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The double magnetic tube as a model of coronal loop oscillations

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The new model of coronal loop in the form of the double magnetic flux tube embedded into the uniform external magnetic field is proposed to explain the coronal oscillations phenomena. We investigate the MHD-waves in the magnetic flux tube, wich consists of the dense hot cylindrical cord surrounded by the co-axial shell. The plasma and the magnetic field are taken to be uniform inside the cord and also inside the shell. The magnitudes of Alfven and sound speeds in the cord, in the shell and in the environment are V_{Ai}, C_{si}, V_{Am}, C_{sm}, V_{Ae}, C_{se} correspondingly. Under the coronal conditions we have

$$C_{se} < C_{si} < V_{Ai} < V_{Ae}, \quad C_{si} < V_{Am}, \; C_{se} < C_{sm} < V_{Am}, \quad C_{sm} < V_{Ai}.$$

The equilibrium condition is

$$\rho_{0i}C_{si}^2/\gamma + \rho_{0i}V_{Ai}^2/2 = \rho_{0m}C_{sm}^2/\gamma + \rho_{0m}V_{Am}^2/2 = \rho_{0e}C_{se}^2/\gamma + \rho_{0e}V_{Ae}^2/2.$$

Our solutions of linearized ideal MHD equations have the form of cylindrical waves

$$f(\mathbf{r}, t) = f(r)\cos(m\varphi)\cos(k_z z)e^{-i\omega t},$$

where ω is the frequency of the oscillations, and k_z is the longitudinal wavenumber. The dispersion equation for magnetosonic waves in the double magnetic tube is derived in the general form. Dispersion curves are obtained by numerical calculations. The spectrum of MHD-oscillations in the double tube turned to be twice more rich than that of the simple uniform tube. Two slow and two fast magnetosonic modes can exist in the thin double tube.

For mode $m \geqslant 0$, the solutions of dispersion equation in the limit $k_z \to 0$ represent the magnitudes of speeds of two slow magnetosonic waves

$$(\omega^2 - C_{Ti}^2 k_z^2)(\omega^2 - C_{Tm}^2 k_z^2) = 0.$$

The first slow mode is trapped by the cord, the other one is trapped by the shell. The oscillations of the second mode have the opposite phases inside the cord and the shell. The speeds of the slow modes propagating along the tube are close to the tube speeds inside the cord and the shell.

For $m > 0$ in the limit $k_z \to 0$ we have two fast magnetosonic waves

$$(a^{2m} - b^{2m})[\rho_{0m}^2(\omega^2 - V_{Am}^2 k_z^2)^2 + \rho_{0i}(\omega^2 - V_{Ai}^2 k_z^2)\rho_{0e}(\omega^2 - V_{Ae}^2 k_z^2)] +$$
$$+(a^{2m} + b^{2m})\rho_{0m}(\omega^2 - V_{Am}^2 k_z^2)[\rho_{0i}(\omega^2 - V_{Ai}^2 k_z^2) + \rho_{0e}(\omega^2 - V_{Ae}^2 k_z^2)] = 0.$$

The behavior of the fast modes depends on the magnitude of Alfven speed both inside

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V_{Am}(km $\cdot$ s^{-1})	$a = 4\ 000$ km	$a = 6\ 000$ km	$a = 8\ 000$ km	$a = 10\ 000$ km	$a = 12\ 000$ km
850	2905	1412	863	582	419
1 050	612	330	211	146	107
1 400	200	126	85.0	60.9	45.9
2 100	87.5	65.8	47.2	35.0	27.0
2 800	64.1	52.5	38.9	29.0	22.6

Table 1. Values of Q-factor in dependence on the Alfven speed in the shell V_{Am} and the radius of the tube a.

the shell. If it is less than the Alfven speed inside the cord and in the environment, then one fast mode is trapped by the shell and the other one may be trapped by the shell under the certain conditions. In the opposite case when the Alfven speed in the shell is greater then those inside the cord and in the environment, then one fast mode is radiated by the tube into the environment, and the other one also may be radiated under certain conditions. The oscillations of the cord and the shell with the opposite phases are the distinctive feature of the radiative process. For the radiating mode the frequency can be presented as $\omega = \omega_0(1+\epsilon)$, where ω_0 corresponds to the zero approximation and $|\epsilon|$ is small. The effect of decay is described by $Im\epsilon = Im\omega/\omega_0$,

$$2V^2 Im\epsilon((a^{2m} - b^{2m})[\rho_{0e}\rho_{0i}(2V^2 - V_{Ae}^2 - V_{Ai}^2) + 2\rho_{0m}^2(V^2 - V_{Am}^2)] + (a^{2m} + b^{2m}) \times$$
$$\times[\rho_{0m}\rho_{0e}(2V^2 - V_{Ae}^2 - V_{Am}^2) + \rho_{0m}\rho_{0i}(2V^2 - V_{Ai}^2 - V_{Am}^2)]) + (\pi(k_e a)^{2m}/$$
$$/(2^{2m}m!(m-1)!)((a^{2m} - b^{2m})[\rho_{0e}\rho_{0i}(V^2 - V_{Ae}^2)(V^2 - V_{Ai}^2) - \rho_{0m}^2(V^2 - V_{Am}^2)^2] +$$
$$+(a^{2m} + b^{2m})\rho_{0m}(V^2 - V_{Am}^2)[\rho_{0e}(V^2 - V_{Ae}^2) - \rho_{0i}(V^2 - V_{Ai}^2)]) = 0,$$

where V is the designation for the phase speed ω_0/k_z, b is the radius of the cord and a - the radius of the tube.

The Table 1 represents the results of numerical calculations of the Q-factor ($Q = -Re\omega/2Im\omega$) for the following magnitudes of speeds: $C_{se} = 100$ km$\cdot$s^{-1}, $C_{sm} = 120$ km$\cdot$s^{-1}, $C_{si} = 140$ km $\cdot$ s^{-1}, $V_{Ae} = 700$ km $\cdot$ s^{-1}, $V_{Ai} = 350$ km $\cdot$ s^{-1}. The magnitude of the Alfven speed in the shell V_{Am} is changed in the interval 850 km $\cdot$ s^{-1} $\leqslant V_{Am} \leqslant$ 2 800 km $\cdot$ s^{-1}, and the radius of the tube a varies from 4 000 km to 12 000 km. The radius of the cord b=2 600 km. We take the wavenumber $k_z = 0.24 \cdot 10^{-4}$ km^{-1}, it corresponds to the tube length L=130 000 km.

The proposed model allows to explain the basic phenomena connected to the solar coronal oscillations: i) the damping of transversal oscillations of coronal loops recorded by TRACE (see Nakariakov et al. (1999), Ofman and Aschwanden (2002)) can be produced by the radiative losses in the double radiating tube, ii) the presence of two different slow modes of perturbations propagating along the loop with the close speeds (see (Robbrecht et al. (2001)), iii) the opposite phases of oscillations of modulated radioemission, coming from the close coronal sources having sharply different dencities (see Qin et al. (1996)).

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