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On the nature of fast sausage waves in coronal loops

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ABSTRACT

The effect of the parameters of coronal loops on the nature of fast sausage waves are investigated. To do this three models of the coronal loop considered, a simple loop model, a current-carrying loop model and a model with radially structured density called “Inner μ” profile. For all the models the Magnetohydrodynamic (MHD) equations solved analytically in the linear approximation and the restoring forces of oscillations obtained. The ratio of the magnetic tension force to the pressure gradient force obtained as a function of the distance from the axis of the loop. In the simple loop model for all values of the loop parameters the fast sausages wave have a mixed nature of Alfvénic and fast MHD waves, in the current-carrying loop model with thick annulus and low density contrast the fast sausage waves can be considered as purely Alfvénic wave in the core region of the loop, and in the “Inner μ” profile for each set of the parameters of the loop the wave can be considered as a purely Alfvénic wave in some regions of the loop.

1. Introduction

In the solar corona the plasma dynamically responds to the excitations from the interior of the sun and the explosive events such as filament eruptions and flares. Nakariakov et al. (2016) have reviewed observations and theoretical modeling of MHD oscillations in the solar corona and some features of oscillations such as damping, MHD waveguides and drivers of MHD oscillations. Also Wang (2016) presented a detailed context of recent findings in coronal wave investigations. In the highly structured solar corona the response of the plasma to the excitations include a wide range of MHD waves classified as kink, sausage and Alfvén waves. Edwin and Roberts (1982) investigated propagating MHD waves in a magnetic slab structure in the solar atmosphere and were the first to introduce terms such as body, surface, kink and sausage modes. Edwin and Roberts (1983) studied MHD oscillations in a magnetic flux tube and classified the waves that are trapped in various conditions of the flux tube. This classification is based on the manner in which the parts of the loop are displaced during the oscillations. Another classification of MHD waves is based on the restoring forces of the waves which classifies the MHD waves as Alfvén, slow MHD and fast MHD waves. The review paper by Nakariakov and Verwichte (2005) discusses the trends in the observational investigation of MHD oscillations in the solar corona and theoretical study of interaction of MHD disturbances with various structures.

In MHD sausage waves the axis of the loop is not displaced and the cross-section of the loop oscillates, hence the signature of sausage waves is the perturbation in the emission from the coronal loops. Nakariakov and Melnikov (2006) stated that in the slow MHD sausage waves the emission perturbations are in anti-phase with the plasma density perturbations. The MHD sausage waves have been identified by Su et al. (2012) using the data which was obtained by the Atmospheric Imaging Assembly (AIA). These waves also have been detected in the data acquired from the Rapid Oscillations in the Solar Atmosphere (ROSA) imager which was reported by Morton et al. (2012).

The MHD sausage waves have been studied in various loop models by Edwin and Roberts (1983), Erdélyi and Fedun (2006) and Erdélyi and Fedun (2007). Macnamara and Roberts (2011) studied analytically the behavior of the ratio of the frequency of the first-overtone to the fundamental mode of the sausage and kink waves in a magnetic slab in the presence of density structuring, and found that the density structuring may have contribution to the deviation of the period ratio from 2 for long and thin slab structures. Li. et al. (2014) considered standing sausage waves in coronal loops in the presence of flow and concluded that even in the presence of field-aligned flows which are smaller than the background Alfvén speed, it is substantially less likely that the coronal loops support trapped standing sausage waves. Recently the propagation of sausage waves in magnetic flux tubes has been investigated by Pardi et al. (2014) and Barbulescu and Erdélyi (2016). Yu et al. (2017) have studied the phase speed and group speed of MHD sausage waves in a coronal loop with uniform magnetic field and radially structured density, they investigated the dependence of the group speed on the longitudinal wavenumber.

One of the properties of the fast sausage waves is that they are trapped in a magnetic flux tube if their wavelength is smaller than a

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cutoff wavelength. Meerson et al. (1978) studied the axisymmetric oscillations in a magnetic flux tube. They showed that the oscillations can be damped due to the MHD radiation from the flux tube to the surrounding environment. Spruit (1982) derived propagation speeds for oscillation modes of a thin flux tube. He showed that oscillations can be damped due to the radiation of acoustic or MHD wave into the external environment. Also Cally (1986) investigated leaky and non-leaky waves in flux tubes and obtained the oscillation frequency and damping rate of leaky waves. Foullon et al. (2010) reported radiation pulsations in coronal loops with period of about 10 min which are signature of the fast sausage waves, but sausage waves with such long periods cannot be trapped by the magnetic flux tubes with straight magnetic field. Khongorova et al. (2012) considered a current-carrying loop and showed that the long period sausage waves can be trapped by it. One important issue regarding the MHD oscillations in coronal loops is the nature of oscillations. The MHD oscillations are Alfvénic (fast) if the magnetic tension force (pressure gradient force) is the dominant restoring force. In a uniform MHD fluid the ratio of restoring forces for fast waves sensitively depends on the orientation of the wave vector relative to the magnetic field. For instance the magnetic tension force dominates in the case of quasi-parallel propagation, whereas total pressure gradient force dominates for quasi-perpendicular propagation. Goossens et al. (2009) studied the nature of the kink waves in flux tubes by determining the ratio of restoring forces. They pointed that in a non-uniform plasma which Alfvén frequency is a function of position, the ratio of the restoring forces and hence the nature of the kink MHD waves depends on position according to the structure of the environment which is perturbed by the wave. They showed that in the inhomogeneous layer of the loop the magnetic tension force is the dominant restoring force and concluded that the adjective Alfvénic is appropriate to characterize the kink MHD oscillations. Recently Bahari and Khalvandi (2017) studied the effect of twisted magnetic field on the nature of kink waves in coronal loops. In this paper we are interested in the manner in which the nature of the fast sausage waves differ for the simple coronal loop model with longitudinal magnetic field, the more structured current-carrying coronal loop and for the "Inner μ" profile considered by Yu et al. (2017).

