Section D

Particle Acceleration in Astrophysical Plasmas

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Particle Acceleration in Solar Flares

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Abstract.
We review the basic, observationally driven requirements for a successful model of particle acceleration in impulsive solar flares and then evaluate the viability of three classes of acceleration mechanisms. We argue that stochastic resonant acceleration is by far the most promising of the mechanisms.

1. Introduction

Particle acceleration is a ubiquitous phenomenon throughout the universe. Within the solar system, solar flares are the most striking example, releasing up to 10^{32} ergs of energy over timescales of several tens of seconds to several tens of minutes. Much of this energy is in the form of suprathermal particles, which either remain trapped at the Sun or escape into interplanetary space. The radiation from trapped particles (Ramaty & Murphy 1987) consists in general of (1) continuum emission, which ranges from radio and microwave wavelengths to soft ($\sim$ 1–20 keV) X-rays, hard ($\sim$ 20–300 keV) X-rays, and, finally, gamma-rays (above $\sim$ 300 keV) which may have energies in excess of 1 GeV; (2) narrow, gamma-ray nuclear deexcitation lines between $\approx$ 4 and 8 MeV; and (3) high-energy neutrons. The particles that escape into space (Reames 1990) can be detected directly and often have compositions quite different than that of the ambient solar atmosphere.

Primarily as a result of the work of Reames and collaborators, it is now generally accepted that flares are roughly divided into two classes: impulsive and gradual. While this picture is a little simplistic, and Cliver (1996) has proposed a refinement, we will adopt it in this paper. Gradual events are large, occur high in the corona, have long-duration soft and hard X-rays and gamma-rays, are electron poor, are associated with Type II radio emission and coronal mass ejections (CMEs), and produce interplanetary energetic ions with coronal abundance ratios. Impulsive events are more compact, occur lower in the corona, produce short-duration radiation, and exhibit dramatic abundance enhancements in the escaping energetic ions (as well as those that remain trapped). Their ^{3}He/^{4}He ratio is ~ 1, which is a huge increase over the coronal value of about 5×10^{-4}, and they also possess other ion abundance enhancements as well (see below). The general scenario that emerged from these observations is that energetic particles in gradual events are accelerated by a CME-driven shock, while particles in impulsive events are accelerated by another mechanism(s). We see no reason to suppose that this is incorrect, and so many aspects of the acceleration problem are (more or less) basically solved for the former type of flare. In this paper, we will therefore deal subsequently only with impulsive flares.

The present, canonical solar flare picture is that particles are accelerated in and around the ionized coronal region of a magnetic loop, which consists of closed field lines that are anchored at both ends in the denser photosphere. The length of the coronal portion of this loop can vary quite a bit, but typically lies in the 10^8 to 10^9 cm range. The average magnetic field and plasma number density of the loop can be roughly constrained by modeling the microwave and X-ray emission, and are probably around 100 to 500 G and 10^9 to a few times 10^{10} cm^{-3}, respectively. In addition to the closed magnetic field lines, there are overlying open field lines that are anchored at one end in the photosphere but then extend into interplanetary space. Acceleration within this overall geometry will naturally lead to both trapped and escaped particles. It further predicts that they belong to the same population, which is, in fact, confirmed by the observed similarity of the ion compositions in the two types of particles (Murphy et al. 1991; Mandzhavidze & Ramaty 1993).

After acceleration near the top of or throughout the coronal section of the loop, energetic electrons streaming along the magnetic field lines produce microwaves via gyrosynchrotron emission in the corona, and then hard X-rays and continuum gamma-rays via bremsstrahlung emission when they strike the dense chromosphere. Most of the energetic electron energy, however, goes into heating the ambient chromosphere. This heated plasma then radiates at soft X-ray wavelengths and expands into the coronal portion of the loop. In addition, the coronal electron beam excites electron plasma waves, which then undergo mode conversion into radio waves with a frequency of about the local plasma frequency. If the electrons are on closed field lines, this radio emission takes the form of inverted U or J bursts (e.g., see Aschwanden et al. 1992), while electrons on open field lines yield coronal and then interplanetary Type III bursts (e.g., see Aschwanden & Benz 1997).

