

What We Don't Understand about Ion Acceleration in Flares

Donald V. Reames

NASA/Goddard Space Flight Center, Greenbelt, MD

Abstract. There are now strong associations between the ^3He -rich, Fe-rich ions in “impulsive” solar energetic particle (SEP) events and the similar abundances derived from γ -ray lines from flares. Compact flares, where wave energy can predominate, are ideal sites for the study of wave-particle physics. Yet there are nagging questions about the magnetic geometry, the relation between ions that escape and those that interact, and the relative roles of cascading Alfvén waves and the EMIC waves required to enhance ^3He . There are also questions about the relative timing of ion and electron acceleration and of heating; these relate to the variation of ionization states before and during acceleration and during transport out of the corona. We can construct a model that addresses many of these issues, but problems do remain. Our greatest lack is realistic theoretical simulations of element abundances, spectra, and their variations. By contrast, we now have a much better idea of the acceleration at CME-driven shock waves in the rare but large “gradual” SEP events, largely because of their slow temporal evolution and great spatial extent.

1. Introduction

We have learned a great deal about ion acceleration in solar flares in recent years (see *e.g.* Reames 1999 and references therein). Most striking are the unusual abundance enhancements observed in the energetic particles that come to 1 AU (*e.g.* Reames, Meyer, & von Rosenvinge 1994 and references therein). Persistent enhancements of $^3\text{He}/^4\text{He}$ by factors of ~ 1000 , and Fe/C by factors of ~ 10 , relative to coronal values, have been measured in hundreds of flare-associated SEP events. These ^3He -rich SEP events were closely associated with C- and M-class X-ray flares (Reames et al. 1988) occurring at a rate corresponding to ~ 1000 flares yr^{-1} on the solar disk. Thus, during the 1980s, it was already possible to predict that similar abundances might be observed in the broad γ -ray lines produced where the particles interact in the low solar atmosphere. These abundances were subsequently observed (Murphy *et al.* 1991; Share & Murphy 1998; Mandzhavidze, Ramaty, & Kozlovsky 1999). The abundance enhancements suggest resonant wave-particle interactions (Fisk 1978; Roth & Temerin 1997) or stochastic acceleration with a complex wave spectrum (Miller & Viñas 1993; Miller & Reames 1995), or both. Furthermore, the abundance enhancements can be used to infer ionization states, hence a plasma temperature (Reames, Meyer, & von Rosenvinge 1994), and the distribution of ioniza-

tion states can also be directly measured at 1 AU (Luhn et al. 1987; Popecki et al. 1999).

The largest SEP events observed near earth are not associated with flares at all, but with fast shock waves driven by coronal mass ejections (CMEs) (e.g. Reames 1999). These “gradual” SEP events can persist for days as the shock expands into the heliosphere and the particles can span $\sim 180^\circ$ of solar longitude, just like the shocks that accelerate them (e.g. Reames, Kahler, & Ng 1997). In these events, ionization states of elements up to Fe are generally similar to those in the corona or solar wind with $Q_{Fe} \sim 14$, even up to 600 MeV/amu (Tylka et al 1995). These ions are neither flare-heated nor stripped by the dense material of the low corona. For these large energetic SEP events, the “flare myth” (Gosling 1993) of their origin is dead. However, though gradual events are large, they are relatively rare, occurring at a rate of only 10-20 events yr^{-1} , a rate much lower than that of even the largest flares. Gradual events are not the subject of this paper.

Despite our progress in understanding the properties of flare-accelerated ions using SEP and γ -ray observations, when we try to construct a comprehensive picture of that acceleration, we find that we confront more questions than answers. In what magnetic topology does the acceleration take place? At what altitude? What is the order of acceleration of electrons and ions and is that consistent with the mechanisms of abundance enhancements? Is one mechanism enough? Does heating occur before, during, or after acceleration? Are the ions we see at 1 AU from the same population as those that produce γ -rays?

