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Coronal heating efficiency for resonant (A.C.) and non-resonant (D.C.) mechanisms

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Abstract. Ionson (1985a) extended his unified theory of coronal resonance heating having non-resonant (D.C.) and resonant (A.C.) components. Narain and Kumar (1995) calculated heating efficiency for resonant and non-resonant components for coronal heating. Since some inconsistencies are noticed in these calculations, we decided to reinvestigate the work of Narain and Kumar (1995). The results are found to vary remarkably. Reasons for these variations are discussed.

Keywords : Sun: corona - Sun: magnetic fields - Sun: X-rays- MHD

1. Introduction

Ionson (1982) envisaged the LCR circuit approach for the steady-state heating in solar coronal loops and got encouraging results. Later on Ionson (1984) proposed a theory of resonant (A.C.) electrodynamic heating for solar coronal loops whereas Heyvaerts and Priest (1984) investigated the non-resonant (D.C.) heating process. Ionson (1985a) proposed a unified modification for the theory of coronal heating. According to that the entire mechanical flux F_0 entering the coronal loop at the foot-point and the coronal heating flux F_H are related through the relation

$$F_H = \epsilon\, F_0,$$

where ϵ defined as the coronal heating efficiency can be expressed as (Ionson, 1984)

$$\epsilon = \epsilon_{\mathrm{DC}} + \epsilon_{\mathrm{AC}} = \sum_{m=0} \epsilon_m \tag{1}$$

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where ϵ_0 is the contribution due to the D.C. component and ϵ_1, ϵ_2, ϵ_3, ... are the contributions due to various harmonics of the A.C. component.

Narain and Kumar (1995) calculated the D.C. and A.C. components of ϵ for wide ranges of parameters. Since we noticed some inconsistencies in their calculations, we decided to reinvestigate the work of Narain and Kumar (1995).

2. Theory

The harmonic number m in equation (1) is given by

$$\nu_{res} = \frac{m}{t_A}$$

where $m = 1$ gives the fundamental value of the frequency ν_{res} and the numbers $m = 2, 3\ldots$ give the first, second, ..., respectively, overtone values of ν_{res}. The Alfvén transit time t_A for the coronal loop of length l (from one foot to the other) is given by

$$t_A = \frac{2l}{v_A}$$

where v_A is the Alfvén velocity. Accounting for the two peak normalized convection spectrum of Ionson (1984, 1985a), we get

$$\epsilon_m = \frac{Y}{\pi} \int_{-\infty}^{\infty} \Big[\sum_{i=1}^{2} w_i \; t_{wi} \; f_i(\nu) \Big] f_m(\nu) \mathrm{d}\nu \tag{2}$$

where w_i are the weight factors corresponding to peaks in the photospheric power spectrum (Figure 1 of Ionson, 1985a) such that

$$\sum_{i=1}^{2} w_i = 1$$

$$Y = \frac{t_{loss}}{t_{diss}} \; \frac{2\pi t_{loss}}{t_A}$$

where t_{diss} is the time scale of the dissipation of energy through the electrical resistivity and the viscosity of the plasma inside the coronal loop. It depends on the plasma density and the loop length. Since a coronal loop is not an electrodynamically closed system, the incoming magnetic stresses may leak from the loop. To account for this leakage of magnetic flux, the time scale t_{leak} is introduced. Thus, in order to account for the total loss, the time scale t_{loss} is given by

$$t_{loss} = \left[\frac{1}{t_{leak}} + \frac{1}{t_{diss}}\right]^{-1}$$

The function

$$f_i(\nu) = \left[1 + \left(\nu t_{wi} - \frac{1}{\nu t_{wi}}\right)^2\right]^{-1} \tag{3}$$

and

$$f_m(\nu) = \left[1 + \left(\nu t_A - \frac{m^2}{\nu t_A}\right)^2 \left(\frac{2\pi t_{loss}}{t_A}\right)^2\right]^{-1}$$

Here, m can take values 0, 1, 2, ..., and t_{wi} is the inverse of the full width at half maximum (FWHM) of the frequency of the i-th peak ($t_{wi} = 1/\Delta\nu_i$) in the photospheric power spectrum. The expression presented in this section are the same as those of Ionson (1985a,b).

