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A Model for ^{3}He Rich Events in Solar Flares

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Abstract

A model for ^{3}He rich events in solar flares, which was recently proposed with attention to nonlinear effects of current-driven instabilities, is extended to study energies of ^{3}He ions. Selective acceleration of ^{3}He ions is by electrostatic H cyclotron waves with frequencies near $2\Omega_{^3\mathrm{He}}$ ($\Omega_{^3\mathrm{He}}$ is the cyclotron frequency of ^{3}He). Theoretical expressions for wavenumbers, $k_\parallel$ and $k_\perp$, of the H cyclotron waves and for the maximum energy of ^{3}He ions are presented. As initial electron drift speed v_d increases, the value of $k_\perp$ decreases; which leads to the increase in the maximum ^{3}He energy. The theory agrees with simulation results obtained by a two-dimensional, electrostatic, particle code. It is also predicted that when the initial electron drift energy is of the order of 10 keV, ^{3}He ions are accelerated to energies of the order of MeV/n.

Keywords:
current-driven instabilities, particle acceleration, particle simulation, ^{3}He rich events

1. Introduction

Intensive studies have been made on ^{3}He rich events in solar flares ([1] and references therein). These events are characterized by enhancement of energetic ^{3}He ions; the abundance ratio ^{3}He/^{4}He in particles with energies of the order of MeV/n sometimes exceeds unity, although this ratio in the solar corona is usually $\sim 10^{-4}$.

The ^{3}He rich events are associated with enhancement of 1−100 keV electrons [2] and posses impulsive hard X-ray emission in the early phases of flares [3,4]. A standard interpretation of this hard X-ray emission is that electrons are initially accelerated to the energies $\gtrsim$ 10 keV and then stream along the magnetic field toward and into the chromosphere, producing bremsstrahlung via interaction with ambient protons. Soft X-ray emission from heated plasma is observed to follow the hard X-ray emission with a little time delay [3,4]. This indicates that the electrons exist initially as an intense energetic beam with relative cold temperature ($v_d > v_\mathrm{Te}$, where v_d is the stream velocity along the magnetic field and v_Te is the thermal velocity) and are later heated.

As a mechanism for the ^{3}He rich events, instabilities driven by electron currents are believed to be important, and several theoretical models have been proposed based on the linear stability theories [5-7]. There are, however, some conflicts between the observations and these models. For example, these models assumed that the instabilities are driven by weak currents with $v_d < v_{Te}$, although strong currents with $v_d > v_{Te}$ exist in the early phases of the flares. On the basis of the linear stability theory, it was expected that the strong currents would destabilize many kinds of waves with a wide range of frequencies and that selective acceleration of ^{3}He ions would be difficult [6].

Recently, in order to solve this discrepancy, nonlinear development of current-driven instabilities and associated energy transport have been investigated by means of particle simulations [8,9]. In ref. [9], the simulations demonstrated that strong currents can cause selective acceleration of ^{3}He ions though electrostatic H cyclotron waves with $\omega \simeq 2\Omega_{^3\mathrm{He}}$. These waves are excited via nonlinear effects of the instabilities. Furthermore, the condition where $\omega \simeq 2\Omega_{^3\mathrm{He}}$ waves become dominant was theoretically studied. It was predicted that if an electron beam with its initial drift energy higher than 1 keV exists, the enhancement of energetic ^{3}He ions would be produced.

In this paper, we present a theory for the maximum energy of ^{3}He ions. We then show that if the initial electron energy is of the order of 10 keV, ^{3}He ions are accelerated to energies of the order of MeV/n. These energies are the same order as the observed values in the ^{3}He rich events.

In Sec. **2**, we outline the nonlinear development of strong current-driven instabilities. In Sec. **3**, we present a theory predicting the wavenumbers of H cyclotron waves with $\omega \simeq 2\Omega_{^3\mathrm{He}}$ and the maximum energy of ^{3}He ions accelerated by these waves. We also show that the theory is in good agreement with simulation results. We then compare the theory with the observations.

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2. Nonlinear development of current-driven instabilities

We consider instabilities by electron currents with $v_d > v_{Te}$, assuming that the electrons have a shifted Maxwell distribution. According to the linear theory, Buneman waves are the most unstable [10], while H cyclotron waves are almost stable. Figure 1 shows typical time variations of a Buneman wave and a H cyclotron wave; these were obtained by a two-dimensional electrostatic particle code [9]. The bottom panel shows time variations of electron temperatures, $T_{e\parallel}$ and $T_{e\perp}$, where subscripts $\parallel$ and $\perp$ represent quantities parallel and perpendicular to the magnetic field, respectively. The temperatures are normalized to their initial values.

