Ions Preheated in $^3$He-Rich Solar Particle Events

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A wave-particle resonance absorption model in the two-ion plasma is suggested in explanation to the coronal ions preheating in $^3$He-rich solar particle events. It is found that $^3$He and Fe ions are preferably preheated by the ion-ion hybrid waves at their fundamental and second harmonic ion cyclotron frequencies, respectively.

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One of the puzzling phenomena in solar particle acceleration is that the isotopic abundance ratio of helium $^3$He/$^4$He in the energies around 1 MeV/nucleon is dramatically enriched during impulsive solar flares, which were observed by many satellites.$^{[1,2]}$ These solar energetic particle (SEP) events are also called the $^3$He-rich solar particle events. The characteristics of these events are: (a) The abundance ratio of He ions ($^3$He/$^4$He) in the $^3$He-rich solar particle events approaches to 0.1–1.0, as compared with the abundance ratio of He ions ($^3$He/$^4$He) in corona is about $\sim 5 \times 10^{-4}$, which increases to $10^2$–$10^3$ times of the normal one.$^{[1]}$ (b) The abundance of some heavy ions also increases, it increases to 8 times of the normal one for Fe ion, and 2.8 times for Mg ion.$^{[3]}$ (c) The spectra of $^3$He, $^3$He, H, Fe ions over above $\sim 1$ Mev/nucleon are the power-law spectra with the similar index $\sim 2.6$, which, however, do not correlate with the abundance ratio of He ions.$^{[3]}$ (d) The $^3$He-rich acceleration events are only observed in solar impulsive flares,$^{[4]}$ it often associates with the solar radio type-II bursts. (e) Share and Murphy$^{[4]}$ have analysed the $\gamma$-ray lines from de-excitation of nuclear reaction of $^{16}$O($^3$He, p)$^{18}$F, which supports that $^3$He ions are accelerated in the corona.

In order to explain the $^3$He-rich solar particle events, several models have been suggested. The Monte Carlo calculation was adopted by Termerin and Roth,$^{[5]}$ they proposed that $^3$He ions were accelerated selectively by H$^+$ electromagnetic ion cyclotron waves, but it is difficult to form a power-law spectrum. Zhang$^{[6]}$ proposed that $^3$He ions were preheated by second-harmonic electrostatic H ion cyclotron wave, but it is far from the cyclotron resonance frequency of $^3$He ion. Rypolopous$^{[7]}$ proposed a stochastic diffusion model, $^3$He ions were resonantly accelerated by two-ion hybrid wave, but this model requires a high $^4$He density $n_{\text{H}}/n_{\text{H}} \sim 0.25$.

However, from the above-mentioned characteristic, it is reasonable to believe that the SEP in $^3$He-rich solar particle events are accelerated by a two-step acceleration processes.$^{[8]}$ The energy spectra of various ions such as Fe, Mg and $^3$He isotopic are a power-law spectrum with the similar power-law index, which indicates that these ions are accelerated by the similar stochastic acceleration mechanism, at least in the last stage of ion acceleration for the $^3$He-rich solar particle events. The Alfvén turbulence acceleration should be a good candidate for stochastic acceleration in impulsive solar flares. Wu et al.$^{[9]}$ have calculated the spectra of He and Fe ions by Alfvén turbulence acceleration under the condition that the ion initial velocity is larger than the Alfvén velocity. It is worth noting that the threshold velocity of ions for the Alfvén turbulence stochastic acceleration is $v_s > V_A$. However, the thermal velocity of ions are much smaller than the local Alfvén velocity in solar flares, as discussed in Ref. [11]. Thus, a preheating mechanism is required for $^3$He-rich solar particle events. It is well known that the acceleration mechanisms in common are not very sensitive to the parameters of ion charge number $Q$ and ion mass number $A$, besides the wave-particle resonance interaction.