2. From ^3He -rich SEPs to Flares to Gamma-Ray Lines

The trail of unusual abundances began 30 years ago when Hsieh and Simpson (1970) observed the first evidence of ^3He enrichment in SEP events near Earth. Before long, 1000-fold enhancements with values of $^3\text{He}/^4\text{He} \sim 1$ were routinely observed, and a ~ 10 -fold enhancements in Fe/O was found in the same ^3He -rich events. It was soon recognized that these events must involve a resonant plasma process (Fisk 1978), but the early measurements with insensitive instruments had suggested that these events were rare. In those days, we still thought that the large (gradual) SEP events came from “normal” flares despite difficulties in association.

With a new generation of instruments launched on the ISEE-3 spacecraft in 1978, we began the quest for the identity of the solar source of these “unusual” ^3He -rich flares. Our first step on this path was to associate the ^3He rich events with the 2-100 keV electrons that seemed to always come with them (Reames, von Roseninge, & Lin 1985). Using the velocity dispersion of the ions, and especially of the electrons, we could project back to determine the flare time within 5-10 min. The electrons accompanying the ^3He were recognized as those that generated kilometric type III radio bursts (Reames & Stone 1986). These bursts also provided timing, and the centroid of the electron distribution could be tracked in space and time as the electrons (and ions) streamed out from the Sun, even providing confirmation of the source longitude. Thus, the serendipitous association of the ^3He -rich ions with electrons and type III bursts gave us excellent identification of the source flares.

Armed with our new data we began to study the associated $H\alpha$ (Kahler et al. 1987) and X-ray (Reames et al. 1988) flares. In the initial study of only 12 ^3He -rich events, 9 had associated $H\alpha$ flares. In the second study of 31 ^3He -rich events, a wide range of X-ray properties were found for the 25 that could be measured, 5 events were M-class X-ray events and 17-were C-class, and their hard- and soft-X-ray time profiles were examined over a wide energy range. The corresponding $H\alpha$ flare classifications ranged from subflares to 2B flares. Only 3 of the 25 events had no apparent X-ray association. Of 12 events observable by SMM, 11 had associated hard X-ray bursts. We were beset by disappointment. There was nothing at all unusual about the flares associated with the ^3He -rich events. We could not have picked a more “normal” sample of flares.

Worse yet, the events were not even rare. Our improved hardware found ~ 100 ^3He -rich events yr^{-1} during solar maxima near 1980 and 1990 as shown in Figure 1 (Reames, Meyer, & von Rosenvinge 1994). From the longitude distribution, we expected the events to be seen only over $\sim 20^\circ$ at magnetically preferred longitudes. Hence, 100 events yr^{-1} near Earth corresponds to ~ 1000 events yr^{-1} on the face of the Sun, compared with ~ 4000 yr^{-1} for hard X-ray bursts, or 10000 yr^{-1} for $H\alpha$ flares or type III bursts. *It was beginning to look as if all flares that accelerated ions were ^3He -rich.* For 1000 ^3He -rich events there were only ~ 10 of the non- ^3He -rich, “gradual” events, and these gradual events were now being associated with fast CME-driven shocks, not flares.

From the SEP perspective, essentially all flares were ^3He -rich and Fe-rich. From this knowledge of SEP properties, it was suggested (Reames 1990) that particles interacting to produce γ -rays in the flare loops might have similar abundances. These predicted abundances of the accelerated “beam” were subsequently observed