As predicted by the linear theory, the Buneman waves grow at first. However, they quickly saturate owing to electron trapping [11]. The electron trapping drastically changes the shape of electron velocity distribution function $f_e(v_\parallel)$ and significantly broadens its width. Because of this process, the parallel electron temperature $T_{e\parallel}$ significantly rises. The saturation level of $T_{e\parallel}$ is estimated as

$$T_{e\parallel} \sim m_e v_d^2/2. \quad (1)$$

On the other hand, ion temperatures rise little. Thus, a plasma with $T_{e\parallel} > T_H$ is produced. The change in $f_e(v_\parallel)$ then destabilizes the H cyclotron waves which were marginal in the initial state. The phase velocities of these waves are

$$\omega/k_\parallel \simeq v_d. \quad (2)$$

These waves grow to large amplitudes and strongly influence energy transport to ions.

In ref. [9], it was theoretically and numerically shown that the H cyclotron waves with $\omega \simeq 2\Omega_{^3\mathrm{He}}$ and $\omega/k_\parallel \simeq v_d$ would eventually grow to the largest amplitudes if $Te_\parallel \gtrsim 10T_\mathrm{H}$. These $\omega \simeq 2\Omega_{^3\mathrm{He}}$ waves selectively accelerate ^{3}He ions.

3. Energy of ^{3}He ions

3.1 Theory

First, we give theoretical expressions for wavenumbers, $k_\parallel$ and $k_\perp$, of the H cyclotron waves with $\omega \simeq 2\Omega_{^3\mathrm{He}}$. As described in Sec. **2**, the H cyclotron waves are destabilized in a plasma with $T_{e\parallel} > T_\mathrm{H}$. In this plasma, the waves with small $k_\perp$, $k_\perp \rho_\mathrm{H} < 1$, have great growth rates [9]. The dispersion relation of these waves is given by

$$\omega \simeq \left(1 + \frac{n_\mathrm{H} T_{e\parallel}}{2n_e T_\mathrm{H}} k_\perp^2 \rho_\mathrm{H}^2\right)\Omega_H. \quad (3)$$

We then obtain $k_\perp$ of the $\omega \simeq 2\Omega_{^3\mathrm{He}}$ waves as

$$k_\perp \rho_\mathrm{H} \sim \left[\frac{n_e T_H}{n_H m_e v_d^2}\left(\frac{2\Omega_{3He} - \Omega_H}{\Omega_H}\right),\right] \quad (4)$$

where eq. (1) is used. As v_d increases, $k_\perp$ decreases. We estimate $k_\parallel$ from eq. (2) as

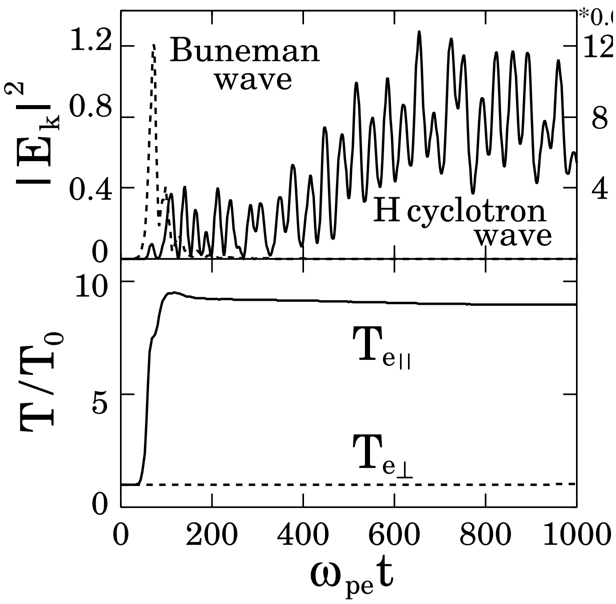

Fig. 1 Time variations of amplitudes $|E_k|^2$ of a Buneman wave and a H cyclotron wave, and time variations of electron parallel and perpendicular temperatures.

$$k_\parallel \simeq 2\Omega_{^3\mathrm{He}}/v_d. \quad (5)$$

The ratio of $k_\perp$ to $k_\parallel$ is written as

$$\frac{k_\perp}{k_\parallel} \simeq \frac{m_\mathrm{H} n_e}{m_e n_\mathrm{H}}\left(\frac{2\Omega_{^3\mathrm{He}} - \Omega_\mathrm{H}}{\Omega_{^3\mathrm{He}}}\right)^{1/2} \gg 1. \quad (6)$$

Hence, the waves propagate nearly perpendicular to the ambient magnetic field.

