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Particle Acceleration in Solar Flares and Coronal Mass Ejections

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Abstract.

The Sun accelerates ions up to tens of GeV and electrons up to 100s of MeV in solar flares and coronal mass ejections. The energy in the accelerated tens-of-keV electrons and possibly $\sim$1 MeV ions constitutes a significant fraction of the total energy released in a flare, implying that the particle acceleration and flare energy release mechanisms are intimately related. The total rate of energy release in transients from flares down to microflares/nanoflares may be significant for heating the active solar corona.

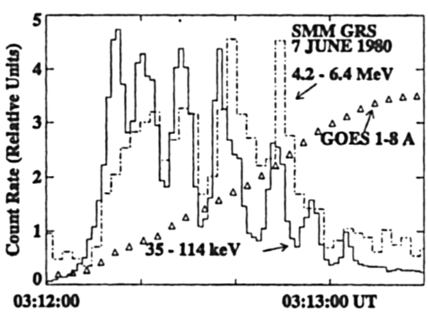
Shock waves driven by fast CMEs appear to accelerate the high-energy particles in large solar energetic particle events detected at 1 AU. Smaller SEP events are dominated by $\sim$1 to tens-of-keV electrons, with low fluxes of up to a few MeV/nucleon ions, typically enriched in ^{3}He. The acceleration in gamma-ray flares appears to resemble that in these small electron–^{3}He SEP events.

1. Introduction

The Sun is the most powerful natural particle accelerator in our solar system, able to accelerate ions to energies of tens of GeV and electrons to hundreds of MeV. This acceleration occurs as a consequence of transient releases of energy in solar flares and coronal mass ejections (CMEs). Solar flares are the most powerful explosions in the solar system, able to release up to 10^{32}–10^{33} ergs in 10^2–10^3 s. The accelerated 10–100 keV electrons (and possibly $\gtrsim$1 MeV/nucleon ions) appear to contain a significant fraction, perhaps the bulk, of this energy, indicating that the particle acceleration and energy release processes are intimately linked. How the Sun releases this energy, presumably stored in the magnetic fields of the corona, and how it rapidly accelerates electrons and ions with such high efficiency and to such high energies, is presently unknown. Furthermore, transient energy releases by the Sun extend down in size to at least microflares and perhaps even nanoflares ($\sim 10^{-6}$ and 10^{-9}, respectively, of the energy release of the largest flare). The total rate of energy release by all these flares and flare-like transients may be significant for the heating of the active corona, which is the dominant source of the soft X-ray luminosity of the Sun.

CMEs are transient ejections of material from the solar corona (the outer atmosphere of the Sun) into the interplanetary medium. On average, $\sim 5 \times 10^{15}$ g of material are ejected per CME, with a range of speeds from $\lesssim$100 km/s to $\sim$2000 km/s. About 1/3 of all CMEs are traveling fast enough, relative to the ambient medium, to drive a collisionless shock wave. These shocks appear to be responsible for accelerating the very high energy particles observed at 1 AU in Large Solar Energetic Particles (LSEP) events. Smaller SEP events detected in the interplanetary medium are dominated by nonrelativistic, $\sim$1 to tens-of-keV electrons, and appear to come from solar flares or flare-like events rather than CMEs. The ion components of these events are weak and usually only extend up to a few-MeV/nucleon energies, but often are highly enriched in ^{3}He and heavy elements.

The ability to release energy impulsively and accelerate particles to high energies is a common characteristic of magnetized cosmic plasmas at many sites throughout the universe, ranging from magnetospheres to active galaxies. The basic physics of these processes can best be studied on the active Sun; the accelerated particles range up to cosmic-ray energies, and the escaping particles can be sampled directly, while those which interact with the solar atmosphere can be observed via their electromagnetic emissions. Furthermore, the proximity of the Sun means the region where the flare energy release and particle acceleration takes place can be located, and the conditions within the region can be studied in detail to provide an understanding of these fundamental physical processes.