The most unique aspect of solar flares is the existence of detectable radiation from the ions, as well as the ions themselves. Energetic ions either escape directly along open field lines or, if they have an energy above about 1 MeV $\mathrm{nucleon}^{-1}$, interact with the ambient nuclei (again in the chromosphere) to produce excited nuclei that subsequently deexcite via gamma-ray line emission. If the energetic ions are protons and alpha particles, this emission is manifested as narrow gamma-ray lines around a few MeV. The inverse reactions also yield gamma-ray lines but are significantly Doppler-broadened. These broad lines are not resolvable but contribute to the nuclear emission in the MeV range. Higher energy ions also produce pions which can yield a very distinctive radiative signature (Murphy, Dermer, & Ramaty 1987).

Nowhere else in astrophysics is the wealth of remote diagnostic data so great. The goal of solar flare research is to deduce the particle acceleration mechanism(s) from these observations. However, since the amount of data is so vast and flares exhibit so much variation, where is one to begin? The approach we see as most fruitful is first to distill the observations into a few central requirements that any theory must account for. While glossing over some of the details, we demand that a theory account for all of these main facts simultaneously. We think that theories which focus exclusively on one or two observations should be avoided, since they might not account for any other and eventually lead to a collection of unrelated and possibly contradictory proposed mechanisms and no overall scheme.

2. Basic Observations

In this section, we list the bulk features of the energetic particles appropriate to large (and therefore more demanding) flares. For a detailed discussion of how these come about, see Miller et al. (1997) or Vestrand & Miller (1998). We briefly note here that most of the information on the number of interacting electrons and their acceleration timescale is provided by fitting hard X-ray bremsstrahlung emissions, while similar information for the interacting ions is obtained by modeling the nuclear deexcitation line and pion radiation emission. Furthermore, while all of the following features may not be present in a given individual flare, they are routinely observed and are essential aspects that should be accounted for by a successful model.

2.1. Electrons

1. Approximately 10^{36} to 10^{37} electrons s^{-1} are accelerated above the hard X-ray producing threshold energy of 20 keV for $\sim 100\,\mathrm{s}$;
2. the total $> 20\,\mathrm{keV}$ electron energy content is thus $\sim 10^{31}$ ergs;
3. the maximum electron energy is $\sim 100\,\mathrm{MeV}$;
4. they are accelerated out of the thermal or quasithermal background; and
5. they are accelerated simultaneously (to within a second or so) with the ions.

An important thing to note immediately is that, for typical flare coronal volumes of $\sim 10^{27}\,\mathrm{cm}^3$ and densities of $\sim 10^{10}\,\mathrm{cm}^{-3}$, the acceleration region will be entirely depleted of electrons in about 1 s. Hence, real-time electron replenishment must also occur.

2.2. Ions

1. Approximately 10^{35} protons s^{-1} are accelerated above the nuclear deexcitation line producing threshold energy of $\approx 1\,\mathrm{MeV}$ for $\sim 100\,\mathrm{s}$;
2. the total $> 1\,\mathrm{MeV}$ proton energy content is thus $\sim 10^{31}$ ergs;
3. the maximum proton energy is $\sim 1\,\mathrm{GeV}$;
4. they are accelerated out of the thermal or quasithermal background;
5. they are accelerated simultaneously with the electrons; and
6. they possess abundance enhancements similar to those given (in the Impulsive Flares column) in Table 1.

A few comments are now in order. First, the number of interacting protons below about an MeV is unknown at present, since these particles do not have a detectable gamma-ray line signature and other diagnostics of their presence have not been fully investigated yet. Second, the above energization rate is more than an order of magnitude higher than that believed prior to 1995. In that year, ^{20}Ne and ^{16}O deexcitation line data became available for several flares (Share & Murphy 1995) and proved to be a good diagnostic of the proton spectrum between ≈ 1 and 10 MeV (Ramaty et al. 1995). Third, the other ions have an energy content about equal to that of the protons, so that the ion and electron energy contents are comparable. (These energy contents have been determined for each of 12 flares that have the necessary data, and approximate equipartition is confirmed in each instance. See Figure 3 of Miller et al. 1997). This is a significant change over the previously-held notion that electrons possess most of the energy. Ions and electrons are now on equal footing, and no theory can be regarded as a success if it does not work for both.