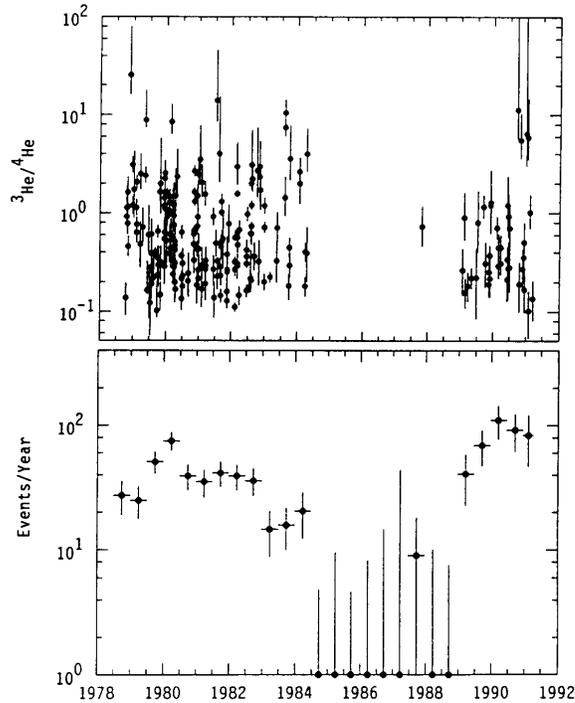


Figure 1. The $^3\text{He}/^4\text{He}$ ratio is shown for individual flare events over 14 years in the upper panel. The event rate, corrected for spacecraft coverage, is shown in the lower panel.

(Murphy *et al.* 1991; Share & Murphy 1998; Mandzhavidze, Ramaty, & Kozlovsky 1999) in the broad lines of γ -ray-line events.

3. Where Does Acceleration Occur?

We have little direct information on when and where the acceleration takes place. There is no characteristic photon emission from the acceleration site. Hard X-rays and γ -rays are produced where electrons and ions plunge into the lower atmosphere, *not* where they are accelerated. Those emissions depend upon the *product* of the energetic particle intensity and ambient density; acceleration occurs where the density is low and photon emission only where it is high. Even the most intense sites of ion acceleration in the heliosphere are invisible in photons; flares are no exception.

Fortunately, however, *electrons* do excite plasma oscillations that result in radio emission when they begin to *stream away* from the acceleration region. The difference in timing, between radio emission and hard X-rays produced by electrons of different energies, has been used to great advantage by Aschwanden *et al.* (1995, 1996) to deduce the height of the acceleration region and to infer its position in the surrounding magnetic topology. Aschwanden *et al.* (1996) conclude that the height of the acceleration region is 1.7 times the loop radius. Hence, the top of the loop is open so electrons can flow down into the loop from above and can also flow out toward interplanetary space. This is the most direct information we have on the spatial location of the acceleration region; its topology allows electrons from a single source to flow in both directions so they can produce both hard X-ray and type III bursts. Of course, this source applies only to electrons, and electron and ion acceleration need not occur together. However, we have no choice but to assume that ion acceleration is closely related if we are to make any further progress in studying flare acceleration. The coincidence in the timing of hard X-rays and γ -rays is sufficiently close to make this assumption reasonable.

4. How Are the Ions Accelerated?

We alluded to acceleration mechanisms in the introduction. These mechanisms are primarily chosen to produce the observed abundance enhancements. Abundances, especially $^3\text{He}/^4\text{He}$, strongly suggest wave-dominated resonant stochastic acceleration. Most flares associated with ^3He -rich events show no evidence of shocks, type II radio emission, or CMEs. The events do have type III radio bursts and hard X-ray bursts, and directly observed electrons. Therefore, we consider two important acceleration mechanisms:

1) Electrons streaming down magnetic field lines generate electromagnetic ion cyclotron (EMIC) waves just below the proton gyrofrequency where they resonate with mirroring ^3He ions (Temerin & Roth 1992; Roth & Temerin 1997). A similar process produces the phenomenon of “ion conics” in the Earth’s aurora where the downward electron beams, EMIC waves, and ions can all be observed *in situ*. Heavier ions, C-Fe can also be accelerated through the second harmonic of their gyrofrequencies, Ω_i , which are proportional to the ion charge-to-mass ratio Q/A . However,

this resonance is narrow and the ionization state Q can be highly dependent on the temperature and its evolution in time.