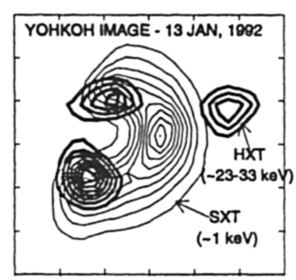


Figure 1. (a-left) Time profiles for a flare showing near-coincident impulsive peaks in 35–114 keV hard X-rays from energetic electrons and 4.2–6.4 MeV γ-rays from energetic ions (after Chupp 1990). (b-right) The M1 limb-flare seen with *Yohkoh* SXT and HXT (after Masuda et al. 1994).

2. Solar Flares

Bursts of hard X-rays ($\gtrsim$20 keV) are the most common signature of the impulsive phase of a solar flare (Figure 1a). These X-rays are produced by bremsstrahlung of accelerated electrons colliding with the ambient solar atmosphere. If these electrons are indeed nonthermal (i.e., electron energy $E_e \gg kT$ of the ambient gas), then the energy lost by the electrons to bremsstrahlung in collisions with ambient ions is only a small fraction ($\sim 10^{-5}$) of their energy lost to Coulomb collisions with ambient thermal electrons. This inefficiency means that, for many

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flares, the energy in accelerated >20 keV electrons must be comparable to the total flare radiative and mechanical output (Lin & Hudson 1976). Thus, the acceleration of electrons to tens of keV may be the most direct consequence of the basic flare-energy release process.

During the flare's impulsive phase, the *Yohkoh* Hard X-ray Telescope (HXT) often observes double footpoint structures at tens of keV energies (Figure 1b), with the two footpoints brightening simultaneously to within a fraction of a second (Sakao 1994). These coincide, spatially and temporally, with Hα and white-light brightenings, implying that nonthermal, tens-of-keV electrons are interacting with a cool ($T<10^5$ K) environment. Very rapid transport of energy from the release site down to the footpoint interaction regions is required. This can only be achieved by fast electrons streaming down the loop and depositing their energy in lower coronal and chromospheric footpoints. The resulting heating of the ambient gas leads to evaporation of chromospheric material and flare radiation in the visible, UV/EUV, and soft X-rays (Figure 1a, triangles). Hard X-ray studies of electron time-of-flight (Aschwanden et al. 1996) further support this nonthermal, thick-target model, but it is unclear how the implied huge currents (up to 10^{36} electrons/s or 10^{17} amps) can conform to the global electrodynamic constraints of the flare environment (Miller et al. 1997).

For some flares occurring near the solar limb, HXT has detected a cotemporal, weaker, hard X-ray source in the corona (Masuda et al. 1994; Alexander & Metcalf 1997) above the soft X-ray loop linking the hard X-ray footpoints (Figure 1b). This source has been interpreted as evidence for energy release by magnetic reconnection in a region above the soft X-ray loop. Further evidence for this interpretation is provided by the observation of cusp-like structures in soft X-rays (Tsuneta 1996).

Hard (>20 keV) X-ray microflares, 10–100 times less intense than small flares, occur every ~5 minutes (Lin et al. 1984) near solar maximum, with the smaller ones occurring more frequently. Recently, high-sensitivity measurements down to ~8 keV with the *Compton Gamma-Ray Observatory* (CGRO) BATSE experiment show that solar impulsive bursts are observed $\gtrsim$3 times more often above 8 keV than above 25 keV (Feffer 1996; Lin 1997). Essentially every active-region transient brightening in thermal soft X-rays (Shimizu et al. 1995) is accompanied by an impulsive, nonthermal, >8 keV burst. This suggests that the flare process may be a fundamental way by which stored magnetic energy is transiently released in the Sun's corona (see Parker 1988). If the nonthermal spectra extend down to ~5 keV, the average rate of energy deposition by microflare accelerated electrons, assuming nonthermal X-ray production, could be a significant fraction of that required to heat the active-region corona.