Finally, Table 1 gives the typical ion abundance ratios for particles $\gtrsim 1\,\mathrm{MeV\,nucleon}^{-1}$ for impulsive flares as well as the gradual events with their associated CMEs (data from Great Debate (1995) and Reames et al. references therein; Share & Murphy (1997)). The abundances for the gradual events are essentially the same as those in the ambient corona and are evidence for the shock-accelerated nature of these particles. The abundances for the impulsive events show enhancements of ^{3}He, Ne, Mg, Si, and Fe relative to C, N, O, and ^{4}He, which in turn are not enhanced relative to one another.

Table 1. Ion Abundance Ratios

Ratio	Impulsive Flares	Gradual Flares (Corona)
^{3}He/^{4}He	$\sim$1 ($\times$2000 increase)	$\sim$ 0.0005
^{4}He/O	$\approx$46	$\approx$55
^{4}He/H	$\approx$0.5	$\approx$0.1
C/O	$\approx$0.436	$\approx$ 0.471
N/O	$\approx$0.153	$\approx$ 0.128
Ne/O	$\approx$0.416 ($\times$2.8 increase)	$\approx$0.151
Mg/O	$\approx$0.413 ($\times$2.0 increase)	$\approx$0.203
Si/O	$\approx$0.405 ($\times$2.6 increase)	$\approx$0.155
Fe/O	$\approx$1.234 ($\times$8.0 increase)	$\approx$0.155

3. Acceleration Mechanisms

Particle acceleration can occur generically through interaction with DC electric fields, shocks, or plasma wave turbulence (by turbulence we mean a superposition of a large number of randomly-phased waves occupying a range of wavenumbers, propagation angles, and frequencies). We consider each in turn.

3.1. Electric Fields

The simplest way to accelerate particles is by a large-scale DC electric field. Most work in this area focuses on the electrons, which we now consider. It is the interplay between the electric field force and the Coulomb drag force from the other electrons that govern whether or not a given electron is accelerated out of the thermal distribution. As the speed of an electron increases from zero, the drag force increases until reaching a maximum at the electron thermal speed v_{te}. Above the electron thermal speed, this drag force decreases with increasing electron speed. The value of the electric field $\mathcal{E}$ where the drag force at the thermal speed equals the electric field force is called the Dreicer field $\mathcal{E}_D$ and is $\approx 10^{-4}\,\mathrm{V\,cm^{-1}}$ for typical flare parameters.

For $\mathcal{E} > \mathcal{E}_D$, the electric force exceeds the drag force on all electrons, which are then freely accelerated to higher energies. For $\mathcal{E} < \mathcal{E}_D$, there exists a critical velocity v_c below which the drag force overcomes the electric force. Electrons with speeds $< v_c$ will then be heated, while those with speeds $> v_c$ will be freely accelerated, or "run away". Electric fields greater (less) than $\mathcal{E}_D$ are called super-(sub-)Dreicer.

Sub-Dreicer Fields Sub-Dreicer acceleration has been considered in detail for several years, mostly for laboratory plasmas (e.g., Knoepfel & Spong 1979). The mechanism and its associated effects have been explored with numerical simulations (e.g., Fuchs et al. 1986), but it is quite simple to derive just the electron distribution. Imagine an electric field of finite length L permeating a plasma. All along the electric field, electrons with parallel velocity (relative to the electric field) above the critical speed v_c will be accelerated along the field lines. Upon reaching the beginning of the field, the energy of an electron will be proportional to the distance it traveled. Since an equal number of electrons were accelerated in each small segment of the loop, the electron energy distribution at the start of the field will simply be *flat* and extend from about v_c to the maximum kinematic drop $e\mathcal{E}L$. Coulomb collisions pitch-angle–scatter the particles, but this essentially flat spectrum is confirmed nicely by simulations (Moghaddam-Taaheri & Goertz 1990).