On the other hand, the coronal plasma considered is composed of many kinds of ions, and most of them are hydrogen ions and helium ions, the helium ions are possessed of about 7–10% in corona. The ion-ion hybrid waves can be formed in the two ions plasma, it may play an important role for $^3$He and Fe ions preheating. We will further discuss selective ions preheating by means of the resonance absorption of the ion-ion hybrid wave and the ion cyclotron wave. It is readily found that the ion selective preheating process in the $^3$He-rich event is similar to ion cyclotron heating of plasma in nuclear fusion,$^{[12,13]}$ it may obtain some useful inspiration from this similarity.

We consider a coronal plasma, it consists of two ion components of hydrogen and helium. The main features of wave propagation may be described by the cold plasma approximation, in which the non-zero elements of the dielectric tensor $\varepsilon_{ij}$ in the range of ion cyclotron frequencies can be expressed as

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\[ \varepsilon_{11} = \varepsilon_{22} = \varepsilon_1 = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2 - \Omega_s^2} \]

\[ \varepsilon_{12} = -\varepsilon_{21} = \varepsilon_2 = -\sum_s \frac{\omega_{ps}^2}{\omega(\omega^2 - \Omega_s^2)} \]

\[ \varepsilon_{33} = \varepsilon_3 = 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \approx -\frac{\omega_{ps}^2}{\omega^2}, \]

\[ \omega_{pH}, \omega_{p4}, \omega_{pe} \text{ and } \Omega_4, \Omega_4, \Omega_e \text{ are the plasma frequencies and cyclotron frequencies of H ions, } \text{He ions and electrons, respectively.} \]

The dispersion relation of magnetized cold plasma becomes

\[ \det |\mathbf{A}^{0} (\mathbf{k}, \omega) | = \begin{vmatrix} \varepsilon_1 - N_z^2 & i\varepsilon_2 & N_{xN_z} \\ -i\varepsilon_2 & \varepsilon_1 - N_x^2 - N_z^2 & 0 \\ N_{xN_z} & 0 & \varepsilon_3 - N_x^2 \end{vmatrix} = 0, \]

where the magnetic field is chosen at the \( z \) direction, and the inhomogeneity may exist in the perpendicular propagation \( x \) direction. From Eq. (2), we can obtain

\[ N_x^2 = \frac{b \pm \sqrt{b^2 - 4bN_z - 4cN_z}}{2\varepsilon_1}, \]

where + and \( - \) signs represent the O mode and the X mode, respectively.\[^{14}\]

\[ b = (\varepsilon_1 + \varepsilon_3)(\varepsilon_1 - N_z^2 - \varepsilon_2), \]

\[ c = \varepsilon_3[(\varepsilon_1 - N_z^2)^2 - \varepsilon_2^2]. \]

Although the dielectric tensor elements \( \varepsilon_1 \) and \( \varepsilon_2 \) go to infinity as \( \omega \to \Omega_H \) and \( \Omega_4 \), but the solution of Eq. (3) is finite. It is found that \( N_x^2 \to \infty \), only if the element of dielectric tensor \( \varepsilon_{11} \to 0 \). This corresponds to the fact that the resonance frequencies occur at lower and upper hybrid frequencies, as the plasma consists of single species of ion and electron, but these frequencies are much larger than the ion cyclotron frequency. However, the resonance frequency occurs at the ion-ion hybrid frequency \( \omega_{ii} \),\[^{8}\], as the plasma consists of two ion components. This frequency is closed to the ion cyclotron frequency of small minority ion, and it can be absorbed by a minority of ions at its fundamental ion cyclotron frequency. It is in explanation of the ion-ion hybrid resonance wave to be preferably absorbed by small minority ion.\[^{12}\]

The frequency \( \omega \) in the wave propagation may be written as \( \omega = \omega_r + i\omega_i \), where \( \omega_r \) is real frequency and the imaginary frequency \( \omega_i < 0 \) represents wave absorption. In the case of \( |\omega_i| \ll |\omega_r| \), the wave absorption \( \omega_i \) can be expressed as

\[ \omega_i = -\frac{\omega_r}{G} \Im A(k, \omega_r). \]

