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Abstract

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Full Text

Preamble

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Electromagnetic Ion Beam Instability in the Solar Corona

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Abstract

Remote-sensing measurements indicate that heavy ions in the corona undergo an anisotropic and mass-charge dependent energization. A popular explanation for this phenomenon is the damping of Alfvén/ion cyclotron waves. In this paper, we propose that the ion beam instability can be an important source of the Alfvén/ion cyclotron waves, and we study the excitation of the ion beam instability in the corona at a heliocentric distance of 3R and the corresponding energy transfer process therein based on plasma kinetic theory. The results indicate that the existence of motionless heavy ions inhibits the ion beam instability. However, anisotropic beams of heavy ions promote the excitation of the ion beam instability. Besides, the existence of α beams can provide a second energy source for exciting beam instability. However, when both the proton beam and the α beam reach the instability excitation threshold, the proton beam-driven instability excites preferentially. Moreover, the excitation threshold of the Alfvén/ion cyclotron instability driven by ion beams is of the order of the local Alfvén speed or even less in the corona.

Key words: plasmas -instabilities -waves -Sun: corona

1. Introduction

The solar corona is characterized by its unusually high temperatures (Cranmer & Winebarger 2019). Besides, the effective temperature of minor ions in the solar corona is proportional to their atomic mass number and they are strongly anisotropic, with $T > T$, where and are with respect to the background magnetic fields (Kohl et al. 1997, 1998). One of the most popular physical explanations for highly anisotropic minor ions in the solar corona is the cyclotron interactions between ions and Alfvén/ion cyclotron waves (Cranmer et al. 1999; Isenberg et al. 2001; Liewer et al. 2001; Marsch & Tu 2001; Hollweg & Isenberg 2002).

There are several theories about the origin of the Alfvén/ion cyclotron waves. First, these waves may be generated by small-scale magnetic activity in the chromospheric network and directly launched into the corona (Axford & McKenzie 1992, 1995; Tu & Marsch 1997). Second, these waves may be produced by a turbulent cascade from much lower frequencies (Li et al. 1999; Hollweg & Isenberg 2002; Li et al. 2004). Third, microinstabilities locally excited by electrons and electric currents in the corona may be their source (Forslund 1970; Toichi 1971;

Markovskii 2001; Markovskii & Hollweg 2002). Besides, Alfvén/ion cyclotron waves can also be locally generated by plasma instabilities related to ion temperature anisotropy (Gary 1993; Klein & Howes 2015; Sun et al. 2019) and ion beams (Montgomery et al. 1976; Daughton & Gary 1998; Liu et al. 2021). In this paper, we mainly focus on this mechanism, as it is much easier to excite Alfvén/ion cyclotron waves through ion beam instability processes in a low-β environment like the solar corona (Hellinger et al. 2006; Sun et al. 2019; Liu et al. 2021). Therefore, ion beam instability may play an important role in the energization processes of coronal ions.

In situ observations of the solar wind show that there are usually differential flows between different ion components, where these differential flows are also named as ion beams in the proton core frame (Feldman et al. 1973, 1974; Marsch et al. 1982; Goldstein et al. 2000; Tu et al. 2004; Alterman et al. 2018; Ďurovcová et al. 2019; Verniero et al. 2020; Mostafavi et al. 2022). Recently, based on in situ observations from Parker Solar Probe (PSP) in the near-Sun solar wind, Verniero et al. (2020) have shown that the number density of the proton beam component can be unexpectedly large relative to the proton core component, and most of the coexistent ion-scale waves are excited by proton beams. Besides, significantly enhanced ion-scale waves are observed in the near-Sun solar wind (Bowen et al. 2020, 2020; Liu et al. 2023) and they are more likely excited by ion beams (Verniero et al. 2020; Klein et al. 2021; Liu et al. 2021). Moreover, Bowen et al. (2022) have found obvious cyclotron resonant heating in the near-Sun solar wind. These observations seem to show that energy transfer processes related to ion beams may play a much more important role in ion energization of the near-Sun solar wind and corona.

In this paper, considering the potential importance of ion beams in the coronal environment, we study the excitation of electromagnetic ion beam instability and related energy transfer processes in the corona. Unlike previous studies, we not only consider the major particles (protons, electrons, and α particles), but we also consider the influence of several minor ions (oxygen ions, magnesium ions, and iron ions). This paper is organized as follows. Section 2 introduces the theoretical model and plasma parameters. Section 3 exhibits our main results and related analysis. The discussion and summary are shown in Sections 4 and 5, respectively.