Sub-Dreicer fields in flares have been championed by Holman (1985) and collaborators. In flares, the field must be very long: taking the field to be of order $10^{-5}\,\mathrm{V\,cm^{-1}}$, the length must be about 3×10^9 cm in order to yield a maximum energy around 10 to 100 keV, which would just be sufficient to account for hard X-ray emission. This field must exist in the coronal section of the flare loop and extend over its whole length.

Presumably, it is the "simplicity" of this mechanism that continues to attract proponents, but we point out three problems which in fact make this the most complicated model around. First, when the electrons with their flat energy distribution strike the chromosphere, they will produce hard X-ray bremsstrahlung radiation that has an E_γ^{-s} spectrum (units of photons per unit photon energy E_γ) with $s = 1$; however, the observed spectra have power-law indices s greater than 2. Reconciliation of these results would require a suitable distribution of electric field strengths and/or lengths such that the superposition of many composite E_γ^{-1} spectra with different high-energy cutoffs produce what is observed. We will see below that many electric fields are needed for another reason, and so a distribution of strengths and lengths is not out of the question. However, the nature of this distribution is unknown and will need to be assumed, so that the overall model, which includes the kernel electron distribution as well as the distribution of fields, will have an impressively large number of free parameters. Benka & Holman (1994) do not employ a distribution of fields, but instead achieve a harder spectrum by using an *ad hoc* energy-dependent escape term with no physical justification.

Second, even if the field were taken to be Dreicer, the observed size of flares places a limit of about 1 MeV on the electron energy, which is substantially lower than the maximum observed. This situation can be corrected by invoking anomalous resistivity, which amounts to saying that the Coulomb collision rate is negligible compared with the scattering rate that results from resonance with waves. If this rate is assumed to be very high, the electric field required to accelerate a thermal electron (the effective Dreicer field) will also become much larger than that for the usual Coulomb collision case. Hence, the electric field could be large ($\approx 10^{-2}\,\mathrm{V\,cm^{-1}}$, say) and still be sub-(effective)Dreicer. The problem now is generating suitable waves (such as electron plasma or lower hybrid) in the face of ferocious Landau damping. Also, if such waves are present, the concomitant stochastic acceleration would be significant or even dominant.

Third, the requirement that the magnetic field produced by the streaming accelerated electrons not exceed the coronal magnetic field yields a severe constraint on the geometry of the current channels carrying the electric fields. A simple application of Ampere's Law to a large flare which produces an accelerated electron current of about 2×10^{18} A over a flare footpoint area of $10^{18}\,\mathrm{cm}^2$ indicates that the radius of a cylindrical current channel carrying these electrons cannot be greater than ~ 100 cm. This implies that the flaring corona must be filamented in such a way that neighboring current channels have oppositely directed electric fields, so that the oppositely directed currents yield a small net current through a large Amperian path. For the above parameters, $\approx 10^{12}$ cylindrical current channels are needed. The aspect ratio of each is about 10^7, or equal to that of a 10 km long piece of 12-gauge wire! Requiring that 10^{12} of these channels be formed and remain stable for (what turns out to be) a magnetic diffusion timescale of ~ 100 s is, to put it mildly, a stretch. At the very least, their formation is unsubstantiated theoretically.

The replenishment issue yields a similar problem. A single electric field will not admit upflowing, cospatial electrons from the chromosphere (electrons cannot be driven both ways by the same field), and so the current again needs to be filamented into oppositely directed fields. Emslie & Henoux (1995) have proposed a mechanism for closing the currents in the chromosphere and find by another argument that the number of filaments must be about that given above.

This hyperfilamentation problem is reduced somewhat by assuming that the currents are in sheets rather than cylinders, in which case $\approx 10^4$–10^6 sheets are required (Emslie & Henoux 1995). However, it is not clear how to incorporate such sheets into a cylindrical flare geometry. If one were to try to bypass this issue by placing them above and perpendicular to the top of the loop (as in the Litvinenko geometry below), then one is confronted with the formidable problems of current closure and the escape of the electrons from the sides of the channels.

Conclusion: sub-Dreicer electric fields are a particularly unattractive candidate for flare particle acceleration. Not only do they have all the problems discussed above concerning the electrons, but ion acceleration to gamma-ray producing energies and the abundance enhancements are also untenable (Holman 1995).

