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FAST AND SLOW MHD WAVES IN THERMALLY ACTIVE PLASMA SLAB[1]

ABSTRACT

We considered the combined influence of the thermal activity and the magnetic structuring on properties of the compressional magnetohydrodynamic (MHD) waves. To model MHD waves we use the single magnetic slab geometry. To derive dispersion equations for the symmetric (sausage) and anti-symmetric (kink) waves, we apply the assumption of strong magnetic structuring. In our calculations we use parameters corresponding to the highly magnetized coronal loop. The thermal activity leads to the changes in the phase velocity and in the wave increment/decrement. We show that the spatial scales where the dispersion effects caused by the thermal activity is most pronounced are longer than the geometry dispersion spatial scale. The thermal activity and wave-guide geometry have comparable effect on the slow-waves phase velocity dispersion. However, the main source of the phase velocity dispersion for the fast MHD waves remains the wave-guide geometry. We also show that the damping of slow MHD waves caused by the thermal activity is greater than the damping of fast MHD waves.

Key words: thermal activity; strong magnetic structuring; coronal loop; magnetic slab; MHD waves; symmetric and anti-symmetric waves; dispersion; wave-guide geometry.

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Introduction

The solar atmosphere is the rarified and highly-magnetized plasma. Due to this fact, there are numerous magnetic structures, which exist in the solar corona including coronal loops, prominences, polar plumes and etc. In fact, these magnetic structures play the role of the wave-guides for the compressional and compressional MHD waves, which routinely observed in the solar corona [1; 2]. The geometry of these wave-guides is prescribed by the balance between the gas-dynamic and magnetic forces and lead to the dispersion of the compressional modes.

However, the magnetic structures owe their existence not only to mechanical but also to the thermal balance. The coronal cooling/heating rates are temperature and density dependent. As a consequence, some compressional perturbation can disturb balance between these processes, and can be amplified or damped by the additional impact from the non-adiabatic processes. Thus, there are some feedback between waves and plasma. In other word, the coronal plasma is the thermally active one [3; 4]. Furthermore, the non-adiabatic processes affect propagation speed of the compressional perturbation [5].

Further, we analyze the combined influence of the thermal activity and the magnetic structuring on properties of the compressional magnetohydrodynamic (MHD) waves propagating in the highly magnetized plasma. Most similar studies use strong limitations on the wavelength and the magnitude of the external magnetic field [6; 7]. In our study, we will not use such strong assumption and apply the most general approach.

The paper is organized as follows. In the Section 2, we introduce the initial equations and obtained dispersion relation. In the Section 3, we show calculated dispersion curves. In the Section 4, we discuss the obtained results.

1. Model and dispersion relation

We analyze the waves in the fully ionized optically thin coronal plasma. We neglect the gravitational forces and the effects of viscosity, thermal conductivity and finite magnetic conductivity. The difference of basic equations from equations describing the ideal plasma is in the energy transport equation:

$$\frac{\rho^{\gamma}}{\gamma-1}\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{P}{\rho^{\gamma}}\right)=-\rho W(\rho,T)=L(\rho,T)-\Gamma(\rho,T)\ , \tag{1.1}$$

Here, ρ, T, and P are the plasma density, temperature and pressure, respectively. The parameter γ, is for the adiabatic index. In the equation (1) the function $W(\rho,T)$ describes the net heat-loss function which is the difference between radiative cooling $L(\rho,T)$ and some heating $\Gamma(\rho,T)$ processes. These rates balance each other in the case of the stationary conditions $L(\rho_0,T_0)=\Gamma(\rho_0,T_0)$, or $W(\rho_0,T_0)=0$.