2.1. Theoretical Model

In this paper, we ignore weak collisions in the solar corona and treat it as collisionless plasma. To study wave dynamics in the solar corona, we use a model consisting of Vlasov’ s equation and Maxwell’ s equations to obtain the wave equation in Fourier space:

$$\mathbf{D} \cdot \mathbf{E} = 0$$

where $\mathbf{D} = \mathbf{I} + \ /(i\omega\epsilon_0)$, ϵ_0 is the permittivity of free space, is the conductivity tensor, ω is the wave frequency, and $\mathbf{E}$ is the wave electric field. The plasma wave eigenmodes correspond to solutions of Equation (1). Xie & Xiao (2016) and Xie (2019) developed a numerical solver (BO/PDRK) for Equation (1) that is useful for performing comprehensive studies of ion and electron kinetic instabilities (Sun et al. 2019, 2020; Liu et al. 2021). In this paper, we use BO/PDRK to obtain the wave dispersion relation in coronal ion beam plasma.

In plasma instability studies, it is very important to understand the kinetic processes when instability is generated. In this paper, we use the energy transfer rate to quantify the exchanged energy between particles and waves. The energy transfer rate is calculated using the plasma current $\mathbf{J}$ and the wave electric field $\mathbf{E}$. The equations for the energy transfer rate are shown as follows:

$$P_s = \frac{1}{2}\mathrm{Re}(\mathbf{J}_s^* \cdot \mathbf{E})$$

$$\frac{\partial W_{EB}}{\partial t} = -\sum_s P_s$$

where $W_{EB} = \epsilon_0|\mathbf{E}|^2/2 + |\mathbf{B}|^2/2\mu_0$ is the electromagnetic energy. The detailed derivation processes are shown in the appendix of Liu et al. (2021). The advantage of Equation (3) is that $P_s = -\gamma$. Hence, we can directly measure the contribution of each resonance effect on wave growth or damping. Here γ represents the imaginary part of ω, where $\gamma > 0$ (or < 0) corresponds to wave growth (or damping).

2.2. Parameter Specification

To study ion beam instability in the solar corona at a heliocentric distance of 3R , we use radial distributions of magnetic field strength and plasma parameters stated in Bale et al. (2016). The magnetic field strength is given by:

$$B_0 = 2.0766 \times 10^4 \text{ nT}$$

The solar wind velocity is:

$$V_{sw} = 151.3129 \text{ km s}^{-1}$$

The electron number density is given by (also see Sittler & Guhathakurta 1999):

$$N_e = N_0 \left(\frac{R_\odot}{r}\right)^2$$

with $N_0 = 3.26 \times 10^5\ \text{cm}^{-3}$. The proton temperature is:

$$T_p = T_0 \left(\frac{R_\odot}{r}\right)^{0.9}$$

where $T_0 = 226.4$ eV. Therefore, the basic parameters used in this paper are: $N_e = 4.5547 \times 10^5$ cm^{-3}, $V_A = 634.8629$ km s^{-1} (Alfvén speed).

In this paper, in addition to four kinds of usual particles (proton core "pc," proton beam "pb," alpha particles "α," and electrons "e"), we also consider three typical heavy ions in the corona: oxygen ions "O," magnesium ions "Mg," and iron ions "Fe." The velocity distributions of all seven particle types follow a drifting Maxwellian distribution:

$$f_s(v_\parallel, v_\perp) = \frac{N_s}{\pi^{3/2} v_{Ts\parallel} v_{Ts\perp}^2} \exp\left[-\frac{(v_\parallel - V_s)^2}{v_{Ts\parallel}^2} - \frac{v_\perp^2}{v_{Ts\perp}^2}\right]$$

where m_s, N_s, T_s, and V_s denote the mass, number density, temperature, and drifting speed for each particle component "s" ; k_B is the Boltzmann constant; and the subscripts and represent directions parallel and perpendicular to the background magnetic field, respectively.