Super-Dreicer Fields Super-Dreicer electric fields occur within the context of reconnection, and are typically several orders of magnitude larger than the Dreicer field. Martens (1988) and Litvinenko (1996) proposed that the open magnetic field lines above the solar flare loop reconnect and generate an electric field of about $10\,\mathrm{V\,cm^{-1}}$ oriented parallel to the solar surface and normal to the footpoint-to-footpoint line along the loop (actually more like an arcade of loops here). The field is in a current sheet of length and height $\approx 10^9$ cm and width $\approx 10^4$ cm (the thickness-to-length ratio is 10^{-5}, about an order of magnitude smaller than a sheet of paper). Since the field exists over a length of about 10^9 cm, the highest-energy electrons could be obtained, in principle. However, this kinematic maximum is not always realized because of rapid particle escape out of the side of the current sheet resulting from a small transverse magnetic field component. But it is precisely this rapid escape which allows this geometry to bypass the filamentation and replenishment problems encountered by the sub-Dreicer field model. Namely, mass inflow in the sides of the current sheet provides the seed electrons for the acceleration, which gain typically an energy of about 100 keV before escaping from the sides onto open field lines. Some of these electrons propagate to the chromosphere and generate the hard X-rays, while others escape into space. The crucial point is that there is no electric field along these magnetic field lines, so that a cospatial return current can form from the chromosphere to the current sheet and thus ensure the constant replenishment of electrons in the sheet.

Conclusion: super-Dreicer fields are far more attractive than sub-Dreicer ones and can yield the requisite number of hard X-ray producing electrons. However, they yield an incomplete acceleration model, since it is not likely that gamma-ray producing protons can be obtained, and no mechanism for the generation of the observed abundance enhancements has been proposed.

3.2. Shocks

Shocks can be highly efficient particle accelerators and are of prime importance in many areas of astrophysics as well as in gradual solar flares. The usual argument against shock acceleration in impulsive events is the lack of Type II radio emission, which is a classic signature and produced when the shock propagates into regions of different density. However, this objection could be overcome if the shocks are small and rapidly dissipated, and thus confined to the flare loop (Anastasiadis & Vlahos 1991). What then is the continuous trigger for these many small shocks? Also, while shocks have no difficulty accelerating ions from the ambient distribution to perhaps MeV energies under flare conditions (e.g., see Decker & Vlahos 1986), whether they can accelerate enough is totally unknown. The same goes for electrons, which suffer from an additional problem: it is still not known how (or if) shocks accelerate electrons from the thermal background (Achterberg 1999). Also, on a more global scale, how do they admit replenishment of the acceleration region? Perhaps the fairest thing to say about them in impulsive flares is that there are many unanswered questions. However, given that at least ion acceleration is, in general, understood (e.g., Miller et al. 1997, and references therein), and ion abundance enhancements of the type seen in Table 1 have never been produced, it is equally fair to say that shock acceleration will be incomplete and not by itself account for flare acceleration.

3.3. Stochastic Acceleration

The last energization mechanism is stochastic acceleration. Stochastic acceleration may be broadly defined as any process in which a particle can either gain or lose energy in a short time interval, but where it systematically gains energy over longer times. There are two types: Fermi and resonant.

Fermi Acceleration So-called in honor of its originator (Fermi 1949), this form of stochastic acceleration relies on a collection of magnetic inhomogeneities or "blobs" to energize the particles. A particle can either make a head-on collision with a blob, be adiabatically reflected, and gain energy, or make a trailing collision and lose energy; hence, in any interaction, the energy could either increase or decrease. However, since the probability for a head-on collision is greater (because of the larger relative speed between scatterer and particle), there will be a net increase in energy over long timescales.

This is actually the oldest of all flare acceleration mechanisms and was first proposed for flares by Parker & Tidman (1958). It has since been employed extensively for ion acceleration (e.g., Ramaty 1979; Miller, Guessoum, & Ramaty 1990), where it has yielded much information on the number of energetic ions as well as constraints on their spectral shape (e.g., Ramaty & Murphy 1987). It has also been used for electron acceleration and can yield easily the requisite number of hard X-ray producing electrons and also accelerate them directly from the thermal background (e.g., LaRosa, Moore, & Shore 1994; Gisler 1992). In these models, the "blobs" are usually imagined to be large-amplitude MHD waves propagating at about the Alfvén speed $v_{\rm A}$.

