Selective ^{3}He and Fe Acceleration in Impulsive Solar Flares

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ABSTRACT

A parallel bump-on-tail electron distribution in a solar flare plasma is unstable to the generation of H^+ electromagnetic ion cyclotron (EMIC) and shear Alfvén waves. The first mode is excited at frequencies equal to—and above—the ^{3}He cyclotron frequency, and can selectively stochastically accelerate thermal ^{3}He to at least several hundred keV nucleon^{-1}. The second mode is excited around the Fe cyclotron frequency, and can energize Fe to at least $\approx 2\,\mathrm{MeV\,nucleon^{-1}}$. For low levels of turbulence, the acceleration in both cases will occur on an impulsive flare time scale. An electron beam thus produces a large ^{3}He/^{4}He and Fe/C (or Fe/O) ratio in the energetic particles.

1. INTRODUCTION

One of the most striking observations of impulsive solar flares is the large ($\sim$ 0.1–10) ^{3}He/^{4}He ratio in the energetic interplanetary particles (see review by Reames 1990 and references therein). These events are also characterized by enhanced Fe/C and Fe/O ratios, as well as enhancements of Ne, Mg, and Si (Reames et al. 1993). The standard model for these observations is that particles from impulsive flares originate in the region of primary energy release. If so, abundance variations provide a valuable diagnostic of the plasma, and of the acceleration mechanism in particular. The selectivity of this mechanism, especially in regard to the He isotopes, immediately points to a resonant process, such as gyroresonance with waves close to the enhanced ion cyclotron frequency.

The most promising theory of ^{3}He acceleration is the one proposed by Temerin & Roth (1992), who—using an analogy with the Earth's aurora—argue that electron beams are the source of the necessary free energy. They point out that a nonrelativistic beam in a H–He plasma will likely excite H^+ EMIC waves in the neighborhood of the ^{3}He cyclotron frequency, and then show that these waves are capable of selectively energizing thermal ^{3}He ions to MeV energies via the $l = +1$ gyroresonance. This theory has been expanded upon by Miller & Viñas (1993; hereafter MV), who use a full electromagnetic finite-temperature linear-wave Vlasov analysis. MV deduce the conditions under which the H^+ EMIC waves are excited, show that shear Alfvén waves are driven unstable as well, demonstrate that the Alfvén waves will selectively accelerate Fe ions to $\sim$ MeV nucleon^{-1} energies, and account for the +20 charge state of Fe by including collisional ionization by the beam. Helium-3 and Fe acceleration time scales were estimated by using test particle simulations. These simulations, however, are time consuming and do not readily yield particle spectra or average energies. These aspects are more fruitfully explored with a diffusion equation, given below.

2. THE ACCELERATION REGION MODEL

We assume that the impulsive flare acceleration region consists of a H–He plasma permeated by a static uniform background magnetic field $\boldsymbol{B}_0 = B_0\hat{\boldsymbol{z}}$. The four principle components of the plasma are H^+, $^4He^{+2}$, background electrons (all three of which constitute the core), and beam electrons. Each species α has a field aligned drifting Maxwellian velocity distribution $\propto \exp[-(v_\parallel - v_{0\alpha})^2/v_\alpha^2]\exp[-v_\perp^2/v_\alpha^2]$, where v_α and $v_{0\alpha}$ are the thermal and drift speeds, respectively. The core is isothermal at $T_c = 10^6$ K while the beam has a temperature of 10^7 K and a drift energy of 5 keV. We satisfy the zero parallel current condition by going to the ion rest frame and allowing the background electrons to counterstream. In units of the total electron density n_T, the ^{4}He and beam number densities are both 0.1; quasineutrality determines the two other relative densities. Finally, we take the plasma to be underdense, with the ratio of the electron plasma frequency to electron cyclotron frequency equal to 0.32. The ^{4}He/H ratio is about 10% in the acceleration region.

The total (beam + background) electron velocity distribution has a positive slope along the magnetic field for $0.045 \lesssim v_\parallel/c \lesssim 0.14 = v_{0b}/c$. This positive slope is produced by the beam, which can thus excite waves with a parallel electric field through the $l = 0$ resonance. An unstable monochromatic wave which results from this resonant instability thus has $\omega_r \approx v_0 k_\parallel$, where ω_r and $k_\parallel$ are the real frequency and parallel wavenumber, respectively, and v_0 is the parallel speed of the resonant electrons which are primarily responsible for exciting the specific wave. Actually, a given mode will be excited in a broadband continuous spectrum which is a superposition of monochromatic plane waves; equivalently, $n_\parallel = ck_\parallel/\omega_r$ for the plane waves comprising a given type of turbulence is about constant.

