

The role of electromagnetic ion-cyclotron waves in solar ^3He -rich events

A. Broaden^a, T.X. Zhang^{a,*}, V.M. Edwards^a, A. Tan^a, A. Winebarger^b, Jun Zhang^c, S.T. Wu^d

^a Alabama A&M University, Normal, AL 35762, USA

^b Marshall Space Flight Center, NASA, Huntsville, AL 35812, USA

^c National Astronomical Observatories, Chinese Academy of Science, Beijing, China

^d University of Alabama in Huntsville, Huntsville, AL 35899, USA

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ABSTRACT

The preferential heating of ^3He by the electromagnetic ion-cyclotron waves, which propagate in the direction parallel to the magnetic fields in the solar corona, is investigated. The results obtained from this study indicate that the parallel propagating electromagnetic ion-cyclotron waves, if driven, can be efficient at heating ^3He through the first harmonic resonance. This preferential heating of ^3He can lead to a high temperature ratio $T_{^3\text{He}}/T_{^4\text{He}} \sim 10\text{--}20$ and thus largely increases the number of ^3He to be further accelerated to high energies. Comparing to the electrostatic ion-cyclotron waves, we find that the electromagnetic ion-cyclotron waves can be even more efficient at heating ^3He than the electrostatic ion-cyclotron waves if both types of waves are excited with comparable wave energy densities. Therefore, the electromagnetic ion-cyclotron waves, if generated in solar flares, should also play an important role in solar ^3He -rich events along with the electrostatic ion-cyclotron waves.

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1. Introduction

Measurements in the past four decades have shown that, in many solar energetic particle (SEP) events, the abundance ratio $^3\text{He}/^4\text{He}$ is enhanced by a factor of $\sim 10^2\text{--}10^4$ relative to the coronal abundances (Schaeffer and Zähringer, 1962 for the original work; Reames, 1999 for a typical review). Other characteristics found in association with solar ^3He -rich events include: (i) Reames enhancements of heavy ions (Mason et al., 2002, 2004; Reames and Ng, 2004), (ii) high-ionization states of heavy ions (Luhn et al., 1987), (iii) short durations, small intensities, and frequent occurrences (Cane et al., 1986), (iv) unlikely association with coronal mass ejections (CMEs) (Brueckner et al., 1995; Kahler et al., 2001), (v) likely association with type-III radio bursts, hard-X emissions, and γ -ray bursts (Reames et al., 1988; Ergun et al., 1998), (vi) origin from open magnetic topologies (Reames, 2002; Wang et al., 2006; Zhang, 2008), (vii) generation of extreme ultraviolet (EUV) emission and plasma jets (Pick et al., 2006; Nitta et al., 2006; Wang et al., 2007; Zhang and Wu, 2009), etc.

To explain solar ^3He -rich events, Cartwright and Mogro-Campero (1972) proposed a two-stage acceleration scenario, in which the first stage involves a particle preferential heating process by plasma waves, while in the second stage, particles

preheated with velocity above a threshold are further accelerated to high energies in a flare-acceleration process. According to this scenario, if ^3He ions are heated more efficiently than ^4He ions in the particle preferential heating process, then more ^3He ions are injected into the flare-acceleration process. The abundance ratio $^3\text{He}/^4\text{He}$ in high-energy particles is, therefore, enhanced relative to the coronal abundances.

Fisk (1978) studied the current-driven, electrostatic ^4He -cyclotron waves. It was shown that the electrostatic ^4He -cyclotron waves can be excited in the solar corona at frequency close to the ^3He -cyclotron frequency $\omega \simeq \Omega_{^3\text{He}}$ and thus can preferentially heat ^3He through the first harmonic resonance and heavy ions with appropriate charge states through the second harmonic resonance. The electrostatic ^4He -cyclotron waves can only heat H and ^4He ions weakly via the non-resonant dissipations. Fisk (1978) suggested Fermi acceleration as the second-stage acceleration mechanism, but did not quantitatively study abundance enhancements of ^3He and heavy ions in high-energy particles. For the electrostatic ^4He -cyclotron waves to be excited at frequency close to $\Omega_{^3\text{He}}$, the electron temperature and ^4He density must be high enough in the coronal plasma such as $T_{e,0}/T_{H,0} = 5$ and $n_{^4\text{He},0}/n_{H,0} = 0.3$. The turbulent heating mechanism developed by Ibragimov and Kocharov (1977) with ion-acoustic waves (see also Kocharov and Kocharov, 1984) was disputed by Weatherall (1984) and thus does not work at all. The radiation heating mechanism developed by Hayakawa (1983) does not affect heavy ions. The non-resonant preheating mechanism developed by Varvoglis and Papadopoulos

* Corresponding author. Tel.: +1 256 372 8106.