2) Resonant stochastic acceleration by cascading Alfvén waves (Miller *et al.* 1997) occurs when magnetic reconnection produces turbulence on a large spatial scale, like that of a flare loop. This turbulence is therefore injected at small wave number, k , and the energy Kolmogorov-cascades to higher values of k where it is absorbed by the plasma. Waves cascading down the fast-mode branch are absorbed by electrons (Miller, La Rosa, & Moore 1996; Lenters & Miller 1998), those on the Alfvén branch may be first absorbed by Fe, at smallest Ω_i , then ions with successively higher Q/A , (Miller & Reames 1996) and eventually by He and H (Miller & Roberts 1996). This process can produce smooth enhancements of heavy ions, but *cannot* produce the observed enhancements in ${}^3\text{He}$.

5. When Does Acceleration Occur?

The sequence of events during acceleration is one of the most complex puzzles. Some rules of ordering are defined as follows:

1) The Temerin-Roth mechanism assumes the existence of an electron beam initially; thus, ${}^3\text{He}$ and ions are accelerated *after* the electrons.

2) Cascading waves can accelerate both electrons and ions, but cannot enhance ${}^3\text{He}$.

3) Ion acceleration *must* occur at ambient active-region temperatures of $\sim 3\text{-}5$ MK, *before* any significant heating (Reames, Meyer & von Rosenvinge 1994). Abundance ratios such as Ne/C, for example, are enhanced by an average factor of 3.5 relative to coronal values. At >10 MK all ions ${}^4\text{He}$, C, N, O, Ne, Mg, and Si have $Q/A=0.5$; there could be *no* relative enhancements of these elements since all these ions have the same gyrofrequency and are indistinguishable to acceleration mechanisms. The Lorentz force, that describes the evolution of particle velocity, is a function of Q/A and electromagnetic fields \mathbf{E} and \mathbf{B} ; for macroscopic fields, including those in Alfvén waves, ions with the same Q/A are indistinguishable. This means that electrons can't be accelerated significantly earlier than the ions since they would cause heating and ionization. It is estimated that acceleration time scales are less than a few seconds, while plasma heating time scales are ~ 10 s (Miller & Viñas 1993). With a plasma temperature of ~ 3 MK, we find the pattern of average enhancements vs. Q/A shown in Figure 2 (see Reames, Meyer & von Rosenvinge 1994; Reames 1999).

It is interesting that recent observations of the ionization states of energetic Fe in impulsive events show a broad distribution in Q_{Fe} from ~ 12 to 26 (Popecki et al. 1999). This distribution would be consistent with a situation where particles leak from the turbulent region where the temperature increases as acceleration continues. Acceleration begins when the plasma is cool (~ 2 MK) and continues as it heats to >10 MK. Electron capture by the escaping ions in the high corona might also be a factor, but this process seems incompatible with the presence of highly ionized Fe. The acceleration seems to occur at reasonably low density ($\sim 10^9 \text{ cm}^{-3}$) and high altitude (10-30 Mm).