We establish instability by numerically solving the full hot plasma electromagnetic dispersion relation for the complex frequency $\omega = \omega_r + i\gamma$ at a given wavenumber k and propagation angle θ. A $\gamma > 0$ corresponds to instability, while $\gamma < 0$ means that the wave is damped. We find that two modes are excited below the H^+ cyclotron frequency Ω_H. First, H^+ EMIC waves with $\theta \approx 89°$ and $ck/\Omega_H \sim 10^2$–10^3 are generated between $\omega_r = 0.6$ and $0.82\Omega_H$. These waves are essentially linearly polarized with respect to $\boldsymbol{B}_0$; specifically, the electric field component E_1 normal to both $\boldsymbol{B}_0$ and $\boldsymbol{B}_0 \times \boldsymbol{k}$, where $\boldsymbol{k}$ is the wavevector, is two to three orders of magnitude larger than the other components. A typical growth rate is $\gamma \sim 10^{-3}$–$10^{-2}\Omega_H$. Electrons which excite this wave have $v_\parallel/c \approx 0.6$, and so $n_\parallel$ is about constant at 16. Second, shear Alfvén waves with $\theta \approx 89°$ and $ck/\Omega_H \sim 100$–600 are generated between $\omega_r \approx 0.1$ and $0.4\Omega_H$. These waves are also linearly polarized and have a growth rate comparable to that for the H^+ EMIC waves. The parallel index of refraction $n_\parallel$ is again approximately constant and can be taken to be 18. For both of these modes, the wave magnetic field amplitude $B \cong n_\parallel E_1 \gg E_1$. Consequently, these waves are not electrostatic even through $\boldsymbol{k}$ is almost parallel to the wave electric field.

3. THE STOCHASTIC ACCELERATION MECHANISM

The H^+ EMIC and shear Alfvén waves are excited at and around the ^3He and Fe cyclotron frequencies, respectively (Q/A for Fe at 10^6 K is $7/56 = 0.125$). A continuous spectrum of H^+ EMIC waves can therefore lead to stochastic acceleration of ^3He through the $l = +1$ gyroresonance; a spectrum of shear Alfvén waves can accelerate Fe. The nature of this stochastic acceleration is best examined through a Hamiltonian formalism (see Karimabadi et al. 1992). We construct the Hamiltonian for an ion and a spectrum of waves, employ a series of canonical transformations and secular perturbation theory (Lichtenberg & Lieberman 1983, § 2.4), and eventually arrive (details given in Miller et al. 1993) at an autonomous near-integrable form $H = H_0 + H_1$, where H_1 is a small perturbation of the integrable part $H_0 = \gamma - (p_\parallel/mc)/n_\parallel$ (γ is the Lorentz factor, p denotes momentum, and m is the ion mass). The quantity H_0 is a constant of the motion, which can also be shown by noting that energy is conserved in the wave frame. Ions thus move on surfaces of constant H_0 (H surfaces) in $p_\perp$-$p_\parallel$ space. The gyroresonance condition $\omega - k_\parallel(p_\parallel/m\gamma) - l\Omega/\gamma = 0$ for an ion of cyclotron frequency Ω and a given monochromatic wave can also be plotted in $p_\perp$-$p_\parallel$ space and yields an R surface. The intersection between the two surfaces gives the momentum components required in order to resonate with the wave.

We illustrate these resonance diagrams for H^+ EMIC waves and ions. The inside, middle, and outside solid lines in Figure 1 are the H surfaces for $H_0 = 0.9998$, 1, and 1.0002, respectively. The minimum and maximum values bracket the ones which can be realized by typical thermal particles, and $H_0 = 1$ corresponds to an initially cold ion. The two sets of dashed lines are $l = +1$ R surfaces for protons and alpha particles and 10 monochromatic waves equally spaced in frequency between 0.6 and $0.82\Omega_H$; the leftmost line in each set is for $0.6\Omega_H$, and the rightmost is for $0.82\Omega_H$. For protons, the R surfaces do not intersect any H surface and these particles will not be able to resonate with the waves. The R and H surfaces do intersect for $^4He^{+2}$ ions, but at a minimum energy of $\approx 400\,\mathrm{keV\,nucleon^{-1}}$. Hence, thermal $^4He^{+2}$ ions will not be able to resonate with these waves. We show the same H surfaces in Figure 2, but now plot the R surfaces for $^3He^{+2}$ ions and the same 10 representative waves. In this case, all of the H surfaces are intersected by some R surfaces at thermal energies, so that all ambient $^3He^{+2}$ ions will resonate with some waves. Consider specifically the $H_0 = 1$ H surface. The R surface which is tangent to this surface at $p_\parallel = p_\perp = 0$ is for $\omega = (Q/A)\Omega_H$, and it is immediately seen that intersections