Nuclear collisions of accelerated protons, α-particles, and heavier nuclei with the ambient solar atmosphere result in a rich spectrum (Figure 2) of lines (Ramaty & Murphy 1987; see also Ramaty & Mandzhavidze 2000, these Proceedings). Gamma-ray line emission has been observed from many solar flares, mostly by the *Solar Maximum Mission* (SMM) and CGRO (Chupp 1990; Share & Murphy 1995; Murphy et al. 1997). Energetic protons and α-particles colliding with carbon and heavier nuclei produce narrow de-excitation lines (widths of ~few keV to ~100 keV), while energetic heavy nuclei colliding with ambient hydrogen and helium produce much broader lines (widths of a few hundreds keV

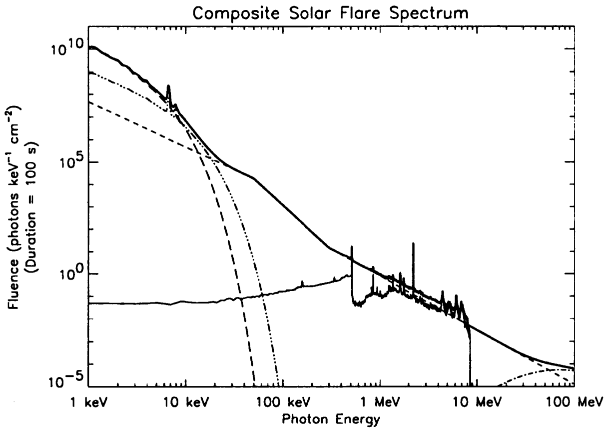

Figure 2. The composite spectrum (Dennis 1999) for a large flare, from multitemperature thermal flare plasma (dot-dash and long dash lines on left) through the hard X-ray/gamma-ray continuum (short dash and solid lines), gamma-ray lines (lower solid line), and pion decay (dot-dash line in lower right).

to an MeV). Neutron capture on hydrogen and positron annihilation produce narrow lines (at 2.223 MeV and 0.511 MeV, respectively) which are delayed.

In Figure 1a, the 4.1–6.4 MeV gamma-ray emission, which is dominated by broad and narrow lines produced by nuclear collisions of $\gtrsim$ 10 MeV ions, has a similar profile to the hard X-rays but with a delay of about 2 seconds. Thus, electrons and ions appear to be accelerated to high energies nearly simultaneously, on short time scales. Gamma-ray and neutron emission at tens to hundreds of MeV, observed in very large flares, have similar time scales indicating that ions and electrons of hundreds of MeV to GeV energies are also accelerated rapidly.

The gamma-ray line observations show that $>$ 10 MeV ions are accelerated in essentially all large flares with intense hard X-ray emission but, because of the relatively low sensitivity of the gamma-ray observations, it is not known whether all flares accelerate $\gtrsim$10 MeV ions. The 10–100 MeV/nucleon ions that produce the bulk of the γ-ray line emission contain only a small fraction of the energy in the $\gtrsim$20 keV electrons. However, systematic study of SMM γ-ray–line flares (Share & Murphy 1995) shows that the 1.634 MeV ^{20}Ne line is unexpectedly enhanced. Because the cross section for ^{20}Ne has an unusually low energy threshold ($\sim$2.5 MeV), this effect may be due to large fluxes of low-energy ions with a total energy content perhaps comparable to that in the accelerated electrons, rather than to an overabundance of neon (see Ramaty & Mandzhavidze 2000, these Proceedings; Ramaty et al. 1995; Emslie, Brown, & MacKinnon 1997).