E-mail address: tianxi.zhang@aamu.edu (T.X. Zhang).

(1983) cannot in general guarantee selectivity (Riyopoulos, 1991). The ion–ion hybrid waves developed by Wang (2003) are similar to ^4He -cyclotron waves, which preferentially heat ^3He and heavy ions through the first and second harmonic resonances.

On the basis of Fisk's early work on the resonant heating of ^3He , Zhang (1995) studied the current-driven, electrostatic H-cyclotron waves. It was shown that the electrostatic H-cyclotron waves can be excited in the solar corona at frequency close to twice the ^3He -cyclotron frequency $\omega \simeq 2\Omega_{^3\text{He}}$ and thus can preferentially heat ^3He through the second harmonic resonance and heavy ions with appropriate charge states through the third harmonic resonance. In comparison with the electrostatic ^4He -cyclotron waves, the electrostatic H-cyclotron waves can be excited by currents more easily, in more common coronal plasma condition, and more efficiently at heating ^3He , electrons, and heavy ions. The charge states of heavy ions heated by the electrostatic H-cyclotron waves are also more consistent with the observations than the charge states of heavy ions heated by the electrostatic ^4He -cyclotron waves. Similar to the electrostatic ^4He -cyclotron waves, the electrostatic H-cyclotron waves can only heat H and ^4He ions weakly via the non-resonant dissipations. In addition, Zhang (1995) quantitatively studied the second-stage acceleration of the preheated particles according to the Fermi acceleration mechanism and further calculated the abundance enhancements and energy spectra of high-energy particles including ^3He , electrons, and heavy ions such as C, N, O, Si, and Fe nuclei. The results obtained have self-consistently explained various aspects of the heating and accelerations in solar ^3He -rich events (Zhang, 1995, 1999, 2003; Zhang and Wang, 2003, 2004; Zhang et al., 2005).

In this paper, we investigate the role of the electromagnetic ion-cyclotron waves, which propagate in the direction parallel to the magnetic fields, in solar ^3He -rich events according to the two-stage acceleration model. In Section 2, we will first provide the dispersion relation of the parallel propagating electromagnetic ion-cyclotron waves and then numerically solve the dispersion relation. In Section 3, we will first analyze the resonances of ions with the parallel propagating electromagnetic ion-cyclotron waves according to the heating rate analytically derived in Appendix A and then, based on the derived heating rate expression, calculate the temperatures of ^3He and ^4He as functions of the heating time. We will further compare between the electrostatic and electromagnetic ion-cyclotron waves in the heating of ^3He to see which type of waves may heat ^3He more efficiently. In Section 4, we will compute the abundance enhancements of $^3\text{He}/^4\text{He}$ in high-energy particles relative to the coronal abundances. And in the last section, we will discuss and summarize the results that we obtained. The electromagnetic ion-cyclotron waves can also propagate in the direction oblique to the magnetic fields. The preferential heating of ^3He by the oblique propagating electromagnetic ion-cyclotron waves will be quantitatively studied in the future.

2. Dispersion relation of the waves

In a multi-ion magnetized cold plasma with the coronal composition $n_{\text{H},0} > n_{^4\text{He},0} \gg n_{^3\text{He},0}$ and n_{others} , the parallel propagating electromagnetic ion-cyclotron waves can be described by the following dispersion relation (Stix, 1992; Steinacker et al., 1997):

$$k_{\parallel}^2 c^2 = \omega^2 - \frac{\alpha^2 \Omega_{\text{H}}^2}{\gamma} \left[\frac{\omega}{\Omega_{\text{H}} + \gamma \omega} - \frac{(1 - 2Y_{^4\text{He}})\omega}{\Omega_{\text{H}} - \omega} - \frac{2Y_{^4\text{He}}\omega}{\Omega_{\text{H}} - 2\omega} \right]. \quad (1)$$