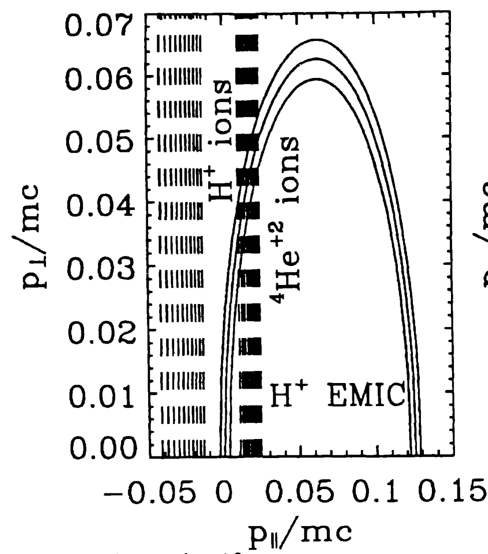

Fig. 1: H^+ and $^4He^{+2}$ resonance diagrams.

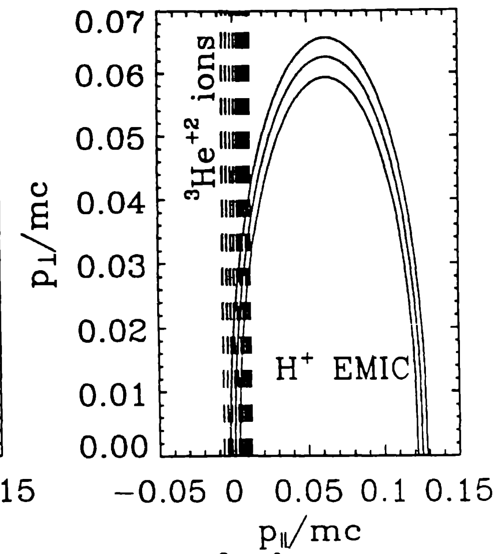

Fig. 2: $^3He^{+2}$ resonance diagram.

occur only for waves with $\omega \geq (Q/A)\Omega_H$. Hence, for initially cold ions, the only waves of importance are those with frequency greater than the particle cyclotron frequency.

A particle in resonance with a given wave executes pendulum motion in $p_\|$ on the H surface about the intersection with the R surface. The maximum excursion away from the resonance value is called the trapping half width. When trapping half widths of neighboring waves overlap, stochasticity results and the particle can move along the section of H surface covered by both trapping widths. If there are many overlapping waves present in the spectrum, a large segment of the H surface can be covered and high energies attained. A continuous spectrum ensures resonance overlap, and in this case we see from Figure 2 that the maximum ^3He energies on the three H surfaces are $\simeq 490$, 700, and 900 keV nucleon^{-1}. The resonance diagram for $^{56}Fe^{+7}$ and shear Alfvén waves can be similarly constructed, and indicates that the maximum Fe energy (for $H_0 = 1$) is ≈ 2 MeV nucleon^{-1}. Oxygen and carbon have charges of +6 and +5, respectively, and their corresponding maximum energies (again for $H_0 = 1$) are ≈ 200 and ≈ 10 keV nucleon^{-1}.

Motion along the H surface can be described by the diffusion equation (Karimabadi & Menyuk 1991)

$$\frac{\partial f}{\partial t} = \frac{1}{\gamma}\frac{\partial}{\partial \gamma}\left(\gamma D_{\gamma\gamma}\frac{\partial f}{\partial \gamma}\right), \tag{1}$$

where $N(\gamma) = 2\pi n_\| \gamma f(\gamma)$ is the energy spectrum and $D_{\gamma\gamma}$ is the diffusion coefficient which is quickly evaluated using the Hamilton equations of motion and unperturbed orbits. We find that for harmonic number l

$$D_{\gamma\gamma} = \frac{1}{2}\frac{1}{\gamma^2}\left(\frac{p_\perp}{mc}\right)^2 \Omega |k_{\|r}| \int dk_\perp \, W_E(k_\perp, k_{\|r}) \frac{l}{(k_\perp \rho)^2} J_l^2(k_\perp \rho), \tag{2}$$

where $k_{\|r} = l\Omega/[\gamma(c/n_\| - v_\|)]$ is the resonant wavenumber, $\rho = p_\perp/m\Omega$ is the gyroradius, and W_E is the electric field spectral density of the turbulence in units of $U_B = B_0^2/8\pi$.