3. Large Solar Energetic Particle Events (LSEPs)

Studies of solar energetic particles in the interplanetary medium (IPM) indicate that there are two main classes of events (Table 1). LSEP events produce a sig-

Table 1. Solar Energetic Particle Event Characteristics

Characteristic	Large Solar Energetic Particle (LSEP) Events	Nonrelativistic ^{3}He-rich Events
Dominant Particle Species	$\gtrsim$10 MeV protons	~2–100 keV electrons
Electron to Proton Ratio	small	large
$^3He/^4He$ Ratio	"normal" solar ($\sim 5 \times 10^{-4}$)	~0.1–1 ($\sim 10^2$ to $\gtrsim 10^3$ times normal)
Heavy Nuclei	"normal" solar	enhanced abundances of Fe, Mg, Si, S
Ionization States	typical of 1–2 $\times 10^6$ K normal corona (e.g., Fe^{+13})	highly stripped, (e.g., Fe^{+20}) typical of $\sim 10^7$ K plasma
Extent in Solar Longitude	$\gtrsim$ 100 degrees	tens of degrees
Event Rate (at solar maximum)	tens per year	$\gtrsim 10^3$ per year
Flare Association	large solar flare (but sometimes missing)	mostly small flares but often no flare
Solar Soft X-ray Burst	gradual, e-folding decay times $>$ 10 minutes	impulsive, e-folding decay times $<$ 10 minutes
Interplanetary Association	Coronal Mass Ejection (CME) with fast shock	interplanetary type III radio burst

nificant flux of $\gtrsim$10 MeV protons (Figure 3a) and are the most intense and most energetic events. They usually occur after a large solar flare and occasionally exhibit acceleration up to relativistic energies, as in the first LSEP event discovered by Forbush (1946). Besides energetic ions, electrons are also observed, but the fluxes of energetic protons dominate over electrons. Tens of LSEP events are detected per year near solar maximum.

The solar energetic particles propagate away from the Sun along the Archimedean-spiral interplanetary magnetic field (Figure 3b). For magnetically well-connected LSEP events, the energetic particle fluxes typically rise rapidly soon after a large solar flare (Figure 3a), with the fastest particles arriving earliest. The observed velocity dispersion in the onset times is usually consistent with particles of all energies being accelerated simultaneously near the Sun and travelling the same distance along the spiral interplanetary magnetic field. The rapid rise to maximum is usually followed by a much slower decay which has been attributed to scattering of the particles by irregularities in the interplanetary magnetic field and/or to prolonged acceleration.

The observed ionization states of LSEP particles are typical of a 1–2 $\times 10^6$ K plasma, indicating they come from the quiescent solar corona and not from the hot, $\gtrsim 10^7$ K, solar-flare plasma, from the solar photosphere, or from the chromosphere where temperatures are less than 10^5 K. The elemental composition of

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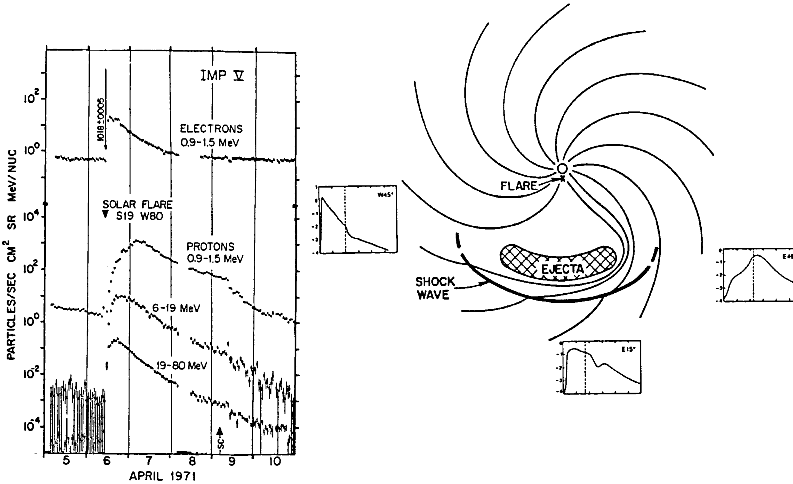