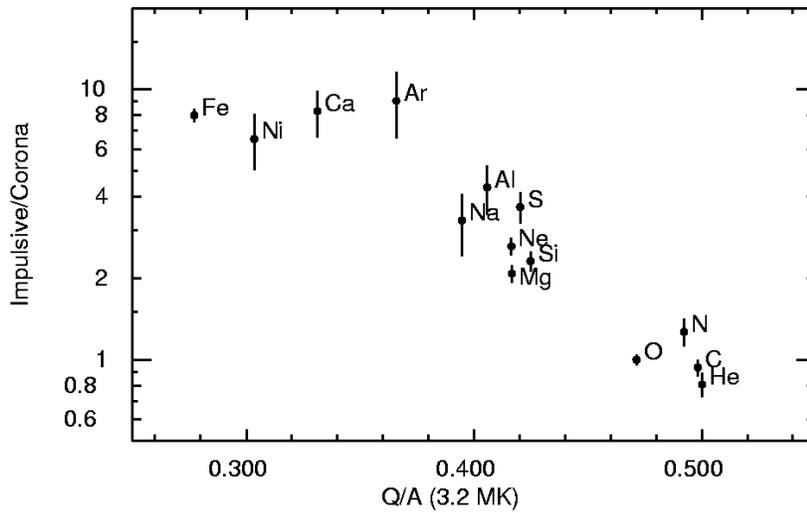


Figure 2. Average abundance enhancements of energetic ions in flares relative to coronal abundances is shown as a function of Q/A .

6. A Model

The cartoon in Figure 3 attempts to present a self-consistent picture that overcomes the conflicting requirements described above. The basic magnetic configuration is that defined by Aschwanden et al. (1996). Resonant stochastic acceleration of both electrons and ions takes place in region (A) in the figure where reconnection of oppositely directed fields takes place above the region of new loop formation.

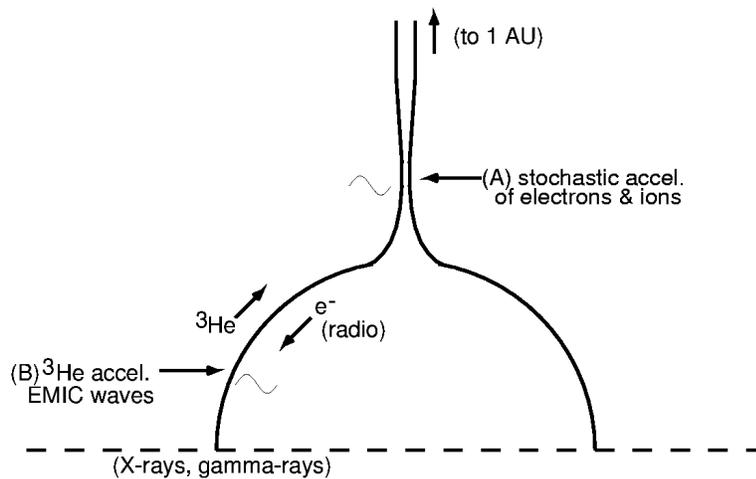


Figure 3. The cartoon shows the resonant acceleration sites of (A) electrons and most ions and (B) ^3He by electron-generated EMIC waves. Particles escape to 1 AU at the top of the figure, produce neutrons, X- and γ -rays in the loop footpoints, and electrons emit radio bursts along the legs of the loop.

Field lines above the acceleration region are open to the interplanetary medium so that outflowing electrons produce type III radio emission, and these electrons and accompanying ions may be observed at 1 AU. Electrons and ions also stream down the legs of the loop to the footpoints where they produce hard X-rays, γ -ray lines, and neutrons that escape easily. As the electrons stream downward, they generate EMIC waves that resonantly interact with ^3He as shown in one of the two legs at (B) in Figure 3. The density at (B) is actually higher than at (A), so the supply of ^3He is ample, although the plasma must not be collisional. The two isotopes of He may actually be accelerated in different source regions, ^4He at (A) and ^3He at (B), but the situation rapidly becomes complicated when the ^3He from (B) propagates up into region (A) where further acceleration can take place. In addition to acceleration in the legs of the new loop like (B), some ^3He may also be accelerated above (A) as the electrons stream outward. Much later, of course, the loops will close below the reconnection region and will fill with hot dense plasma from evaporation of the beam-heated corona.

