Draft version October 24, 2018
Typeset using LaTeX **RNAAS** style in AASTeX62

Temporal and spatial scales for coronal heating by Alfvén wave dissipation in transverse loop oscillations

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Keywords: MHD — Sun: corona — Sun: magnetic fields — waves

We address the temporal and spatial scales involved in the process of resonant absorption of magnetohydrodynamic (MHD) waves and their possible role in heating the solar corona by Alfvén wave dissipation. The presented ideas were developed by us years ago and discussed with some researchers in the field. They are referred to by Arregui (2015), but a detailed discussion was never published. We believe they can be of interest to researchers on MHD wave heating.

The heating of the solar corona by Alfvén wave dissipation has been discussed for a long time (Ionson 1978). Resistive diffusion of Alfvén wave energy would presumably take place in an inhomogeneous layer at the boundary of waveguides such as coronal loops. Under coronal conditions the resistive diffusion coefficient, based on Spitzer classical resistivity, and the Lundquist number are

$$\frac{\eta}{\mu_0} = 0.8\,\mathrm{m^2 s^{-1}},\; R_\mathrm{m} = \frac{\mu_0\, R\, v_\mathrm{Ai}}{\eta} \tag{1}$$

with R the loop radius and v_Ai the internal Alfvén speed. Under typical coronal conditions ($R = 4000\,\mathrm{km}$, $v_\mathrm{Ai} = 1000\,\mathrm{km\,s^{-1}}$) $R_\mathrm{m} \sim 10^{12}$. For fusion plasmas $R_\mathrm{m} \sim 10^9$. Because of this high magnetic Reynolds numbers, resistivity is unable to immediately dissipate enhanced oscillations in the inhomogeneous layer. This was pointed out by Lee & Roberts (1986) who clarified that damping does not mean dissipation and provide estimates for the ratio between the heating rate and the initial flux of energy.

In a remarkable mathematical exercise, Ruderman & Roberts (2002) provided analytical expressions for the time evolution of the azimuthal velocity component associated with the kink motion in the presence of resistivity. The expressions are not simple (see e.g., their Eq. [68]), because energy is pumped into the layer and at the same time phase mixing and dissipation are taking place. Because of the quick damping reported in observations it is believed that inhomogeneous layers are in reality quite thick. Under such conditions all the energy is quickly transmitted to the layer on a short time scale, phase mixing develops quite slowly and resistive dissipation will not operate during the energy transfer from large to small scales. Only when all the energy has been transferred to the layer resistivity will become important. Given a value of the resistivity, dissipation becomes important when the following length-scale is reached in the inhomogeneous layer

$$l_{ra} = \left(\frac{\eta}{2\,|\omega'_A|}\right)^{1/3}, \tag{2}$$

being ω'_A the derivative of the local Alfvén frequency in the direction of the inhomogeneity. This approximate expression is based on the comparison of the different terms in the (uncoupled) visco-resistive Alfvén wave equation (see for

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example Ruderman et al. 1997; Goedbloed & Poedts 2004). It is easy to show that a given spatial scale, l_{ra} is built in the layer at the time

$$t_{ra} = \frac{1}{l_{ra}\,|\omega'_A|}. \tag{3}$$

Inserting Eq. (2) in Eq. (3),

$$t_{ra} = \eta^{-1/3}\,|\omega'_A|^{-2/3}. \tag{4}$$

This result was also obtained by Heyvaerts & Priest (1983) using a slightly different approach.

For a loop with a thin layer, $l/R = 0.1$, and a density contrast, $\rho_{\rm i}/\rho_{\rm e} = 3$, the damping per period for the transverse kink oscillation is $\tau_D/P = 13$ (using the damping formula by Goossens et al. 2002). From Eq. (4), $t_{ra}/P \approx 170$, which is much longer than the damping per period. For a thicker layer, $l/R = 0.5$, we have $\tau_D/P = 3$ and $t_{ra}/P \approx 500$, hence the time needed to reach the spatial scale for efficient dissipation is longer. Thus, based on the linear results and for typical coronal conditions energy dissipation is only efficient at very long times and there is no heating during the observed oscillations. Other nonlinear mechanisms of energy dissipation need to be investigated further to asses their effect in the context of standing transverse oscillations.

Consider now the associated wave heating and corresponding temperature increment. Assume that all the transverse mode energy is converted into heat. We focus on the standing wave problem, considering a flare that deposits a finite amount of energy in a nearby loop. Taking the displacement of the tube to be of the order of the loop radius, and typical loop parameters ($L = 180\,{\rm Mm}$, $R = 4\,{\rm Mm}$, $v_{\rm Ai} = 10^3\,{\rm km\,s^{-1}}$, $\rho_{\rm i} = 10^{-12}\,{\rm kg\,m^{-3}}$ and $\rho_{\rm i}/\rho_{\rm e} = 3$), the energy of the transverse oscillations is of the order of 10^{19} J (Terradas et al. 2007). To estimate the temperature rise from the conversion into thermal energy we directly relate the temperature increment with the injected energy associated to the kink oscillation

$$\Delta E = M c_v \Delta T, \tag{5}$$

where M is the mass of the heated plasma and $c_v = 1.24 \times 10^4\,{\rm J/kg\,K}$ is the specific heat capacity at constant volume for a mono-atomic gas. If the whole tube is heated, the mass will be that of a cylindrical tube of radius R and $\Delta T \simeq 1.5 \times 10^5\,{\rm K}$. This increment is not negligible when compared to the typical temperature of coronal loops $\sim 10^6\,{\rm K}$. In reality the heating will be concentrated in a very narrow region inside the inhomogeneous layer. If we assume a scale of $0.1R$ around the resonant position and its corresponding mass, now the temperature increment is $\Delta T \simeq 7.8 \times 10^5\,{\rm K}$. According to these numbers, the heating associated to standing kink oscillations should produce an observable increase in temperature, nevertheless because conductivity is very efficient under coronal conditions the temperature variations should be smoothed out along the loop on short time scales. There are indeed observations of oscillating loops showing some temperature changes. However, these temperature variations are produced during the oscillations, which is in contradiction with the long time scales needed for resistivity to become important, and therefore have presumably a different origin.

We acknowledge Spanish MINECO and FEDER funds through projects AYA2014-54485-P and AYA2014-60476-P.

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