Figure 3. (a-left) Example of a Large Solar Energetic Particle (LSEP) event from a solar flare at W80° solar longitude (van Hollebeke, Wang, & McDonald 1974). The passage of a shock wave is indicated by the sudden commencement (labeled SC at lower right) seen at the Earth. (b-right) The interplanetary magnetic field is drawn out to an Archimedes spiral as shown in the upper half. In the lower half, the rectangles show representative profiles of 20 MeV protons seen by observers when the source flare is at various solar longitudes, assuming a fast coronal mass ejection (CME) is propagating outward with a shock wave (heavy line) ahead (adapted from Cane et al. 1988). For each profile, the dashed line indicates the time of passage of the CME shock wave. The vertical axis is the logarithm (base 10) of the proton flux, while each tick of the horizontal time scale is one day.

the LSEP particles, once they have been corrected for the q/m (charge to mass) dependence of the acceleration and propagation processes, appear to closely reflect typical coronal abundances.

LSEP particles are often spread over about $\sim$100 degrees in solar longitude away from the flare site (Figure 3b). The observed lack of compositional variation with longitude, and the rapid onsets for LSEP events even for flares located far from the connection longitude, suggests that the acceleration itself is widespread, as expected for acceleration by widespread shock waves (see review by Lin, 1987). Since LSEP events and fast CMEs are typically accompanied by flare soft X-ray emission of relatively long duration, with e-folding decay times of $\gtrsim$ tens of minutes, LSEPs are also called "gradual" events.

Because of the scattering in the IPM, the time of acceleration near the Sun is difficult to determine accurately, but the LSEP energetic ions appear to be accelerated tens of minutes after the flare (Figure 4a), even after first-order corrections for scattering are taken into account (Kahler 1994). The delays are interpreted as evidence for acceleration of the ions by the CME shock when it reaches altitudes of $\sim$ 5 to 15 solar radii. In LSEP-type events, the electrons also appear to be injected tens of minutes after the flare, especially in events which were not magnetically well connected (Krucker et al. 1999). For these delayed events, the EUV Imaging Telescope (EIT) on the *Solar and Heliospheric Observatory* (SOHO) often detects a flare wave propagating across the Sun at speeds of ~hundreds of km/s. The delays appear consistent with acceleration of the electrons by the wave/shock as it crosses the magnetic field line connected to the spacecraft at 1 AU.

An increase in the energetic ion fluxes, particularly at low ($\lesssim$1 MeV) energies, is often observed around the time of passage of a fast CME shock past the spacecraft, indicating that the shock can continue to accelerate particles even in the IPM near 1 AU. At late times in LSEP events, the shape of the time profile of the particle fluxes varies with solar longitude of the flare (Figure 3b) in a way that is consistent with distortion of the interplanetary magnetic structure by the CME and with continued acceleration by the shock wave as the CME and shock propagate outward through the IPM (Cane, Reames, & von Rosenvinge 1988). Above several MeV energies, however, interplanetary shock acceleration effects are rarely, if ever, detected unless energetic particles are already present in the IPM. One of the primary unanswered questions for LSEP particle acceleration is: how are particles accelerated near the Sun by CME shocks to very high (GeV) energies?

4. Solar, Nonrelativistic Electron–^{3}He-rich Events

The second type of solar energetic particle event (Table 1) is dominated by electrons (Figure 4b) of ~1 to tens-of-keV energies. Such nonrelativistic electron events occurred far more frequently, $\sim 10^3$ events per year over the whole Sun at solar maximum, than the LSEP events (Lin 1985). Recent measurements show that the electron spectrum often continues to monotonically increase down to $\sim$ 1 keV (Lin et al. 1996); many events are only detected below $\sim$ 10 keV. At these low energies, the electrons must have been accelerated high in the solar corona or else they would be lost to Coulomb collisions before escaping the Sun. As the electrons escape the Sun and travel outward through the IPM, they excite plasma waves which in turn produce solar type-III radio bursts.

