1993). These data show that both the interplanetary electron and proton spectra tend to be harder than the interacting spectra. Further, the ratio of numbers of interplanetary to interacting protons can be smaller or larger than 1, whereas the ratio for electrons can be always smaller than 1.

The ratio of electron (0.5MeV) to proton (10MeV) at the sun significantly exceed 100. This value is used to distinguish impulsive flares from gradual flares. The present results suggest that the gamma-ray producing particles in both impulsive and gradual flares are

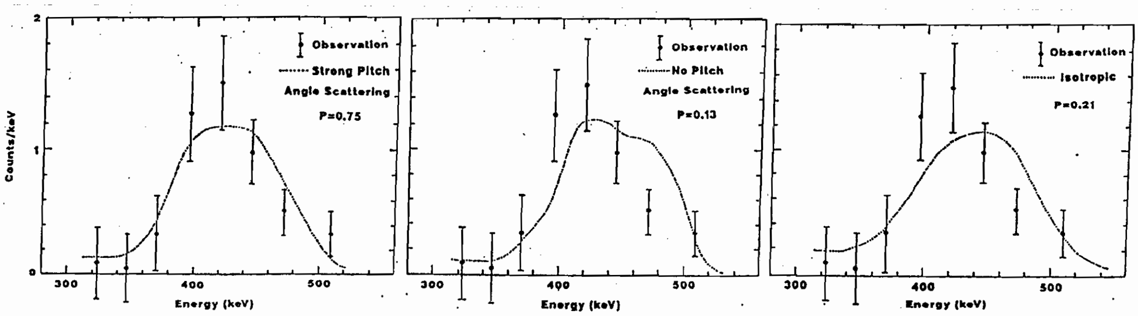

Fig. 3. Count spectra of Be and Li deexcitation lines observed for the 1991 November 15 flare. Calculated curves for strong pitch-angle scattering, no pitch-angle scattering and isotropic distribution are given in Fig3(a), 3(b) and 3(c), respectively.

accelerated by the same mechanism. There are two possibilities to explain the harder spectra of interplanetary particles. One is that acceleration mechanism for the particles observed in interplanetary space is different from that for gamma-ray producing particles. The other is that the particles observed in interplanetary space are accelerated by the same mechanism operating on open magnetic field lines, but higher energy particles preferentially escape to interplanetary space.

The present Be and Li line feature seems to support that the He nuclei suffer strong pitch-angle scattering with turbulent plasma and form a downward-peaked distribution. However, only two events of Be and Li lines have been reported so far. We need more Be and Li line events observed with a high-resolution Ge spectrometer to discuss the detailed angular distribution of accelerated ions.

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