Based on recent observations from PSP, the number density ratio of proton beam in the near-Sun solar wind is usually higher than 0.1N (Verniero et al. 2020; Klein et al. 2021). Therefore, the number density of proton beam in this paper is set as $N_{pb} = 0.25N_e$. In addition, according to Level 3 data obtained by Solar Probe ANalyzers for Ions (SPAN-I; Livi et al. 2022) on board PSP, the number density ratio of α particles is set as $N_\alpha = 0.05N_e$. Moreover, based on observations from the Solar and Heliospheric Observatory (SoHO) (Kohl et al. 1997, 1998), we chose three heavy ions (O^{5+}, Mg^{9+}, and Fe^{11+}). The number densities of these heavy ions are as follows: $N_O = 0.001N_e$, $N_{Mg} = 0.0001N_e$, $N_{Fe} = 0.0001N_e$ (Reames 1994; Wu & Yang 2007). We note that the abundances of these heavy ions here are relatively higher than those in Asplund et al. (2009). This may be caused by the difference in elemental abundance between the photosphere and the corona. Lastly, to ensure charge neutrality, the number density of proton core is $N_{pc} = 0.643N_e$.

We study ion beam instability in the proton core frame, which means $V_{pc} = 0$. To be consistent with observations, we consider not only the proton beam but also other factors. For example, observed alpha particles and heavy ions usually drift faster than the proton core component (Marsch et al. 1982; von Steiger et al. 1995; von Steiger & Zurbuchen 2006; Alterman et al. 2018; Ďurovcová et al. 2019). Besides, the temperature of ions in the corona is usually proportional to their atomic mass number and they are strongly anisotropic, with $T_{i\perp} > T_{i\parallel}$ (Kohl et al. 1997, 1998; Li et al. 1998). Therefore, both the differential speed relative to the proton core and the temperature anisotropy of heavy ions are taken into account.

We use drifting electrons to ensure zero current conditions, i.e., $\sum_{is} N_{is}V_{is} - N_{eV}e = 0$, where "is" denotes each ion particle component. In addition, the temperatures of protons and electrons are the same.

3.1. Influence of Temperature Isotropic Minor Ions

In this section, we only consider the influence of temperature isotropic heavy ions on the ion beam instability through V_{pb}- distributions. Based on the magnetic field and plasma parameters listed in Subsection 2.2, the proton beam instability at $r = 3R_{\odot}$ is exhibited in Figure 1, where represents the angle between the wave propagation direction and the background magnetic field. The plasma in Figure 1 consists of only proton core, proton beam, α particles, and electrons in case (a), and all particles have the same temperature as protons. Case (b) considers three additional heavy ions (oxygen ions, magnesium ions, and iron ions), and all particles have the same temperature as protons.

Obviously, in both cases of Figure 1, only three types of ion beam instabilities are excited: the oblique Alfvén/ion cyclotron instability (OA/IC, region I surrounded by red dots), the oblique Alfvén/ion beam instability (OA/IB, region II surrounded by black dots), and the parallel fast-magnetosonic/whistler instability (PFM/W, region III surrounded by blue dots). Comparing case (a) and case (b) in Figure 1, we can see that the most obvious change occurs in region I, which is mainly manifested in the increase of the excitation threshold ($V_{pb,thre} \sim 0.5V_A$ in case (a) and $V_{pb,thre} \sim 0.9V_A$ in case (b)) and the decrease of the excitation range. This indicates that the oblique Alfvén/ion cyclotron instability is most easily influenced by heavy ions. In summary, in a plasma where all particles have the same temperature, the addition of temperature isotropic heavy ions inhibits the excitation of the oblique Alfvén/ion cyclotron instability (reducing the parameter range of instability excitation).

However, in actual observations of the solar corona, the temperature of ions differs and is proportional to their atomic mass number (Kohl et al. 1997, 1998). Besides, remote observations from SoHO indicate that heavy ions always flow faster than protons (Kohl et al. 1997, 1998). Therefore, we also take these two influencing factors into account separately. The related results are shown in Figure 2. Considering that observed velocities of proton beam are usually concentrated in the region less than twice the local Alfvén speed, the proton beam velocity is limited to 0.1-2V_A. Compared with the results shown in Figure 1(b), the excitation of the oblique Alfvén/ion cyclotron instability exhibited in Figure 2(a) is further inhibited when ions have temperatures proportional to their atomic mass number.

In Figure 2(b), the temperature settings for all ions are the same as in Figure 1(b). However, the α particles, oxygen ions, magnesium ions, and iron ions flow faster than the core protons, with a relative drifting speed equal to the local Alfvén speed. Different from Figure 1(b), the excitation range of the oblique Alfvén/ion cyclotron instability shows significant change. There are two obvious excitation regions of the oblique Alfvén/ion cyclotron instability. This indicates that the addition of four other types of ion beams promotes the excitation of the oblique Alfvén/ion cyclotron instability. In this case, there are five types of ion beams (proton beam, α beam, oxygen beam, magnesium beam, and iron beam), and all of them can become the energy source of excited instabilities. To determine which ion beams are the main energy source of the oblique Alfvén/ion cyclotron instability, it is necessary to analyze its energy transfer process therein to understand the excitation mechanism.