To analyze the properties of the MHD waves we apply the standard methods of the perturbation theory. In other words, we linearize basic equations using substitution of the following form: $a=a_0+a_1, a_1/a_0\sim\varepsilon<<1$, where a is some plasma parameter. We model the coronal wave-guide by the magnetic slab with the magnetic field directed along z-axis as follows:

$$B_0(x)=\begin{cases} B_i, & |x|\leqslant x_0,\\ B_e, & |x|>x_0.\end{cases} \tag{1.2}$$

Here, B_0 and x_0 are the stationary value of magnetic field strength and the slab half-width, respectively. Searching the solution of the linearized equation in the form $a_1=\widetilde{a}_1(x)\,e^{i(\omega t+k_z z)}$, one may obtain dispersion relation for the set (fast/slow and body/surface) of the sausage/kink magnetoacoustic waves in the magnetic slab as follows:

$$(k_z^2c_{\mathrm{A}i}^2-\omega^2)\frac{k_{x_e}}{k_{x_i}}=-\frac{\rho_{0_e}}{\rho_{0_i}}\left(k_z^2c_{\mathrm{A}e}^2-\omega^2\right)\begin{pmatrix}\coth\ (\mathrm{k_{x_i}x_0})\\ \tanh\ (\mathrm{k_{x_i}x_0})\end{pmatrix}. \tag{1.3}$$

The complete derivations steps can be found in our previous study (see [8]). We use the and hyperbolic functions for the kink and sausage modes, respectively. We introduce the following characteristic temporal scale to describe the thermal activity influence:

$$\tau_V=C_V/W_{0T},\qquad \tau_P=C_PT_0/\left(W_{0T}T_0-W_{0\rho}\rho_0\right), \tag{1.4}$$

where C_V and C_P are the specific heat capacities at constant volume and constant pressure, respectively. We also use the derivatives $W_{0T}=\partial Q/\partial T|_{\rho_0,T_0}, W_{0\rho}=\partial Q/\partial\rho|_{\rho_0,T_0}$

Some characteristic speeds of fast and slow MHD waves are shown below:

$$c_{\mathrm{A}}=\sqrt{\frac{B_0^2}{4\pi\rho_0}},\quad c_{\mathrm{S}}=\sqrt{\gamma\frac{k_{\mathrm{B}}T_0}{m}},\quad c_{\mathrm{SQ}}=\sqrt{\frac{\tau_V}{\tau_P}\gamma\frac{k_{\mathrm{B}}T_0}{m}},\quad c_{\mathrm{T}}=\sqrt{\frac{c_{\mathrm{S}}^2c_{\mathrm{A}}^2}{(c_{\mathrm{A}}^2+c_{\mathrm{S}}^2)}},\quad c_{\mathrm{TQ}}=\sqrt{\frac{c_{\mathrm{A}}^2c_{\mathrm{SQ}}^2}{\left(c_{\mathrm{A}}^2+c_{\mathrm{SQ}}^2\right)}}. \tag{1.5}$$

Here, speed c_{A} is for the Alfven speed. The speed c_{S} is the usual speed of sound for ideal plasma. The so-called tube speed c_{T} is a result of the pure wave-guide dispersion effect. The speed c_{SQ} is long-wavelength limit value of the slow-wave or acoustic perturbation in the case the thermally active uniform plasma. And the last but not the least is the speed c_{TQ}, which is a result of the both wave-guide and thermal activity dispersion effects.

In the dispersion relation (3) we also use following notations:

$$k_{x_{i,e}}^2=\frac{\left(A_{\mathrm{Q_{i,e}}}^2m_{\mathrm{Q_{i,e}}}^2+i\omega\tau_{V\,i,e}A_{i,e}^2m_{i,e}^2\right)}{\left(A_{\mathrm{Q_{i,e}}}^2+i\omega\tau_{V\,i,e}A_{i,e}^2\right)},$$