One very attractive aspect of stochastic acceleration is that it does not suffer from the replenishment or filamentation issues discussed above for the electric fields. Since the acceleration is not directed, a deficit of electrons or protons in the corona will quickly establish an electrostatic field that will draw a cospatial return current from the electron- and proton-rich chromosphere. The geometry of the acceleration region can therefore be very simple and could consist of a single, large flux tube. Of course, a subdivision of the loop into smaller elements is also permitted but is not required.

Despite its many successes, Fermi acceleration has problems as well. Most significant is that, while electron and ion acceleration have been examined separately, they have never been considered simultaneously with a consistent set of modeling parameters. Moreover, there is the injection problem. Blobs that move at about $v_{\rm A}$ are able to energize electrons directly from the thermal background, since v_{te} is comparable to $v_{\rm A}$. However, since the proton thermal speed is much less than this, the typical pitch angle of thermal protons in the wave frame will be quite low, enabling the particles to pass through a magnetic compression without being reflected. To overcome this, the protons need initial speeds of around $v_{\rm A}$, or an energy $\sim 1\,\rm MeV$. That is, they need to be preaccelerated before they can be Fermi accelerated. Fermi acceleration is therefore incomplete. Also, no mechanism of producing the ion abundance enhancements has been proposed.

Conclusion: while providing a wealth of initial insight into the nature of the accelerated ions, and serving as a useful modeling tool, Fermi acceleration cannot account for all the bulk observations.

Resonant Acceleration The far richer type of stochastic acceleration relies on resonance with plasma waves. It has often been said that there is a zoo of plasma waves, and, unfortunately, the many different names that one encounters surely add to this perception. However, the situation is not all that bad, and all these "different" waves are really just different regions of the same fundamental dispersion surface in frequency-wavevector space. A review of this dispersion surface, called a Stringer diagram, is not possible here, and the reader is referred to Swanson (1989) for an excellent discussion.

Resonant acceleration is sometimes criticized for being "too complicated". Actually, it is quite simple since it involves only two ingredients: resonance and resonance overlap. Resonance occurs when the condition $x \equiv \omega - k_{||}v_{||} - \ell|\Omega|/\gamma = 0$ is satisfied. Here, $v_{||}$, γ, and Ω are the particle's parallel speed (with respect to the ambient magnetic field $\boldsymbol{B}_0$), Lorentz factor, and cyclotron frequency; while ω and $k_{||}$ are the wave frequency and parallel wavenumber. The quantity x is the frequency mismatch parameter. If the harmonic number $\ell \neq 0$, its sign depends upon the sense of rotation of the electric field and the particle in the plasma frame: if both rotate in the same sense (right- or left-handed) relative to $\boldsymbol{B}_0$, then $\ell > 0$; if not, then $\ell < 0$. At resonance, the frequency of rotation of the wave electric field is an integer multiple of the frequency of gyration of the particle in the particle's guiding center frame, and the sense of rotation is the same. The particle thus sees an electric field for a sustained length of time and will either be strongly accelerated or decelerated, depending upon the relative phase of the field and the gyromotion. If $\ell = 0$, there is matching between the parallel motion of the particle and the wave-parallel electric or magnetic field.

When a particle is in resonance with a single small-amplitude wave, $v_{||}$ executes approximate simple harmonic motion about the parallel velocity which exactly satisfies the resonance condition (Karimabadi et al. 1992). There is no energy gain on average. The frequency ω_b of oscillation is proportional to the square root of the wave amplitude, and, if $|x| \leq 2\omega_b$, the particle and wave effectively are in resonance. Hence, the exact resonance condition $x = 0$ does not have to be satisfied in order for a strong wave-particle interaction to occur.

