博士学位论文摘要选登

动力学阿尔文波的非线性波 - 波相互作用及其在日地空间等离子体中的应用

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动力学阿尔文波是垂直波长接近离子回旋半径或电子惯性长度时的色散阿尔文波，在等离子体粒子加热、加速或反常输运等现象中能起重要作用. 因此，在各类天体和空间等离子体环境中动力学阿尔文波的特性也一直是引起人们广泛兴趣和倍受关注的研究课题. 本论文系统、深入地研究了不同等离子体环境下动力学阿尔文波的非线性波 − 波耦合相互作用过程，特别是对不同环境下波 − 波耦合导致的动力学阿尔文波非线性生长率进行了细致的分析.

论文首先研究了在不同等离子体 β 参数条件下，动力学阿尔文波间的局域非线性波 − 波耦合过程，其中 β 是等离子体热压与磁压的比，$Q \equiv m_{\rm e}/m_{\rm i}$ 是电子与离子质量比. 我们的结果显示：(1) 在 $\beta \ll Q$ 的惯性参数区，泵波衰变为两个反向传播的动力学阿尔文波的反向衰变率显著高于衰变为两个同向传播的动力学阿尔文波的同向衰变率；(2) 在衰变过程的波长变化上，泵波向短波长波的衰变率也明显高于向长波长波的衰变率，意味着衰变过程主要向更小尺度方向发展；(3) 在 $Q \ll \beta \ll 1$ 的动力学区和 $\beta \approx 1$ 、甚至 $\beta > 1$ 的高 β 区，衰变率随 β 的增大而减小，但随离子与电子温度比 $T_{\rm i}/T_{\rm e}$ 的增大而增大.

论文其次研究了动力学阿尔文波和大尺度 MHD 阿尔文波、大尺度对流元间的非局域波 − 波耦合过程. 结果表明：(1) 不同等离子体参数区的动力学阿尔文波和 MHD 阿尔文波耦合方式存在明显差别，在 $\beta < Q$ 的惯性区，衰变过程主要是 “一个大尺度 MHD 阿尔文波衰变为两个小尺度动力学阿尔文波”, 而在 $\beta > Q$ 的动力学区主要是 “一个大尺度 MHD 阿尔文波和一个小尺度动力学阿尔文波耦合成另一个小尺度动力学阿尔文波”; (2) 在 $\beta \ll Q$ 的惯性区和 $Q \ll \beta \ll 1$ 的动力学区，动力学阿尔文波通过调制不稳定性分别能有效地激发静电和静磁对流元.

论文最后讨论了动力学阿尔文波与高频哨声波及哨声波之间的波 − 波耦合. 结果表明：(1) 哨声波可以通过 “一个哨声波衰变为一个动力学阿尔文波和另一个哨声波” 的参量不稳定性有效激发动力学阿尔文波，所激发的动力学阿尔文波传播方向可与泵波方向相同，也可与泵波方向相反，而且这两种情形下的增长率近似相等；(2) 在哨声波之间的波 − 波耦合过程主要是作为泵波的长波长的哨声波衰变为短波长哨声波，其中反向传播的衰变过程占主导地位.

本论文结果在解释极区反向电子束流的激发、太阳大气中动力学阿尔文波的激发及行星际空间中朝向太阳传播的哨声波的激发机制上具有重要作用.

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The Nonlinear Wave-Wave Interaction of the Kinetic Alfvén Wave and Its Application in the Solar-Terrestrial Space Plasmas

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Kinetic Alfvén waves (KAWs) are dispersive Alfvén waves with perpendicular wavelengths comparable to the ion gyroradius or the electron inertial length. The KAWs can play an important role in plasma heating, particle acceleration, and anomalous particle transport, and have been extensively applied to various active phenomena of plasma. Therefore, the wave characters for the KAWs in various astrophysical and space plasmas have been an interesting subject with extensive attentions. In this thesis we study in depth nonlinear wave-wave interaction processes of the KAWs in various plasma environments, and focus on the nonlinear growth rates of the KAWs caused by these wave-wave coupling processes.

In this thesis, we first study the local nonlinear wave-wave coupling among three KAWs in different plasma beta conditions, where $Q \equiv m_{\rm e}/m_{\rm i}$ is the electron-ion mass ratio and β is the kinetic-magnetic pressure ratio of the plasma. Our results show that: (1) in the inertial region, the reverse decay, where the pump wave decays into two reversely propagating KAWs, is stronger than the parallel decay, where the pump wave decays into two KAWs propagating in the same direction; (2) in the aspect of the wavelength change, the decay rate of the pump wave into the shorter-wavelength daughter waves is higher than that into the longer-wavelength daughter waves, implying that the decay process develops mainly towards exciting small-scale waves; (3) in the kinetic region ($Q \ll \beta \ll 1$) and the high-β region, the nonlinear growth rate decreases with β, but increases with the ion-electron temperature ratio $T_{\rm i}/T_{\rm e}$.

Secondly, we study the non-local coupling of small-scale KAWs with large-scale Alfvén waves (AWs) and convective cell. The results show that: (1) in the inertial region of $\beta < Q$, the decay occurs in the way of "AW $\rightarrow$ KAW1 + KAW2", but in the kinetic region of $\beta > Q$, the coupling occurs in the way of "AW + KAW1 $\rightarrow$ KAW2"; (2) the modulation instability of KAWs can excite the electrostatic convective cell in the inertial region of $\beta \ll Q$ and the magnetostatic convective cell in the kinetic region of $Q \ll \beta \ll 1$.

We finally discuss the coupling between KAWs and high-frequency whistler waves (WWs) and the three-wave coupling among WWs. The results show that: (1) the decay process of "WW $\rightarrow$ WW + KAW" can effectively excite KAWs, and the excited KAW can propagate parallel or antiparallel to the pump WW; (2) the three-wave coupling process of WWs occurs in the way that the long-wavelength pump wave decays into the short-wavelength waves, and it is dominated by the reverse decay.

The results of this thesis show that our results can explain the excitation of two reversely-propagating electron fluxes in the Earth's auroral zone, the generation of KAWs in the solar atmosphere, and the production of WWs propagating towards the Sun in the interplanetary space.