$$m^2=\frac{\left(k_z^2c_{\mathrm{A}}^2-\omega^2\right)\left(k_z^2c_{\mathrm{S}}^2-\omega^2\right)}{\left(c_{\mathrm{A}}^2+c_{\mathrm{S}}^2\right)\left(k_z^2c_{\mathrm{T}}^2-\omega^2\right)},m_{\mathrm{Q}}^2=\frac{\left(k_z^2c_{\mathrm{A}}^2-\omega^2\right)\left(k_z^2c_{\mathrm{SQ}}^2-\omega^2\right)}{\left(c_{\mathrm{A}}^2+c_{\mathrm{SQ}}^2\right)\left(k_z^2c_{\mathrm{TQ}}^2-\omega^2\right)},$$

$$A^2=\left(c_{\mathrm{A}}^2+c_{\mathrm{S}}^2\right)\left(k_z^2c_{\mathrm{T}}^2-\omega^2\right),A_{\mathrm{Q}}^2=\left(c_{\mathrm{A}}^2+c_{\mathrm{SQ}}^2\right)\left(k_z^2c_{\mathrm{TQ}}^2-\omega^2\right).$$

Further, we will use dispersion relation (3) to calculate the dependencies of phase velocities and increment/decrement of MA waves on the wavenumbers in the solar atmosphere conditions.

2. Results

Let us apply the obtained dispersion relation to the coronal conditions. In the current study we will focus on properties of waves in the highly magnetized coronal loop. The magnetic slab parameters corresponding to the mentioned loop are shown in Table.

The parameterization of the radiative cooling function $L(\rho,T)=\chi\rho T^{\alpha}$, has been calculated using the CHIANTI Version 10.0 database [9]. The heating rate has been modeled as $\Gamma(\rho,T)=h\rho^{0.5}T^{-3.5}$. Such heating scenario has been seismologically proposed by [10] using the observations of the damped slow magnetoacoustic waves in the long-lived coronal plasma structures. The dispersion curves for body fast/slow sausage/kink magnetoacoustic waves are shown in Figures 1, 2.

Table

Slab parameters used for calculations

Таблица

Параметры слоя, используемые для расчетов

Parameter	Value
Magnetic field strength inside the slab (B_{0_i})	100 G
Temperature (T_{0_i})	6 MK
Number density inside the slab (n_{0_i})	10^{11} cm^{-3}
Density contrast (n_{0_i}/n_{0_e})	10
Slab width ($2x_0$)	2 Mm