This brings us to the second ingredient: resonance overlap, which is what yields large average energy gains. To understand overlap, consider two neighboring waves, i and $i+1$, where $i+1$ will resonate with a particle of higher energy than i will. A particle initially resonant with wave i will periodically gain and lose a small amount of $v_{||}$. If the gain at some time is large enough to allow it to satisfy $|x| \leq \omega_{b,i+1}$, where $\omega_{b,i+1}$ is the bounce frequency for wave $i+1$, then the particle will resonate with that wave next. After "jumping" from one wave to the next in this manner, the particle will have achieved a net gain in energy. If other waves are present that will resonate with even higher energy particles, the particle will continue jumping from resonance to resonance and achieve a maximum energy corresponding to the last resonance present. If the wave spectrum is discrete, then the spacing of waves is critical; if the spectrum is continuous (as is almost certainly the case in flares), however, then resonance overlap will automatically occur. Of course, the particle can also move down the resonance ladder, but, over long timescales, there is a net gain in energy, and stochastic acceleration is the result.

The most important harmonic numbers for flare acceleration are $\ell = +1$ and 0. If $\ell = +1$, the interaction is called cyclotron resonance, and we readily see from $x = 0$ that in order for a wave to cyclotron resonate with a low-energy particle (say near the thermal speed), the wave must have a frequency near the cyclotron frequency of the particle. On the other hand, as the particle gains energy, the frequency of the resonant wave can either increase or decrease from the cyclotron frequency. The second important resonance is the $\ell = 0$ resonance, which leads to transit-time acceleration if the resonance is with the wave-parallel magnetic field. Transit-time acceleration can produce huge particle-energy gains (Miller 1997).

It should not be a surprise that with the richness of the dispersion surface there have been many studies of resonant acceleration, each employing a different plasma wave (see Miller et al. 1997 for a review). For example, Barbosa (1979) used Alfvén waves to accelerate ions. Hamilton & Petrosian (1992) and Steinacker & Miller (1992) used whistlers for low-energy electron acceleration, and Alfvén and fast mode waves for relativistic electron acceleration. Unfortunately, these studies have typically had somewhat narrow applications, focusing on just one species of particle in a restricted energy range. The argument that was sometimes made was that all these different modes should be excited, and thus all these separate mechanisms would work together to produce the overall acceleration characteristics that we observe. However, it has not been shown that this is indeed the case; moreover, without a rigorous understanding of wave excitation, the combination necessarily would have resulted in a model with a huge number of free parameters.

Before one tries to sort out this collection of models, it is worthwhile to ask whether or not there is good reason to believe that resonant acceleration is occurring in flares at all. The answer is yes and is supported strongly by the observed ^{3}He enhancement. This enhancement is as spectacular as it is strange. The ^{3}He cyclotron frequency is located between the H and ^{4}He cyclotron frequencies, and these ions are not enhanced or preferentially accelerated. The only way this could occur is if ^{3}He were accelerated by waves that were excited in a narrow frequency range just around its cyclotron frequency. This was the original idea of Fisk (1978), who also proposed a specific wave mode and excitation mechanism, and it remains the only explanation today. We prefer a variant of this model that is somewhat more general and which uses an electron beam to excite H^+ EMIC (electromagnetic ion cyclotron) waves around ^{3}He (Temerin & Roth 1992; Miller & Viñas 1993). Given the richness of electrons in flares, the formation of a beam at some point should not be a difficult criterion to satisfy.

Since ^{3}He requires resonant acceleration and the precedent has been established, it is therefore reasonable to take seriously the idea that the other particles are also resonantly accelerated. Is it then possible to do this, and account for the remaining points in §2 in a simple manner, without an assortment of disjoint mechanisms? Again, the answer is yes. As discussed in Miller (1998; in preparation), cascading MHD waves are able to simultaneously accelerate ions and electrons, and account for all the major features of particle acceleration in a simple and self-consistent manner.