Next, we consider particle orbits in a monochromatic H cyclotron wave with $\omega \simeq 2\Omega_{^3\mathrm{He}}$ and estimate the maximum energy of ^{3}He ions under two assumptions; 1) the wave amplitude does not change in time, 2) the amplitude is so small that the stochastic acceleration [12] does not occur.

For the resonant particles with $\omega - 2\Omega_{^3\mathrm{He}} - k_\parallel v_\parallel \simeq 0$, we have a constant of motion, $\mathrm{J}_{n0}(k_\perp \rho)\cos\xi$, ([12] and references therein), with J_2 the Bessel function of the second order. Here, the magnetic field is set to be in the z direction. The wave is assumed to propagate in the (x, z) plane, and the quantity ξ is defined as

$$\xi \equiv n\theta - (\omega - k_\parallel v_\parallel)t + k_\perp x_{g0} + k_\parallel z_0, \quad (7)$$

where θ is the gyration phase, and x_{g0} and z_0 denote the initial position. The maximum Larmor radius ρ_Max satisfies

$$|\mathrm{J}_2(k_\perp \rho_\mathrm{Max})| = |\mathrm{J}_2(k_\perp \rho_0)\cos\xi_0|, \quad (8)$$

where ρ_0 the initial Larmor radius.

We suppose that $k_\perp \rho_0 \ll 1$. Then, the right-hand side of eq. (8) is very small, and ρ_Max can be estimated from the first zero point of J_2 as

$$\rho_\mathrm{max} \simeq 5/k_\perp. \quad (9)$$

The particles have this maximum Larmor radius, almost independent of the initial gyration phase θ_0 or the initial position, x_g and z_0.

The ratio of the maximum energy to the initial thermal energy is written as

$$\frac{v_{\rm Max}^2}{v_{\rm T^3He}^2} \simeq \frac{25}{(k_\perp \rho_{\rm H})^2}\frac{v_{\rm TH}^2}{v_{\rm T^3He}^2}\frac{\Omega_{\rm ^3He}^2}{\Omega_{\rm H}^2}, \qquad (10)$$

where $v_{\rm TH}$ and $v_{\rm T^3He}$ are the initial thermal velocities of H and ^{3}He ions, respectively. Equation (10) shows that in the wave with $k_\perp \rho_{\rm H} \ll 1$, the maximum ^{3}He energy is much greater than the initial energy. As $k_\perp$ decreases, the maximum ^{3}He energy increases.

Using eq. (4), we approximately write eq. (10) as

$$\frac{v_{\rm Max}^2}{v_{\rm T^3He}^2} \sim 25\frac{m_e v_{\rm d}^2}{T_{\rm ^3He}}\frac{\Omega_{\rm ^3He}}{(2\Omega_{\rm ^3He} - \Omega_{\rm H})} \sim 50\frac{m_e v_d^2}{T_{\rm ^3He}}, \qquad (11)$$

where $T_{\rm ^3He}$ is the initial ^{3}He temperature. The maximum ^{3}He energy is proportional to the initial electron drift energy $m_{\rm e} v_{\rm d}^2$.

3.2 Particle simulation

We perform simulations by means of a two-dimensional (two space and three velocity components) electrostatic particle code with full ion and electron dynamics. The plasma is assumed to consist of electrons, H, ^{4}He, and ^{3}He ions with the abundance of ^{3}He being small. Initially, the electrons have a shifted Maxwell distribution with $v_{\rm d}$. We solve the initial value problem of this system.

According to the theory, the wavenumbers $k_\perp$ of the H cyclotron waves and the maximum ^{3}He energy depend on $v_{\rm d}$. We here present the results obtained by the simulations with various values of $v_{\rm d}$ (for other parameters, see ref. [9]).

When $v_{\rm d}$ is sufficiently large, the H cyclotron waves with $\omega \simeq 2\Omega_{\rm ^3He}$ eventually grow to the greatest amplitudes. Figure 2 shows the wavenumber $k_\perp$ of the greatest amplitude wave as a function of $v_{\rm d}$. The dots are simulation results, and the solid line represents the theory, eq. (4). The simulation results are in good agreement with the theory.

