Measurement of Accelerated Particles at the Sun

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Abstract. Solar γ-ray lines and continua provide information on flare-accelerated particles that interact at the Sun. We primarily discuss observations of flare spectra made by the OSSE experiment on *CGRO* and the gamma-ray spectrometer on *SMM*. Continuum γ-ray spectra reflect the MeV electron population. These spectra show various shapes above 0.1 MeV: single power laws, broken power-laws (both hardening and softening > 0.1 to 0.3 MeV), and spectra that harden ≥ 1 MeV. The spectra and directionality of accelerated protons and α–particles are revealed in the narrow lines from excited ambient nuclei and α-^{4}He fusion. These measurements imply power-law spectral indices between ~ -3 and -5 for energies >5 MeV/nucleon, evidence for both broad angular distributions and directionality in the interactions, and high accelerated α/p ratios (~0.5) in many flares. The presence of accelerated ^{3}He is revealed in weak line features suggesting ^{3}He/^{4}He ratios of ~0.1 or greater. Strongly Doppler-broadened lines reveal the composition and directionality of heavy accelerated ions. Fe appears to be enhanced by about the same ratio found in impulsive SEPs. We present some preliminary results on flares that individually were not detected at energies ≥ 1 MeV; their summed spectra exhibit hardening >1 MeV that may be due to nuclear radiation. There appears to be equipartition of energy between accelerated electrons and ions in flares with strong line emission.

LINK BETWEEN SOLAR GAMMA RAYS AND PARTICLES AT THE SUN

Figure 1 shows the γ-ray spectrum of the 1991 June 4 X12+ solar flare (N30E70) observed by the *Compton Gamma Ray Observatory (CGRO)* OSSE experiment.[1] The captions describe how γ-ray line and continuum studies reveal the physics of flares[2-5]. We use this figure to illustrate what has been learned about ion acceleration, transport, and interaction in flares.

Electron bremsstrahlung

We represent the electron bremsstrahlung by a power law(s) in this fit to the data. The shape of the continuum and its strength is variable from flare-to-flare and within flares. We find single power laws, broken power-laws (both hardening and softening >0.1 to 0.3 MeV), and spectra that harden > 1 MeV[6]. The acceleration process in flares is capable of producing particles that are energetically dominated by ions[7] or by electrons, as in electron-dominated episodes of some flares[8]. The nuclear contribution in these latter events is at least an order of magnitude below that typically found for events in which nuclear lines were observed. A tenfold decrease in the >1 MeV electron bremsstrahlung/nuclear line ratio was observed over a one hour period during the 1991 June 4 flare[1,9].

Narrow Nuclear Lines

About 30% of all flares with emission > 0.3 MeV exhibit characteristic features of ion interactions. Narrow γ-ray line observations are key to understanding the characteristics of accelerated protons and α particles at the Sun. They also provide information on ambient composition, temperatures, and densities. To date 17 distinct and relatively narrow de-excitation lines have been identified in solar flares[6]. These originate from proton and α-particle interactions on ambient material and include lines at 0.847 MeV (^{56}Fe), 1.238 MeV (^{56}Fe), 1.317 MeV (^{55}Fe), 1.369 MeV (^{24}Mg), 1.634 MeV (^{20}Ne), 1.778 MeV (^{28}Si), 4.439 MeV (^{12}C), and 6.129 MeV (^{16}O). Share & Murphy[10] found flare-to-flare variations in relative line fluxes suggesting that the abundance of elements in the flare plasma is grouped with respect to first ionization potential (FIP). They also showed that the Ne/O line ratio (see Figure 1) suggests that power-laws fit the accelerated particle spectra better than the