Here we have neglected the effects on the dispersion relation by ^3He and other heavy ions such as C, N, O, Ne, Si, Mg, and Fe

because the abundances of ^3He and these heavy ions in the solar corona are very low; $k_{\parallel}$ is the parallel wavenumber; ω is the wave frequency; c is the light speed; Ω_{H} is the H-cyclotron frequency; α is the ratio between the electron-plasma frequency and the electron-cyclotron frequency $\alpha = \omega_{pe}/\Omega_e$, which is proportional to the square root of the electron density and inversely proportional to the magnetic field; γ is the ratio between the electron mass and the proton mass $\gamma = m_e/m_{\text{H}} \sim 5.45 \times 10^{-4}$; and $Y_{^4\text{He}}$ is the fraction of ^4He number density $Y_{^4\text{He}} = n_{^4\text{He}}/n_e$, which is usually chosen to be 0.08 or approximately about 0.1 for the solar corona.

Fig. 1 plots the numerical results for the dispersion relation or the frequency of the parallel propagating electromagnetic ion-cyclotron waves as a function of the wavenumber. To numerically solve this dispersion relation, we have chosen $\alpha = 1$, by simply taking from previous studies for a low β plasma (Fisk, 1978; Zhang, 1995), and $Y_{^4\text{He}} = 0.08$. From Fig. 1, we see two branches of ion-cyclotron waves. The branch of H-cyclotron waves (top line) has frequency between the ^4He -cyclotron frequency and the H-cyclotron frequency $\Omega_{^4\text{He}} < \omega < \Omega_{\text{H}}$. The branch of ^4He -cyclotron waves (bottom line) has frequency less than the ^4He -cyclotron frequency $\omega < \Omega_{^4\text{He}}$. The waves with frequency much lower than the ^4He -cyclotron frequency ($\omega \ll \Omega_{^4\text{He}}$) in the branch of ^4He -cyclotron waves are Alfvén waves. In this plot, the frequency and wavenumber are normalized by Ω_{H} and c/Ω_{H} , respectively. The gap between two branches is due to the ^4He -cyclotron damping, which constrains the generation of the electromagnetic ion-cyclotron waves that resonate with ^4He ions. Similarly, the H-cyclotron damping constrains the generation of the electromagnetic ion-cyclotron waves that resonate with H ions.

For a larger α (e.g., $\alpha = 2$), the dispersion relation is shown in Fig. 2, which is similar to Fig. 1 with the branches of H-cyclotron, ^4He -cyclotron, and Alfvén waves. The only significant difference is that these electromagnetic ion-cyclotron waves have larger normalized wavenumbers when α is greater. A wave with a larger wavenumber can have better resonances with ions because the resonant factor defined by Eq. (3) is smaller if the wavenumber is larger.

It should be noted that the electromagnetic ion-cyclotron waves can be excited by electron beams (Temerin and Roth, 1992; Miller and Viñas, 1993) at frequency about ^3He -cyclotron frequency and thus can be resonant with ^3He ions through the first harmonic resonance. Due to the strong ^4He and H-cyclotron damping, the electromagnetic ion-cyclotron waves with frequencies near the ^4He and H-cyclotron frequencies cannot be actually excited by the electron beams in the solar corona. In other words,

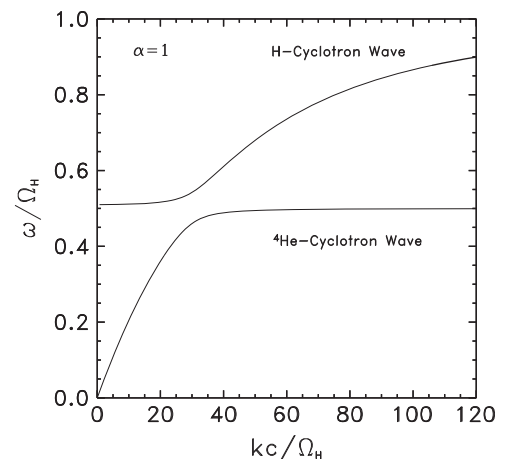


Fig. 1. Dispersion relation of parallel propagating electromagnetic ion-cyclotron waves in a multi-ion magnetized plasma with the coronal composition at $\alpha = 1$.

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