In the next section we describe the models of the loop, in Section 3 the governing equations have been solved and the nature of the waves in different regions of the loop has been discussed. Section 4 is devoted to conclusions.

2. The models of the loop

We consider three models for the coronal loop in order to investigate how the properties of the fast sausage waves differ for various models of the loop. In all the models considered here, the loop is assumed to be static with no background flow, the loop has circular cross-section with constant radius and for simplicity the density stratification of the loop has been ignored. Cylindrical coordinate system is suitable for studying the loop oscillations, in all the models of the loop the axis of the loop is assumed to coincide with z axis.

The first model is a simple loop model similar to the model studied by Edwin and Roberts (1983). The magnetic field in both internal and external regions of the loop is in the direction of the z axis and are denoted by B_i and B_e respectively. The plasma beta parameter which is defined as the ratio of the equilibrium thermal pressure p to the equilibrium magnetic pressure $\frac{B^2}{8\pi}$ is denoted by β_i and β_e in the internal and external regions of the loop respectively. The radius of the loop is a and the density in the internal and external regions of the loop are ρ_i and ρ_e respectively. The equilibrium condition of the loop requires that the total pressure to be continuous at $r = a$, which gives

$$B_i^2(1+\beta_i) = B_e^2(1+\beta_e) \tag{1}$$

The second model is the model considered by Bahari (2017). In this model the loop consists of a core region with radius b and an annulus with radius a embedded in an external region. The magnetic field in the internal and external regions of the loop are longitudinal and is denoted by B_i and B_e respectively, and the magnetic field in the annulus region is in the azimuthal direction and is denoted by $B = B_\phi(r)\hat{\phi}$. For simplicity we assume the plasma in the annulus region to be pressureless, but we consider small beta parameters in the core and external regions denoted by β_i and β_e respectively. The magnetic field in the annulus region is obtained from the equilibrium condition as $B_\phi = \frac{B_0}{\alpha r}$, in which B_0 and α are constants. Also the equilibrium condition requires that the total pressure be continuous at the boundaries $r = b$ and $r = a$ which gives B_i and B_e in terms of B_0, a, b and beta parameters of the loop. The density in the core and external regions of the loop are ρ_i and ρ_e respectively and in the annulus region we assume $\rho(r) = \rho_0/\alpha r^2$, in which ρ_0 and α are constants, hence in the annulus region the Alfvén speed $V_A = B/\sqrt{4\pi\rho}$ is constant. If we set $\beta_i = \beta_e = 0$ this model simplifies to the model studied by Khongorova et al. (2012).

The third model of the loop is a model studied by Yu et al. (2017), which they called "Inner μ" profile. In this model the plasma has been considered in the framework of zero-beta MHD. The background magnetic field which has the same magnitude in the internal and external regions of the loop, is in the direction of z axis and is denoted by B. The plasma density in the external region of the loop is constant and is denoted by ρ_e, but in the internal region of the loop it is a function of r

$$\rho(r) = \rho_e + (\rho_i - \rho_e)f(r), \tag{2}$$

here ρ_i is the plasma density at $r = 0$ and $f(r)$ is defined as

$$f(r) = \begin{cases} 1 - \left(\frac{r}{a}\right)^\mu, & r < a, \\ 0, & r > a. \end{cases} \tag{3}$$

Yu et al. (2017) have studied the phase speed and group speed of MHD sausage waves in this model for various values of μ, but for simplicity we only consider the case $\mu = 2$ for which the governing equations of MHD sausage waves can be solved analytically.

3. MHD equations and restoring forces

The governing equations of MHD oscillations of the loop in the linear approximation are given by Roberts (1981) and Bahari (2017). In the governing equations the plasma displacement has been denoted by ξ, and the perturbations of the thermal pressure, magnetic field and density are denoted by p_1, $\mathbf{B}_1$ and ρ_1 respectively and the ratio of specific heat capacities is shown by γ. In the MHD sausage waves the perturbed quantities of the loop are independent of the azimuthal component ϕ also the dependence of the perturbed quantities on z and t can be Fourier analyzed by putting these quantities proportional to $e^{i(kz-\omega t)}$. Here k is the longitudinal wavenumber and ω is the oscillation frequency.

3.1. The nature of the fast sausage waves in the simple loop model

In this subsection we study the restoring forces and the nature of fast sausage oscillations in the simple loop model. For this model the governing equations have been solved by Edwin and Roberts (1983). The Lagrangian perturbation in the radial displacement $\xi_r(r)$ and the Eulerian perturbation in the total pressure $P_1(r) = p_1(r) + \frac{B_1 \cdot B}{4\pi}$ for sausage waves are found

$$P_1(r) = \begin{cases} A_i J_0(\kappa_i r), & r < a, \\ A_e K_0(|\kappa_e| r), & r > a, \end{cases} \tag{4}$$

$$\xi_r(r) = \frac{1}{\rho(\omega^2 - \omega_A^2)} \frac{dP_1(r)}{dr}. \tag{5}$$

Here A_i and A_e are constants, J is the Bessel function of the first kind and