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14. ABSTRACT
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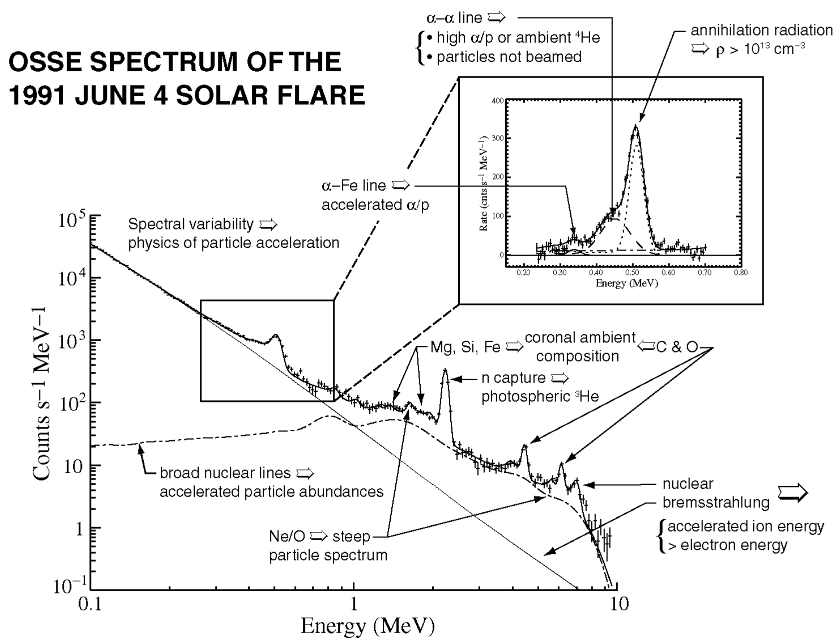


FIGURE 1. OSSE spectrum of the 1991 June 4 solar flare summarizing the physics revealed by γ-ray spectroscopy.

harder (at low energy) Bessel functions used previously. Using the published line fluences, measured cross sections, and kinematical calculations, Ramaty *et al.* showed that the composition of the flare plasma is, on average, close to coronal[11]. However, the flare on 1988 December 16 was depleted in low FIP emission lines which suggests a composition similar to that of the photosphere[10]. This is consistent with a local density of $>10^{14}$ cm^{-2} found in our study of the annihilation line and continuum[12] (see insert Figure 1). This suggests that flare particles may interact in regions with compositions ranging from those found in the upper photosphere to those in the corona. Recently reported spectroscopic measurements of flares with OSSE and *Yohkoh* suggest that the ambient composition may also change within flares[1,13]. This implies that ions accelerated in different flares and at different times in flares may interact at significantly different depths in the solar atmosphere. This could happen, for example, if the height of the magnetic field mirroring point varies.

Recently we have performed detailed spectroscopic studies on the narrow lines that reveal red shifts in the energies for flares near the center of the solar disk[6]. This suggests a dominance for interactions of particles moving in the downward direction.

The delayed 2.223 MeV neutron-capture line is the most intense line observed in spectra of flares that are not too close to the limb. Its narrow width and strength makes it an excellent indicator of the presence of ions in flares. Measurement of its intensity and temporal variation relative to prompt de-excitation lines has provided information on the spectra of ions above ~10 MeV[2] and on the concentration of ^{3}He in the photosphere[14]. The latter measurements are possible because ^{3}He nuclei capture neutrons in competition with photospheric hydrogen and this affects the decay time of the 2.223 MeV capture line. Observations[1,13] with *SMM*/GRS, *GRANAT*, *CGRO*/OSSE, and *Yohkoh*/GRS suggest ^{3}He/H ratios of $\sim 2 - 4 \times 10^{-5}$. The ratios are dependent on assumptions concerning the depth of interaction and solar atmospheric model, however.

Helium Composition

The inset of Figure 1 shows a detail of the region containing α-He fusion lines at 0.429 MeV (^{7}Be) and 0.478 MeV (^{7}Li); this complex is particularly sensitive to the angular distribution of flare-accelerated α particles. Its shape was found to be consistent with either isotropic or fan-beam distributions of accelerated α particles[15]. In contrast, a downward beam of accelerated particles was ruled out at high confidence [(99.99% and 99.8%)] for the two most intense disk-centered flares.