Hence, based on Equation (3), the energy transfer rate of all ions in the instabilities shown in Figure 2(b) is exhibited in Figure 3. In Figure 3, the energy transfer rates are normalized by max(|P |), which corresponds to the main energy flowing from the instability source particles into unstable waves. Therefore, the color region representing -1, which is marked by “+” in Figure 3 (the yellow “+” and cyan “+” represent the proton beam and α beam, respectively), is the main source of free energy required for instability excitation. The oblique Alfvén/ion cyclotron instability has two regions: one in the region of low proton beam speed (region 1, $0 \leq V\ b/V \leq 0.5$) and the other in the region of relatively high proton beam speed (region 2, $0.9 \leq V\ b \leq 1.5V$). The oblique Alfvén/ion cyclotron instability in region 1 is totally marked by cyan “+” , indicating that the energy source of this unstable region is the α beam. Similarly, the oblique Alfvén/ion beam instability (surrounded by black dotted lines) is totally marked by yellow “+” , meaning its energy source is from the proton beam. The oblique Alfvén/ion cyclotron instability in region 2 is relatively larger and more complicated. At the oblique Alfvén/ion cyclotron instability propagating angle (50°-80°), it is totally excited by the proton beam. The rest areas in region 2 are influenced by both proton beam and α beam, where the region marked by cyan “+” is dominated by the α beam and the rest region is mainly controlled by the proton beam. Generally, the oblique Alfvén/ion cyclotron instability in region 2 is mainly dominated by the proton beam. Obviously, when the proton beam is slowed down due to instability excitation, the existence of the α beam can provide a second energy source for the excitation of the instability in the solar corona.

3.2. Influence of Temperature Anisotropic Minor Ions

Remote sensing observations of the solar corona reveal that the effective temperatures of ions are strongly anisotropic, with $T > T$, where and are with respect to the background magnetic fields (Kohl et al. 1998; Li et al. 1998). Therefore, in this section, we perform instability analysis using parameters closer to the actual coronal plasma environment. The temperature of ions is proportional to their atomic mass number. In addition, α particles, oxygen ions, magnesium ions, and iron ions flow faster than core protons with a relative speed equal to the local Alfvén speed. Moreover, the temperature of three types of heavy ions (oxygen ions, magnesium ions, and iron ions) is anisotropic, with $T /T = 1, 5, 10$. The instability results for the three cases are shown in Figure 4. The instability results shown in Figure 4 are similar to Figure 2(b). Besides, the range of both oblique Alfvén/ion cyclotron instability and oblique Alfvén/ion beam instability excitation parameters becomes larger with increasing temperature anisotropy of heavy ions.

In this case, both ion beams and temperature anisotropy of ions can provide free energy to excite instabilities. Hence, the same analysis as shown in Figure 3 is necessary. Due to the fact that the three cases in Figure 4 are similar, we only analyze case (c). The energy transfer rate results for Figure 4(c) are presented in Figure 5. The energy transfer rate shown in Figure 5 is similar to that in Figure 3. Both the oblique Alfvén/ion cyclotron instability (in region 2) and the oblique Alfvén/ion beam instability are mainly excited by the proton beam. However, the energy source of the oblique Alfvén/ion cyclotron instability close to $V b = 0.9V$ in region 2 is from anisotropic oxygen beam and α beam, with oxygen ions dominating. Besides, the excitation of the oblique Alfvén/ion cyclotron instability in region 1 is also driven by both anisotropic oxygen beam and α beam, where the contribution of oxygen ions is concentrated in regions with relatively larger proton beam velocity, while the contribution of α particles is the opposite. These results indicate that anisotropic beams of heavy ions can also promote the excitation of Alfvén/ion cyclotron waves in the actual coronal plasma environment. Hence, instability driven by ion beams can be a very important source of Alfvén/ion cyclotron waves in the corona.