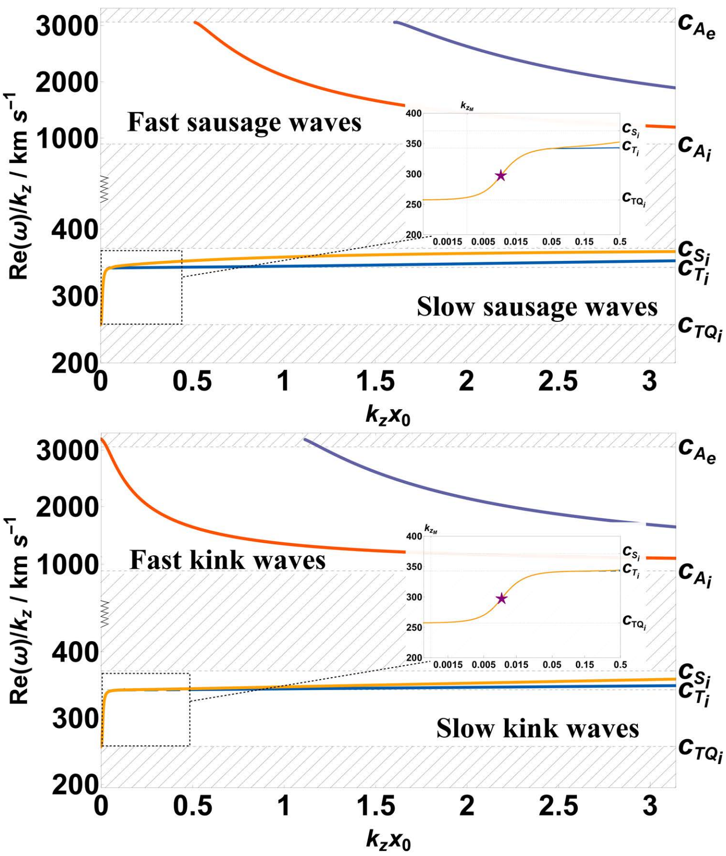

Fig. 2.1. Phase velocities of sausage and kink waves in the highly magnetized coronal plasma (see Table). Fast and slow waves are shown on different spatial scales. The range where the scale is changing is indicated by saw teeth. The top and bottom panels are for the sausage and the kink modes, respectively. We use different colours for different modes. The approximate position where the dispersion effect of the slow waves is the most pronounce is indicated by star. The range of speeds where is no roots corresponding to MHD waves can be found are shown by grey dashing

Рис. 2.1. Фазовые скорости волн перетяжек и изгибных волн в сильно замагниченной корональной плазме (см. таблицу). Быстрые и медленные волны показаны в разных пространственных масштабах. Диапазон изменения шкалы обозначен пилообразным символом. Верхняя и нижняя панели предназначены для волн перетяжек и изгибных волн соответственно. Мы используем разные цвета для разных мод. Приблизительное положение, в котором дисперсионный эффект медленных волн наиболее заметен, обозначено звездой. Серым пунктиром показан диапазон скоростей, в котором не могут быть найдены корни, соответствующие МГД-волнам

It can be easily seen that the slow modes in the thermally active plasma can be found between sound speed c_{Si} and the modified tube speed c_{TQi}. In the ideal plasma case, the long-wavelength limit is c_{Ti}. The fast modes in the plasma with the thermal misbalance range between c_{Ae} and c_{Ai}. The slow waves are highly affected by both thermal activity and wave-guide dispersion. The impact of the thermal activity on the fast-wave dispersion is negligible.

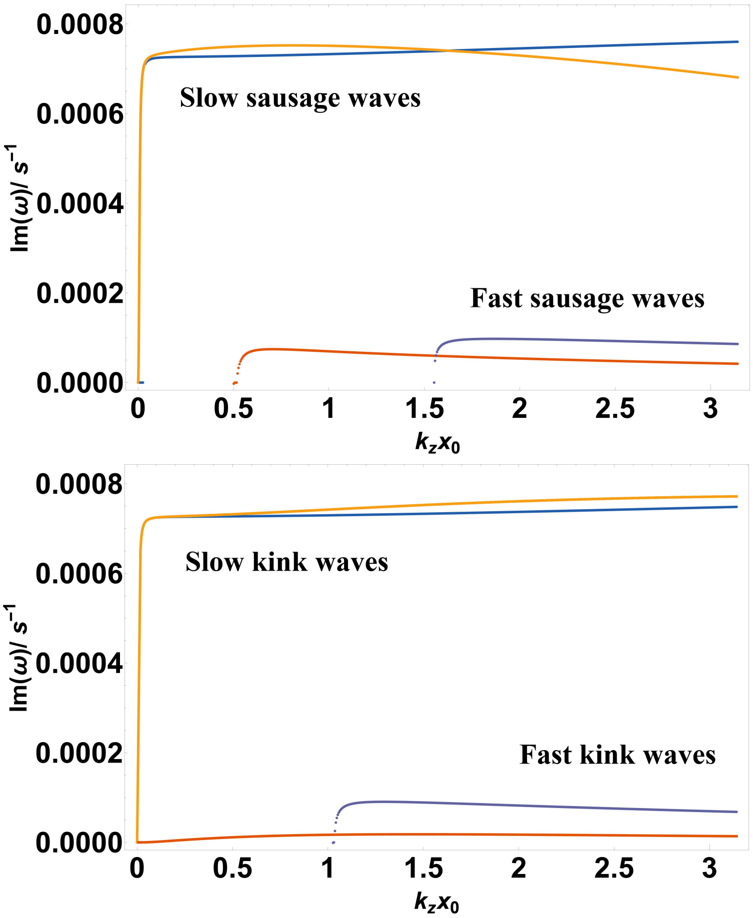

Fig. 2.2. Decrement of sausage and kink waves in the highly magnetized coronal plasma (see Table). The top panel corresponds to the sausage modes. The bottom panel is the for kink modes. Different colours correspond to different modes