A first glance, this model seems unnecessarily complex. Perhaps there is some way to generate EMIC waves directly at (A) and accelerate ^3He there. Wouldn't this remove the necessity of acceleration at (B)? Actually, not. If electrons stream down from (A) to produce hard X-rays in the footpoints of the loops, we cannot *prevent* them from generating EMIC waves, just as they do in the aurora. Nor can we prevent the resonant acceleration of ^3He by these EMIC waves. *Acceleration of ^3He seems to be a direct, inescapable consequence of the electron streaming in flares.*

As plasma and magnetic field are swept laterally into region (A), conditions and physical processes there may vary. If conditions favor generation of high-frequency fast-mode waves over Alfvén waves, energetic electrons may greatly exceed ions. This can produce electron-rich flares and super- ^3He -rich events with $^3\text{He}/^4\text{He} > 10$ and $^3\text{He}/\text{H} > 1$, like the event of 1979 May 17 seen at 1 AU. Of course, there may also be events that take place in a magnetic topology that is completely closed; these flares will simply have no corresponding SEP event at 1 AU.

7. Abundance Variations

Mean elements abundances of SEP ions from impulsive flares, averaged over a hundred events, show persistent enhancements in $^3\text{He}/^4\text{He}$ and heavy ions relative to coronal abundances. However, a unique feature of these abundances is that event-to-event variations about these means are almost completely uncorrelated. Typical cross plots of $^4\text{He}/\text{C}$ and Fe/C as a function of $^3\text{He}/^4\text{He}$ are shown in Figure 4. Each point on a given panel in the figure represents a different impulsive-flare event.

The lack of correlation between $^3\text{He}/^4\text{He}$ and Fe/C has been known for 15 years and is sometimes used as evidence that ^3He and Fe are accelerated in different locations or by different wave modes. This is true of our model as well. However, it is also true that variations in most abundance ratios, such as $^4\text{He}/\text{H}$, $^4\text{He}/\text{C}$, $^3\text{He}/^4\text{He}$, or Fe/C are all uncorrelated with each other. Abundances of other species, such as N, Ne, Mg, and Si, are also uncorrelated, but the statistical errors in these abundances are larger. It may seem natural to expect different acceleration sites for ^3He and Fe,

but *surely*, we cannot have a separate acceleration site or mechanism for each of the major species we observe.

Clearly, we still have problems with our mechanisms and models. Qualitatively, one can imagine ways to produce non-Kolmogorov wave spectra that vary from event to event as follows: (1) The answer may lie in “spiky” wave spectrum, such as the second-harmonic spectrum in the Temerin-Roth model, where one element can be in resonance while its neighbor is not. The pattern of the resonance would then vary as the electron temperature and ionization states vary. (2) The dominant elements may modify the wave spectrum with absorption profiles such as the “He valley” (Steinacker et al. 1997) between the gyrofrequencies of Fe and H. However, variations in ${}^4\text{He}$ and C are especially disturbing since both species have similar values of Q/A . (3) Perhaps differing contribution from sources at sites (A) and (B) in Figure 3 play a role. Quantitatively, there are no adequate simulations to explore this behavior.

By contrast, we note that abundance variations in gradual events, such as Si/O vs. Fe/C, are well correlated (Reames 1995, 1998). In addition, because the ions leak through smooth proton-generated wave spectra near the shock, one sees smooth abundance variations with time as the shock evolves (Tylka, Reames & Ng 1999; Ng, Reames, & Tylka 1999). At shocks, the energy in waves is only a few percent of the energy in SEPs. In flares, wave energy is the *source* of energy in SEPs; hence, it must dominate.