Figure 3 shows the maximum ^{3}He energy as a function of $k_\perp$ of the $\omega \simeq 2\Omega_{\rm ^3He}$ wave. The solid line represents the theoretical value estimated from eq. (10). The simulation results are also in good agreement with the theory.

3.3 Comparison with observations

It has been reported that the ^{3}He rich events are accompanied by the energetic electrons with $\gtrsim$ 10 ke V. We suppose that initial electron drift energy is of the order of 10 keV. We then estimate the wavenumber of an electrostatic H cyclotron wave that would be destabilized by these electrons. The maximum energy of ^{3}He ions accelerated by this wave is also given. We here assume that B=100 G, $T_{\rm H}$ = 100 eV, $n_{\rm H} \sim 10^8$cm^{-3}, and the initial ^{3}He temperature $T_{\rm ^3He}$ = 100 eV.

From eqs. (4) and (5), we obtain $(k_\parallel, k_\perp)$ of the wave with $\omega = 2\Omega_{\rm ^3He}$ and $\omega/k_\parallel = v_{\rm d}$ as

$$(k_\parallel \rho_{\rm H}, k_\perp \rho_{\rm H}) \sim (0.0011, 0.045). \qquad (12)$$

The parallel and perpendicular wavelengths are of the order of 10^5 cm and 10^4 cm, respectively. They are much smaller than the typical flare size, 10^9 cm. Hence, we neglect effect of inhomogeneity of the backgound plasma on the wave.

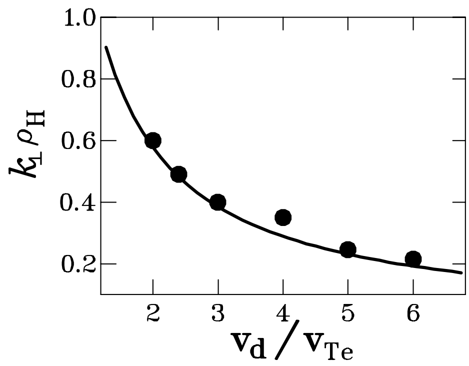

Fig. 2 Wavenumber $k_\perp$ of the greatest amplitude wave as a function v_d.

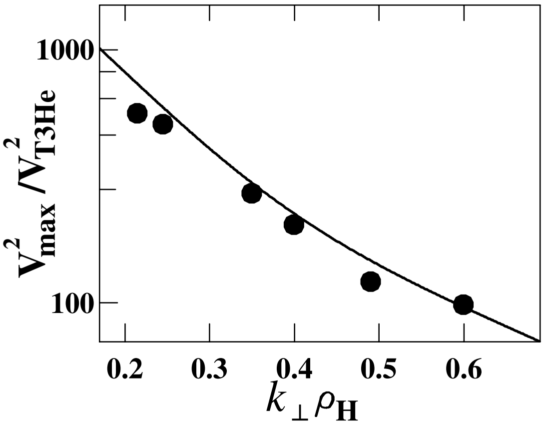

Fig. 3 Wavenumber $k_\perp$ of the greatest amplitude wave as a function v_d.

Electromagnetic component in the wave is negligible. In the extremely long wavelength region, electrostatic H cyclotron waves would be connected to magnetosonic waves [13]. Hence, we can write the condition where the electrostatic approximation is valid as

$$\omega / k_\perp < v_{\rm A}, \qquad (13)$$

where $v_{\rm A}$ is the Alfvén speed. This condition is well satisfied because $\omega/k_\perp \sim 10^6$ cm/s and $v_{\rm A} \sim 10^7$ cm/s.

Substituting eq. (12) into eq. (10), we estimate the ratio of the maximum ^{3}He energy to the initial thermal energy as

$$\frac{v_{\rm max}^2}{v_{\rm T^3He}^2} \sim 10^4. \qquad (14)$$

This indicates that the maximum ^{3}He energy is of the order of MeV/n, which is the same as the observed energies of ^{3}He ions in the ^{3}He rich events [1, 2].

4. Summary

A model for ^{3}He rich events in solar flares has been developed with attention to nonlinear effects of strong current-driven instabilities. We gave a theory for the wavenumbers of the H cyclotron waves with $\omega \simeq 2\Omega_{\rm ^3He}$ and the maximum energy of ^{3}He ions accelerated by these waves. As v_d increases, the value of $k_\perp$ decreases and the maximum ^{3}He energy thus increases. The theory is in good agreement with the simulation results. We have also theoretically shown that if the initial electron energy is of the order of 10 keV, ^{3}He ions are accelerated to energies of the order of MeV/n.

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