The \( G \) may be expressed as

\[ G = \omega_r \frac{\partial}{\partial \omega} \Re A^0(k, \omega_r) \]

\[ = \omega_r \left( \frac{\partial A_0}{\partial \omega} - \frac{4A_0}{\omega}\right) N^2 + \omega_r \left( \frac{\partial B_0}{\partial \omega} - \frac{2B_0}{\omega^2}\right) N^2 \]

\[ + \omega_r C_0. \]

In the cold plasma approximation, \( A_0, B_0, \) and \( C_0 \) can be expressed as\[^{11}\]

\[ A_0 = \varepsilon_1 \sin^2 \theta + \varepsilon_3 \cos^2 \theta, \]

\[ B_0 = -\varepsilon_1 \varepsilon_3 (1 + \cos^2 \theta) - (\varepsilon_1^2 - \varepsilon_2^2) \sin^2 \theta, \]

\[ C_0 = \varepsilon_3 (\varepsilon_1^2 - \varepsilon_2^2). \]

It is further assumed that the \( \alpha \) particle is a small minority of ions, and its density \( n_{\alpha} \) is much less than the main ion density \( n_s \), \( n_s \gg n_{\alpha} \). In this case, \( \Im A(k, \omega_r) \) can be approximately expressed as

\[ \Im A(k, \omega_r) = \psi_{xx} \Im (Q_{xx}(k, \omega_r)) + \psi_{yy} \Im (Q_{yy}(k, \omega_r)) + \psi_{zz} \Im (Q_{zz}(k, \omega_r)) + \psi_{xy} \Re (Q_{xy}(k, \omega_r)) + \psi_{yz} \Re (Q_{yz}(k, \omega_r)). \]

In the cold plasma approximation, the \( \psi_{ij} \) matrix may be written as

\[ \psi_{xx} = N^2 \sin^2 \theta - N^2 (\varepsilon_3 + \varepsilon_1 \sin^2 \theta) + \varepsilon_3 \varepsilon_1, \]

\[ \psi_{yy} = -N^2 (\varepsilon_3 \cos^2 \theta + \varepsilon_1 \sin^2 \theta) + \varepsilon_3 \varepsilon_1, \]

\[ \psi_{zz} = N^4 \cos^2 \theta - N^2 (\varepsilon_3 + \varepsilon_1 \sin^2 \theta) + \varepsilon_3^2 - \varepsilon_2^2, \]

\[ \psi_{xy} = 2\varepsilon_3 (\varepsilon_3 - N^2 \sin^2 \theta), \]

\[ \psi_{yz} = 2(N^4 - N^2 \varepsilon_3) \sin \theta \cos \theta. \]

The \( Q^\alpha \) is the dielectric tensor of a small minority of \( \alpha \) ions. This tensor can be expressed by

\[ Q_{ij}^\alpha = \frac{\omega_{ps}^2}{\omega^2} \sum \zeta_0 Z(\zeta) \Pi_{ij}^\alpha + 2\zeta_0 b_3 b_5 \]

as \( \alpha \) ion velocity distribution is a Maxwellian distribution,\[^{14}\] where \( b_3 \) is a unit component in the magnetic direction. The \( \Pi_{ij}^\alpha \) tensor of \( \alpha \) ion at \( \ell \) harmonic frequency can be expressed as
where 
\[ \zeta = \frac{\omega_r - \ell \Omega_a}{\sqrt{2 k_\parallel v_a}}, \quad v_a = \sqrt{\frac{T_a}{m_a}}, \]

\[ A_\ell(x) = e^{-x I_\ell(x)}, \quad A'_\ell(x) = \frac{dA_\ell}{dx}, \]

and

\[ \sqrt{a_a} = \frac{k_{\parallel} v_a}{\Omega_a}. \]