8. Energy Spectra

Energy thresholds for the nuclear interactions that produce γ -ray lines are generally above ~ 1 MeV, so low-energy spectra of ions are only accessible by measurement of SEP spectra at 1 AU. Recent measurements on the Wind spacecraft have obtained spectra for H, ${}^4\text{He}$, ${}^3\text{He}$, C, O, and Fe to energies as low as 30 keV/amu (Reames et al. 1997). Below 1 MeV/amu, intensities continue to rise with decreasing energy, though not as steeply as at higher energies. However, the energy content

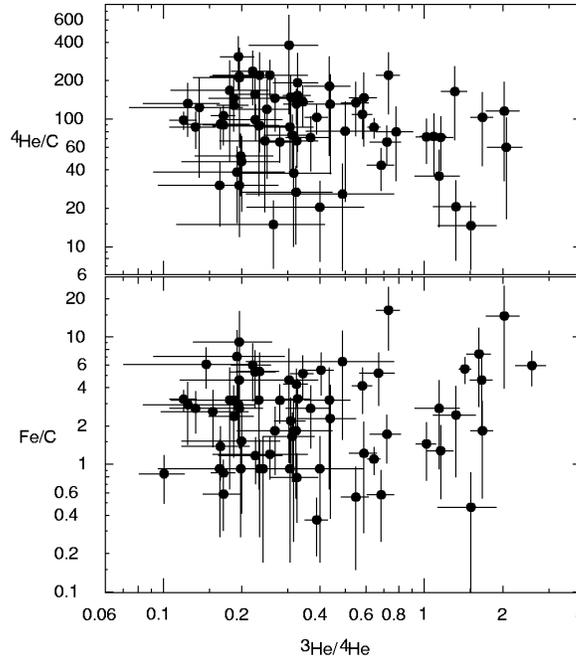


Figure 4. Cross-correlation plots show ${}^4\text{He}/\text{C}$ and Fe/C as a function of ${}^3\text{He}/{}^4\text{He}$ for 66 impulsive SEP events. Abundances of these and other species are uncorrelated.

in ions <1 MeV/amu is certainly greater than that in ions >1 MeV/amu. These measurements affect our understanding of the energy content in flares and the balance between energy contained in electrons and in ions (Ramaty, et al. 1995; Ramaty, Mandzhavidze, & Kozlovsky 1996).

However, one should exercise some caution in interpreting unusual features in spectra at extremely low energies because of the velocity dispersion. Ions at ~ 30 keV/amu take at least 20 hrs to propagate directly to 1 AU, by the time they arrive the magnetic connection to the flare can change considerably; it can either worsen or improve. Occasionally, spectra can either roll over or rise abruptly from this effect. However, typical spectra derived from a large sample of events should allow these effects to compensate and correctly reflect the spectra in the acceleration region.

9. Summary

To use SEP observations to study the physics of solar flares, it was first necessary to determine which events were associated with flares. The SEP events we identified as flare-related had strikingly unusual abundances. Similar abundances have now been inferred from γ -ray lines from flares. Our association was correct. This allows us to use the spectra, abundances, and ionization states observed in impulsive SEP events, together with γ -ray and neutron observations, to constrain the physical models of ion acceleration in flares.

We can deduce plausible models of flares within the constraints, but questions and uncertainties do remain. Observations by the HESSI spacecraft can certainly explore the degree of spatial coincidence between hard X-rays and γ -rays in the footpoints of flare loops. Even more critical is an improvement in the timing relationship between the acceleration of electrons and ions. Is it possible to observe differences in ion acceleration times from γ -ray observations? Is Fe accelerated before or after ^3He ?

An interesting feature is that our model seems to provide, at least briefly, a magnetic connection between the loop footpoints and 1 AU. This suggests that charged secondary products of nuclear reactions, such as e^+ , ^2H , ^3H , Li, Be, and B, might be seen at 1 AU. We should reexamine the limits on these species.

However, the complex physical processes we discuss are even more dependent on an understanding of the theory. We do not yet know what spectra are produced by absorption of EMIC waves. Nor can we use the observed abundances and ionization states to define acceleration parameters. More-complete simulations are needed of the many processes involved, including particle acceleration and transport and the absorption and generation of waves. How does the acceleration depend on magnetic field strength or plasma density that different loop sizes might imply, for example? Beyond these processes are the questions about the dynamics of magnetic reconnection itself and the coupling of energy into waves.

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