In contrast to LSEP events, the electron-to-ion flux ratio is generally very large in nonrelativistic electron events. The ion fluxes are usually very low and dominated by low energy, $\lesssim$ 1 MeV/nucleon ions. ^{3}He is often enriched over ^{4}He by factors of hundreds to thousands over the normal solar abundance ratio of $\sim 5 \times 10^{-4}$. Often protons, as well as ^{4}He, were also observed to be very underabundant. As experiments improved in sensitivity, ^{3}He-rich emission was observed to accompany essentially all of the more intense, nonrelativistic electron events (see Figure 4b).

The nonrelativistic electron–^{3}He events are typically associated with small flares or subflares, or lack a flare entirely, and there is no association with CMEs. The electrons and ^{3}He nuclei often propagate nearly scatter-free through the IPM and quickly escape the inner solar system, leading to relatively rapid decay of the fluxes. Analysis of the velocity dispersion in the onset times indicates that the accelerations of the ^{3}He ions and electrons occur nearly simultaneously. The associated flares, when present, generally have impulsive, short duration (e-folding decay times < 10 minutes) soft X-ray bursts, so these are also called

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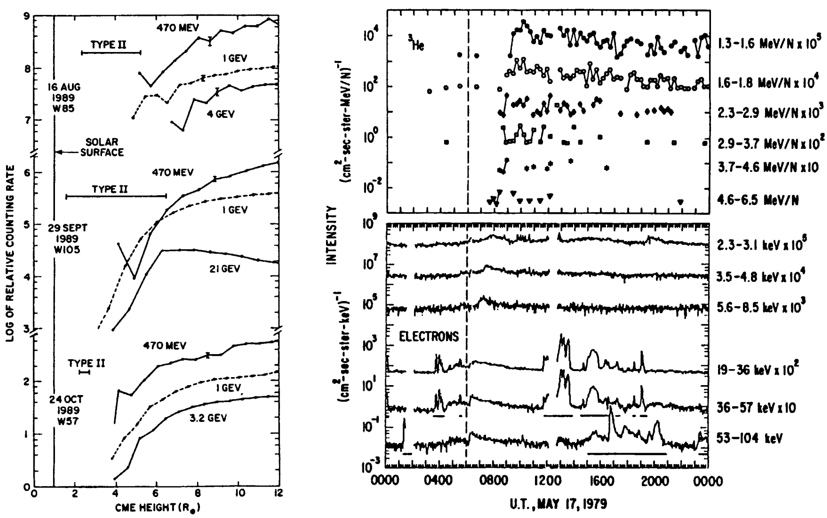

Figure 4. (a-left) Proton injection profiles near the Sun, inferred from the onsets for three LSEP events with ion emission, plotted versus the location of the associated CME. The injections appear to occur when the associated CME is at $\gtrsim$5–15 solar radii (from Kahler 1994). (b-right) Nonrelativistic electron–^{3}He-rich event (Reames, von Rosenvinge, & Lin 1985). The lower panel shows an electron event beginning at ~0620 UT at 53–104 keV. Velocity dispersion is clearly evident with the lowest energy (2.3–3.1 keV) electrons beginning ~0730 UT. The horizontal lines indicate times of contamination by terrestrial, upstream particles or solar X-rays. The upper panel shows the associated ^{3}He event, which also exhibits velocity dispersion. In this event, the ^{3}He/^{4}He ratio is >10 and no solar flare was observed. The vertical dashed line indicates the time of the solar type-III radio burst.

"impulsive" events. The flares are located near W60° longitude, i.e., magnetically well-connected to the terrestrial observer, with a spread of only a few tens of degrees in longitude. The smaller spread indicates that the acceleration process is probably localized in the vicinity of the flare.

The elemental composition in ^{3}He-rich events shows substantial enhancement in the abundances of heavy nuclei; Mg, Si, S, Ne, and Fe, but not O, C, or N (Reames, Meyer, & von Rosenvinge 1994). The ionization states appear to be higher than for LSEPs; in early measurements, Fe was detected with an average charge state of around +20 for ^{3}He-rich events compared to around +13 for LSEPs, suggesting that either the source has a temperature of $\gtrsim 10^7$ K, comparable to the heated flare plasma, or perhaps that the accelerated ions had undergone some stripping of their bound electrons. More recent charge-state measurements with the recently launched ACE spacecraft, however, do not appear to cleanly separate into these two classes.