4. Discussion

Since remote observations revealed the unusually high temperature of the coronal ions (Kohl et al. 1997, 1998; Cranmer & Winebarger 2019), determining the main physical mechanism for heating coronal ions has been a fundamental problem in solar and space physics. In particular, coronal ions are highly anisotropic, with $T > T$ (Kohl et al. 1997, 1998; Li et al. 1998). This suggests that the heating process of coronal ions is anisotropic, concentrated in the perpendicular direction with respect to the background magnetic fields. The cyclotron damping of Alfvén/ion cyclotron waves is usually invoked to explain this observed phenomenon (Cranmer et al. 1999; Isenberg et al. 2001; Liewer et al. 2001; Marsch & Tu 2001; Hollweg & Isenberg 2002). In this paper, we find that both proton beam and α beam can drive oblique Alfvén/ion cyclotron instability to generate Alfvén/ion cyclotron waves. Especially, in the low-beta plasma environment like the solar corona, the excitation threshold of ion beam instability is easily met. In addition, jets associated with magnetic reconnection are injected into the coronal background environment, which can be the source of ion beams (Feldman et al. 1996). Recently, Phan et al. (2022) found that leaked high-energy protons during the magnetic reconnection process may be the source of the proton beam in the near-Sun solar wind. By examining the velocity distribution function (VDF) of protons in Phan et al. (2022), we found that the proton beam generated by magnetic reconnection usually has a relatively high number density ratio. Verniero et al. (2020) and Klein et al. (2021)

also found that the number density of proton beams in the near-Sun solar wind usually has a higher ratio than that beyond 0.3 au. This may indicate that the number density ratio of ion beams can be higher when getting close to the Sun. Theoretically, the region of excitation parameters of ion beam instability increases with ion beam number density (Liu et al. 2021). Therefore, based on these observed phenomena, we think that instabilities driven by ion beams can play an important role in energizing coronal ions.

To better understand the energy transfer rate in the background plasma of the corona, we identify the Alfvén wave mode without any instabilities and calculate the energy transfer rate related to this wave mode. The results are shown in Figure 6, where λ k is the wavevector k normalized by the proton inertial length λ . Here, the plasma consists of all ions mentioned before. In addition, there is only one type of ion beam (proton beam, V b = 0.8V) and all particles have the same temperature. In Figures 6(a)-(b), the Alfvén wave mode is divided into three regions by the cyclotron frequencies of iron and oxygen ions, and the corresponding damping rates at these two locations become larger suddenly. From Figure 6(d), we can see three peaks, from left to right, representing the energy absorption peaks of iron, oxygen, and magnesium ions. Besides, the energy absorption of heavy ions is concentrated in the perpendicular direction. Therefore, heavy ions in the corona can be heated perpendicularly through this process with the existence of excited Alfvén waves. This also suggests that ion beam instability that excites Alfvén waves may play an important role in the process of coronal ion energization.

Through studying ion beam instability in the coronal environment, this work mainly reveals that the ion beam instability is easily excited and is an important source of Alfvén/ion cyclotron waves. This also indicates that instability driven by ion beams may play an important role in energizing coronal ions. However, heavy ions are not preferentially heated in the perpendicular direction during ion beam instability excitation. Actually, when ion beam instability is excited, the free energy of ion beams mainly flows into core protons and the unstable wave mode (the Alfvén/ion cyclotron wave). Finally, these excited Alfvén/ion cyclotron waves can preferentially heat heavy ions in the perpendicular direction through wave-particle interaction processes. Simulations can be used to study this entire process, and we will present it in our future work.

5. Summary

Based on plasma kinetic theory, this work mainly studies the excitation of ion beam instability in the corona at a heliocentric distance of 3R and the corresponding energy transfer process therein. Our results indicate that the addition of heavy ions inhibits the excitation of ion beam instability, manifested in both its excitation threshold and parameter range. On the other hand, anisotropic beams of heavy ions can promote the excitation of ion beam instability. Moreover, the existence of α beams can provide a second energy source for exciting beam instability in the corona. When both the proton beam and the α beam reach the instability excitation threshold, the proton beam-driven instability excites preferentially. In addition, through ion beam instability, the energy of ion beams mainly flows into core protons and unstable waves. Besides, the excitation threshold of the Alfvén/ion cyclotron instability driven by ion beams is of the order of the local Alfvén speed or even less. This indicates that ion beams can easily excite Alfvén/ion cyclotron waves through ion beam instability processes in the corona. Due to the fact that Alfvén/ion cyclotron waves can energize coronal ions through wave-particle interactions, ion beam-driven instability may play an important role in coronal ion energization.

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