We have found high fluxes in the α-He fusion lines relative to the de-excitation lines in the 1991 June 4 flare[1] and in the *SMM*/GRS flares[15]. This led us to conclude that the accelerated α/proton ratio typically had to be large, ~0.5, for an assumed ambient ^{4}He/H abundance ratio of 0.1. Mandzhavidze *et al.* suggested that the ambient ratio might be higher in some flares and described a way in which γ-ray spectroscopy could distinguish between the two explanations[16]. This required the measurement of other lines that result from interactions of α-particles on ^{56}Fe. There is evidence for a weak line at 0.339 MeV from such interactions (see inset of Figure 1) in the *SMM* and *CGRO*/OSSE spectra. Based on this we concluded that, on average, the ambient ^{4}He abundance is consistent with accepted photospheric values and a high accelerated α/p ratio is needed[17]. Mandzhavidze *et al.* performed studies of individual flares and concluded[18] that there is evidence for both a higher accelerated α/p ratio and enhanced ambient ^{4}He.

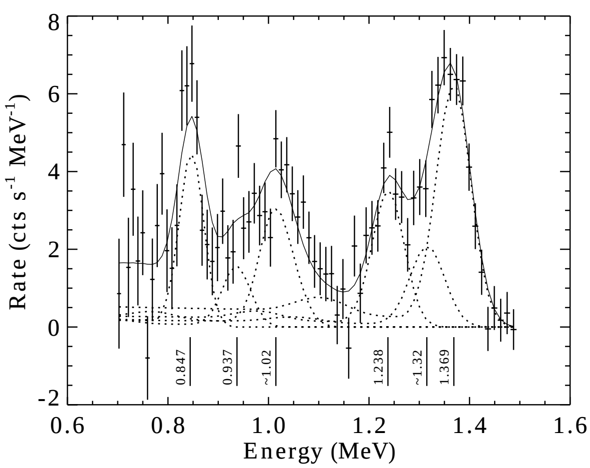


FIGURE 2. Gamma-ray spectrum revealing lines between 0.7 and 1.5 MeV observed in the sum of 19 *SMM*/GRS flares. Line energies are identified.

These same spectral studies have provided information on the accelerated ^{3}He/^{4}He ratio in flares. Shown in Figure 2 is the summed spectrum of 19 *SMM* flares[17] revealing the 0.847 and 1.238 MeV lines from ^{56}Fe, the weak newly-observed line from ^{55}Fe at 1.317 MeV, and the strong ^{24}Mg line at 1.369 MeV. For clarity the best-fit bremsstrahlung, highly broadened lines, and instrumentally degraded radiation have been subtracted before plotting. The key line features for understanding the ^{3}He abundance appear near 0.937 MeV and ~1.02 MeV. The relative strength of the ~1.02 MeV feature suggests a high accelerated α/p ratio from interactions on ^{56}Fe or high ^{3}He/^{4}He ratio from interactions on ^{16}O, or both. There is evidence for ^{3}He in the shift of the data points to higher energies in comparison with a model for ^{3}He/^{4}He = 0. On the other hand the weakness of the 0.937 MeV line generally precludes a flare-averaged ^{3}He/^{4}He-ratio close to 1. Studies of individual *SMM* flares[18] suggest that a ^{3}He/^{4}He ratio of 0.1 was consistent with all the flares and that a ratio as high as 1 could occur in some flares. Therefore the accelerated ^{3}He/^{4}He ratio is often $10^3 \times$ that found in the photosphere.