The characteristics of nonrelativistic electron–^{3}He-rich events (Table 1) indicate that they comprise a class of solar particle acceleration events distinct from LSEPs. The enormous enhancement of ^{3}He suggests some sort of resonant acceleration process. An attractive theory has been suggested in analogy with phenomena observed in the Earth's auroral zone (Temerin & Roth 1992). There, electromagnetic ion-cyclotron waves are often detected that have been driven unstable by auroral electron beams, which may be analogous to the electrons accelerated in solar impulsive events. For plasmas with solar composition, these waves have a frequency between the hydrogen gyrofrequency and the two-ion hybrid frequency, slightly above the ^{4}He gyrofrequency. ^{3}He^{++}, then, is the only ion which can be directly resonant with these waves, and it can be efficiently accelerated up to $\sim$ MeV/nucleon energies.

5. Discussion

How are the energetic particle populations at the Sun, inferred from X-ray and gamma-ray emissions, related to the ones detected in SEPs in the IPM? Where both a flare hard X-ray burst and associated interplanetary electron event are observed, the number of electrons escaping to the interplanetary medium always appears to be only 0.1–1% of the number at the Sun. The sensitivity of the hard X-ray observations is limited, however.

The ratio of the number of escaping $\gtrsim 10$ MeV protons to the number of protons interacting to produce gamma-rays at the Sun varies from $\lesssim 10^{-3}$ to $\gtrsim 10^2$ (Cliver et al. 1989). The observed gamma-ray flares generally have small ratios of escaping-to-interacting ions, while many LSEP events have only upper limits on the gamma-ray line emission. The largest nuclear gamma-ray flares require the acceleration of about the same number of energetic >10 MeV ions as the largest LSEP events, to within an order of magnitude. Observations of nuclear gamma-ray lines show that >10 MeV ions are accelerated in essentially all large flares with intense hard X-ray emission, but it is not known whether small flares accelerate $\gtrsim$10 MeV ions. The high ambient density required for detectable gamma-ray line production implies that the gamma-ray–producing ions are not accelerated by CME shocks.

The ratio of energetic electrons to energetic protons for nuclear gamma-ray flares, obtained through comparisons of the gamma-ray line emission to electron bremsstrahlung continuum emission, is substantially larger than observed for LSEP events, suggesting that nuclear gamma-ray flares may be more similar to nonrelativistic electron–^{3}He-rich events than to LSEP events (see Table 1). The soft X-ray bursts for these flares can be either impulsive or gradual. Recent analysis of the Doppler-broadened nuclear gamma-ray line spectra from SMM and CGRO (Share & Murphy 1999) have shown that accelerated ^{56}Fe is enhanced over ambient Fe by about an order of magnitude, consistent with electron–^{3}He-rich events, but the enhancements of accelerated Mg and Ne over their ambient values are significantly lower than in those events.

The acceleration process in flares, particularly for nonrelativistic electrons, appears to be intimately related to the basic energy release process in flares, but the actual acceleration mechanism remains a mystery. High spectral-resolution hard X-ray observations of a flare show a sharp break (Lin & Schwartz 1987) which suggests field-aligned, DC electric fields (Johns & Lin 1992; Lin & Johns 1993; Holman 1995) are at least partly responsible, but stochastic acceleration by waves (Miller 1991) may also be important. Planned future spacecraft missions, such as the *High Energy Solar Spectroscopic Imager* (HESSI) scheduled for launch in mid-2000, and the *Particle Acceleration Solar Observatory* (PASO) planned to be synchronously orbiting at 0.17 AU (for the following solar maximum) may provide the key observations required for understanding of the physics of these fundamental processes.

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