The model consists of just a few elements: (1) During the primary flare-energy release phase, we assume that long-wavelength MHD (Alfvén and fast-mode) waves are excited, which is consistent with recent simulations (Yokoyama 1998; 2000, these Proceedings) that reveal that three percent of the released energy is in the form of such waves. (2) These waves then cascade in a Kolmogorov-like fashion to smaller wavelengths (e.g., see Verma et al. 1996), forming a power-law spectral density. (3a) When the mean wavenumber of the fast-mode waves has increased sufficiently, they transit-time accelerate super-Alfvénic electrons out of the thermal distribution to relativistic energies (see also Miller et al. 1996). (3b) When the wavenumber of the Alfvén waves has increased sufficiently, they are able to cyclotron resonate with ions in the tail of the thermal distribution and then accelerate them to relativistic energies as well (see also Miller & Roberts 1995). Hence, the basic idea is quite simple.

This scenario has been explored with a comprehensive, quasilinear simulation that self-consistently takes into account ion and electron acceleration (including the contribution of the fast-mode waves to ion acceleration at higher energies), concomitant wave damping, particle escape, and replenishment by a cospatial return current. Perhaps the most remarkable aspect of this model is the number of free parameters: just two, the loop length and the turbulence injection rate, which is not all that free insofar as it is set by the number of particles that need to be accelerated (§2) together with the conservation of energy. Taking the plasma to be pure H, we find, for example, that the necessary proton and electron fluxes can be achieved and maintained for as long as needed by the injection of $\approx 400\,\mathrm{ergs\,cm^{-3}\,s^{-1}}$ of turbulence at almost any initial scale, and that the so-called "electron dominated" flares (e.g., see Petrosian, McTiernan, & Marschhauser 1994) can be produced by reducing the flare loop length to a few times 10^8 cm.

Also, very encouragingly, the effect of the heavy ions has been included and has been found to lead to enhancements quite similar to those in Table 1. Qualitatively, in a multi-ion flare plasma, the Alfvén waves will encounter Fe first. Iron will be strongly accelerated but is not abundant enough to damp the waves. Thus, some wave energy will cascade to higher frequencies where it encounters Ne, Mg, and Si. The same way, these ions suffer strong acceleration, but the wave dissipation is not complete. Some wave energy then cascades to reach ^{4}He, C, N, and O. Thus, iron will resonate with the most powerful waves; Ne, Mg, and Si will resonate with waves having less power; and the other heavies will resonate with even less powerful waves. Hence, Fe should be enhanced more than the Ne group relative to the He group. Since ^{4}He, C, N, and O all have the same cyclotron frequency and behave similarly, they should not be enhanced relative to each other. This qualitative argument has been verified by preliminary simulations, which have been found to yield an Fe/O ratio of about 2.1, and Ne/O, Mg/O, and Si/O ratios of about 0.9, with typical choices of parameters. The ^{4}He, C, N, and O ions are not enhanced relative to each other. This is in quite good agreement with Table 1.

4. Summary

At the very least, it is clear that impulsive solar flares are an excellent laboratory to study astrophysical particle acceleration. They not only possess a wide range of diagnostic data, but have proven to be ferociously efficient accelerators of both ions and electrons, and are sites of some very interesting plasma physics. As far as the acceleration mechanism is concerned, one could adopt two approaches. First, one could use a piecemeal approach, where this or that mechanism is used for a specific detail or observation, neglecting the others. It is impossible to see how this approach can yield anything but a large collection of unrelated models, confusion about the underlying physics, and chaos. It seems more reasonable to first establish the bulk properties of the energetic particles and then develop a framework or unified model that accounts for this behavior. After the unified model has shown itself capable of dealing with the overall situation, it can then be applied to the more specific observations. If a particular model, such as sub-Dreicer electric fields, cannot cope with basic aspects of flares such as both ion and electron fluxes, and maximum energies and abundances, then it does not have a chance of accounting for all the details; it is time to cut that model loose and focus elsewhere.

We think that stochastic resonant acceleration is the basic mechanism that energizes ions and electrons in impulsive flares. It is virtually required for ^{3}He acceleration, and cascading MHD turbulence can nicely account for the remaining ion and electron observations. With this first major hurdle cleared, the model can now be refined to account for many of the averaged-over details, such as spectra, which will be acquired in unprecedented detail with the next generation of solar missions (such as the *High Energy Solar Spectroscopic Imager*—HESSI—Lin 2000, these Proceedings).

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