Accelerated Heavy Ions

We have recently demonstrated the ability to spectroscopically reveal the broad γ-ray lines from interactions of accelerated ions with ambient H and ^{4}He in data obtained by *CGRO*/OSSE and *SMM*/GRS[19]. Broad lines near 0.847 MeV (^{56}Fe) and 4.439 MeV (^{12}C) are individually resolved as can be seen in Figure 3. Broad lines from ^{24}Mg, ^{20}Ne, and ^{28}Si are not resolved from each other. The ^{16}O lines are also blended.

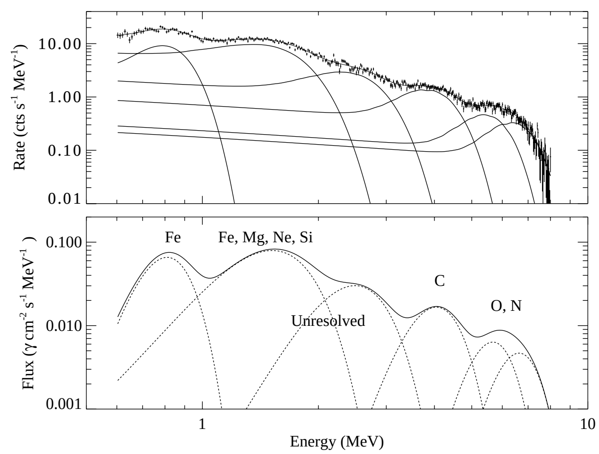
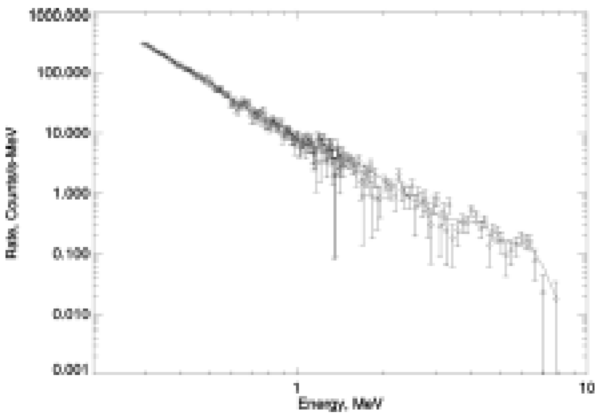


FIGURE 3. γ-ray spectrum revealing broad lines from accelerated heavy ions. Count spectrum after subtracting narrow lines and bremsstrahlung continuum (top panel). Inferred photon spectrum with lines identified (bottom panel).

Measurements of the widths and energies of these broad lines imply that the particles interact over a broad range of incident angles and suggest that they preferentially interact in the sunward direction. Comparisons of broad-line fluxes from individual accelerated nuclei with the respective fluxes in narrow lines from the ambient material measure the relative enhancements in the accelerated particles. We find that the accelerated ^{56}Fe abundance is enhanced over its ambient concentration by a factor consistent with that measured in solar energetic particles (SEP) in space from impulsive flares.

FIGURE 4. Summed spectrum from 40 flares with emission ≤ 1 MeV.



In a related study, we summed spectra from 40 flares observed by the *SMM*/GRS with no significant emission ≥ 1 MeV. We were interested in determining whether the bremsstrahlung actually continued to energies >1 MeV and/or weak nuclear line emission was present. Figure 4 shows the results of this summation. There clearly is emission >1 MeV. The spectrum is consistent with either a sum of two power laws or the sum of a power law and nuclear spectrum. The fall off in counts >7 MeV suggests a nuclear spectrum. However, the spectrum is significantly different from the one shown in Figure 1 in that narrow lines (e.g. the 2.223 MeV line) appear to be weak. It is possible, therefore, that the nuclear contribution is dominated by contributions from heavy ions. Miller discusses the conditions under which this might occur[20].

A catalog of all the flares observed by the *Solar Maximum Mission* (*SMM)*/GRS spectrometer has been published[21] and a compilation of high-energy flares observed by the *CGRO*/OSSE instrument is online at http://gamma.nrl.navy.mil/solarflare/flarelib.htm.

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