\( Z(\zeta) \) is the plasma dispersion function,\(^{[11]} \) and \( I_\ell(x) \) is the modified Bessel function. Usually,

\[ a_a = \left( \frac{N \omega_r v_a \sin \theta}{\Omega_a c} \right)^2 \ll 1, \]

with \( v_a \ll c \). Under this condition, the modified Bessel function \( I_\ell(x) \) can be expanded in small argument \( a_a \), and the absorption coefficient of a ion at \( \ell \) harmonic frequency can be approximately written as

\[
\frac{\omega_i}{\omega_r} \sim \frac{(\psi_{xx} + \psi_{yy} - \psi_{xy})}{G} \frac{\ell \omega_p^2}{2(\ell - 1) \omega_c^2} \left( a_a \right)^{-1} \times \exp(-a_a) \zeta \text{Im} Z(\zeta) \tag{12}
\]

It is convenient to take the coronal plasma parameters of ion temperature \( T_a = 3 \text{ keV} \), the electron density \( n_e = 10^{30} \text{ cm}^{-3} \), magnetic field \( B = 300 \text{ G} \). The ratio of helium ion and hydrogen ion \( n_3/n_H = 0.07 \), and the isotopic abundance ratio of helium ion in corona \( n_3/n_4 = 5 \times 10^{-4} \). The Fe ion abundance ratio \( n_{Fe}/n_H = 3 \times 10^{-5} \). Substituting these parameters to Eq. (12), we can obtain the absorption coefficient of \(^3\text{He} \) ions for the fundamental O mode and X mode at different propagation angles of \( \theta \), as shown in Figs. 1(a) and 1(b), respectively. As compared with \( T_3 = 3 \text{ keV} \), \( T_3 = 1 \text{ keV} \) is taken in Fig. 2. The absorption coefficient of Fe ions of \( T_{Fe} = 3 \text{ keV} \) around their second harmonic cyclotron frequency are shown in Fig. 3. In order to distinguish the curves of the different propagation angles, it is convenient to take the logarithm of negative absorption coefficient \( \log[-\omega_i/\omega_r] \) as an ordinate in Figs. 1–3. The average ionization charge number of Fe ions at this temperature is 16.\(^{[11]} \)

It is found from these figures that: (1) The absolute value of absorption coefficient are larger for the larger propagation angle, this means that the waves are absorbed mainly in the direction perpendicular to the magnetic field. It is well known that\(^{[8]} \) the ion-ion hybrid waves are closed to the quasi-perpendicular direction to the magnetic field, these waves should be available to be absorbed by \(^3\text{He} \) ions around their fundamental cyclotron frequency. (2) The absolute value of fundamental absorption coefficient are much larger than the absolute value of the second-harmonic absorption coefficient. (3) The absolute value of absorption coefficient of the fundamental X mode is smaller than the absolute value of the fundamental O mode, this may be due to the fact that the field of fundamental X mode in cold plasma approximation rotates in the same direction as the electron, it cannot be effectively absorbed by ions.\(^{[13]} \) (4) The Fe ions may be preheated around their second harmonic cyclotron frequency, but it will be not preheated by the O mode in the range of refractive index \( N_e^2 < 0 \), as the ionization charge number of Fe ions is less than

![Fig. 1. Logarithm characteristics of negative absorption coefficient \( \log[-\omega_i/\omega_r] \) for \(^3\text{He} \) ions around their fundamental cyclotron frequency at different propagation angle \( \theta \) with the parameters: \( n_e = 10^{30} \text{ cm}^{-3} \), \( B = 300 \text{ G} \), \( n_3/n_H = 0.07 \), \( T_3 = 3 \text{ keV} \), in the two-ion coronal plasma: (a) O mode, (b) X mode.](image-url)
16; it should be considerable that the Fe ion is ionized and preheated in solar flare processes simultaneously.

We come to conclusion from these results that $^3$He and Fe ions can be preferably preheated by the cyclotron resonance absorption of ion–ion hybrid waves up to the velocity of these ions are larger than the local Alfvén velocity during the impulsive solar flares.

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References