4. RESULTS

We assume for simplicity that both H^+ EMIC and shear Alfvén waves are uniformly distributed over the frequencies and wavenumbers given above (i.e., W_E is constant in these ranges), and consider diffusion along only the $H_0 = 1$ H surface. The total electric field energy density U_E is needed to normalize W_E. We numerically evaluate $D_{\gamma\gamma}$ and then solve the diffusion equation by fully implicit finite differencing, taking the initial kinetic energy $E = 0.1$ keV nucleon^{-1}. For $B_0 = 10^3$ G and $n_T = 10^{10}$ cm^{-3}, we show in Figure 3 the ^{3}He energy spectra at $t = 10^{-3}$, 10^{-2}, 10^{-1}, and 1 s; the spectra are normalized to 1. The level of turbulence is very low, with $U_E/n_T k_B T_c = 10^{-3}$, where k_B is Boltzmann's constant. The average ion energies at these times are $\approx$ 35, 84, 190, and 350 keV nucleon^{-1}. At $\approx$ 1 s, equilibrium is achieved and the spectrum is flat, as expected from the form of equation (1). These waves are therefore very efficient and capable of accelerating thermal ^{3}He ions to high energies on flare time scales. No other ion can resonate with these waves, and they will specifically produce a huge enhancement of ^{3}He relative to ^{4}He.

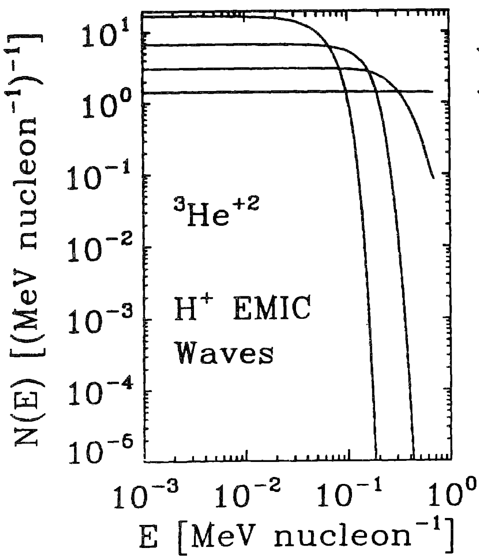

Fig. 3: $^3He^{+2}$ spectra.

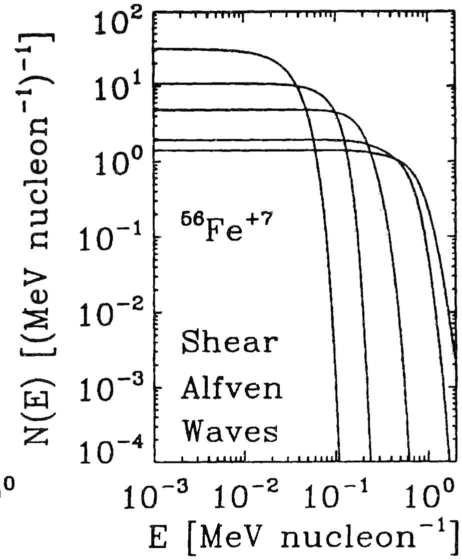

Fig. 4: $^{56}Fe^{+7}$ spectra.

Iron spectra at $t = 10^{-2}$, 10^{-1}, 1, 10 and 20 s are given in Figure 4; U_E for these waves is an order of magnitude higher than for the H$^+$ EMIC waves. Corresponding average energies are $\approx$ 20, 53, 117, 313, and 426 keV nucleon^{-1}. While less efficient than the EMIC waves (mostly because of their broad band), shear Alfvén waves are capable of accounting for Fe acceleration. Furthermore, they will lead to a large Fe/C (Fe/O) ratio above $\approx$ 10 keV nucleon^{-1} ($\approx$ 200 keV nucleon^{-1}). The observed Fe charge state of $\approx +20$ is self-consistently obtained by simply taking into account collisional ionization by the beam and radiative recombination. We find (MV) that an equilibrium charge state of $\approx +19$ is realized in about 10 s. Hence, Fe is simultaneously accelerated and ionized.

Since $n_\parallel$ is not strictly constant, higher energies than the maxima given above will be realized, and it may possible to accelerate ^{3}He and Fe up to the maximum observed energies with these waves. Also, O and C will be energized to higher energies as well, which may account for the fact that Fe/O or Fe/C is enhanced, but not nearly as much as ^{3}He/^{4}He. Wave propagation to regions of lower B_0 may also explain the acceleration of protons and ^{4}He. All of these issues are presently being examined.

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