Рис. 2.2. Декремент волн перетяжек и изгибных волн в сильно замагниченной корональной плазме (см. таблицу). Верхняя панель соответствует волнам перетяжек. Нижняя панель предназначена для изгибных волн. Разные цвета соответствуют различным модам

One may notice that decrement of both fast sausage and kink modes are lower than decrement of slow waves. This effect is in agreement with result obtained for the uniform plasma [4]. However, the magnetic structuring leads to non-monotonic behavior of wave decrement, with maximum in the long-wavelength part of the spectrum. In uniform plasma behavior was shown to be monotonic [4]. The calculated decrement of rather weak and cannot explain observed fast wave damping. The slow-wave decrement is comparable with the observed decay time. Moreover, in highly magnetic plasma decrement of slow-waves become greater (compare with results obtained for the hot loop in [8]. This is due to the fact that with decrease of plasma beta/increase of magnetic field the slow wave becomes more acoustic than magnetic mode.

3. Discussion and conclusions

In the presented study we analyzed the combined influence of the thermal activity and the magnetic structuring on properties of the compressional magnetohydrodynamic (MHD) waves. Using perturbation theory, assumption of strong magnetic structuring and the slab geometry, we obtain the dispersion relation for the set (fast/slow and body/surface) of the sausage/kink magnetoacoustic waves. We solve the obtained dispersion relation numerically and use to the higly-magnetized solar corona conditions. We showed that slow-waves are higly affected by both thermal activity and wave-guide dispersion. In particular the long-wavelength becomes equal to c_{TQ}, which is defined not only by geometry of the wave-guide but also by the acting non-adiabatic processes. As a result, the usage of the value c_{T} for the helioseismological needs may cause mistakes. On the contrary, the oscillation of the fundamental modes may be used for phenomenological determination of unknown coronal heating function. We also showed the phase velocity dispersion for the fast MHD waves remains the wave-guide geometry. In the magnetically structured plasma the wave decrement becomes non-monotonic with maximum in the long-wavelength part of the spectrum. The calculated slow wave decrements are comparable with the observed decay times.

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БЫСТРЫЕ И МЕДЛЕННЫЕ МГД-ВОЛНЫ В ТЕРМИЧЕСКИ АКТИВНОМ ПЛАЗМЕННОМ СЛОЕ[2]

АННОТАЦИЯ

Рассмотрено совместное влияние тепловой активности и магнитного структурирования на свойства магнитогидродинамических (МГД) волн. Для моделирования МГД-волн мы используем геометрию однородного магнитного слоя. Для вывода дисперсионных уравнений для симметричной (волна перетяжек) и антисимметричной (изгибная) волн мы используем предположение о сильном магнитном структурировании среды. В наших расчетах мы используем параметры, соответствующие сильно замагниченной корональной петле. Тепловая активность приводит к изменению фазовой скорости и инкремента/декремента волны. Мы показываем, что пространственные масштабы, в которых эффекты дисперсии, вызванные тепловой активностью, наиболее выражены, длиннее пространственного масштаба геометрической дисперсии. Тепловая активность и геометрия волновода оказывают сравнимое влияние на дисперсию фазовой скорости медленных волн. Однако основным источником дисперсии фазовой скорости для быстрых МГД-волн остается геометрия волновода. Мы также показываем, что затухание медленных МГД-волн, вызванное тепловой активностью, больше, чем затухание быстрых МГД-волн.

Ключевые слова: тепловая активность; сильное магнитное структурирование; корональная петля; магнитный слой; МГД-волны; симметричные и антисимметричные волны; дисперсия; волновод.

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