3. Work of Narain and Kumar (1995)

Narain and Kumar (1995) adopted the same formulation as discussed in the preceding section except that in place of equation (3) they used the expression

$$f_i(\nu) = \left[1 + \left(\nu t_{wi} - \frac{1}{\nu t_{wi}}\right)^2 \left(\frac{t_{wi}}{t_{pi}}\right)^2\right]^{-1} \tag{4}$$

with $t_{pi} = 1/\Delta\nu_{pi}$ where ν_{p1} and ν_{p2} are the peak frequencies. Narain and Kumar (1995) did not mention any reason in support of the inclusion of the factor $(t_{wi}/t_{pi})^2$ in (4).

3.1 Data used by Narain and Kumar (1995)

The data used in the work of Narain and Kumar (1995) are Alfvén velocity $v_A = 5 \times 10^7$ cm/s and therefore

$$t_A = 4 \times 10^{-8}\ l \qquad 2 \times 10^9 \leq l \leq 2 \times 10^{10}\text{cm}$$

$$t_{leak} = 25\ t_A$$

$$t_{diss} = 10,\ \ 10^2,\ \ 10^3,\ \ 10^4\text{s}$$

For convenience, the values of t_{diss} were taken as powers of 10. In fact it can be any value ranging from zero onward. For the photospheric power spectrum they used

(i) for granulation

$$w_1 = 0.33, \qquad t_{w1} = 1.2 \times 10^3\text{s} \qquad t_{p1} = 7.9 \times 10^2\text{s}$$

(ii) for p-modes

$$w_2 = 0.67, \qquad t_{w2} = 4.3 \times 10^2\text{s} \qquad t_{p2} = 2.2 \times 10^2\text{s}$$

Narain & Kumar (1995) in their Figure 1 plotted the value for the model solar convection spectrum reported by Ionson (1985a,b) and therefore when the spectrum used by Narain & Kumar (1995) is that of Ionson, the values of t_{w1} and t_{w2} must be the same as those of Ionson. At this juncture, we do not understand how Narain & Kumar (1995) can claim to determine the values of t_{w1} and t_{w2} which are different from those of Ionson.

Numerical integration of equation (2) is carried out between the frequency limits 0.5 mHz and 7.0 mHz. The value of m is varied from 0 to 4.

For these data, the results obtained are given in Figs. 1, 2, 3 and 4. These Figs. 1, 2, 3 and 4 correspond to the Figs. 2, 3, 4 and 5, respectively, of Narain and Kumar (1995).

In the present Fig. 1, the graphs for $t_{diss} = 10$ s and 10^3 s are very close to each other whereas in the corresponding Fig. 2 of Narain and Kumar (1995) these graphs are separate from each other. Further, for large values of the loop length l, the variations of the graphs are not so steep and large in amount as shown by Narain and Kumar (1995).

In the present Fig. 2, the graphs for different values of m do not cross to each other whereas in the corresponding Fig. 3 of Narain and Kumar (1995) they cross to each other. Further, the heating efficiencies are found much less than those reported by Narain and Kumar (1995).

In the present Fig. 3, the graph for $l = 5 \times 10^9$ cm is at a much lower position than shown by Narain and Kumar (1995) in their Fig. 4. Here, also the heating efficiencies are reduced for the loops of various lengths.

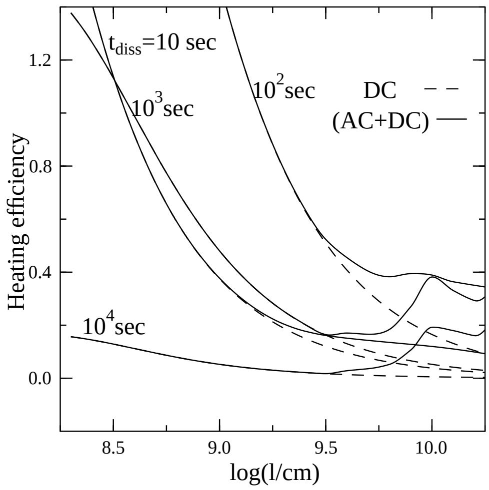

Figure 1. Variation of total electrodynamic coupling efficiency ϵ and its D.C. component with loop length l for four different dissipation times.

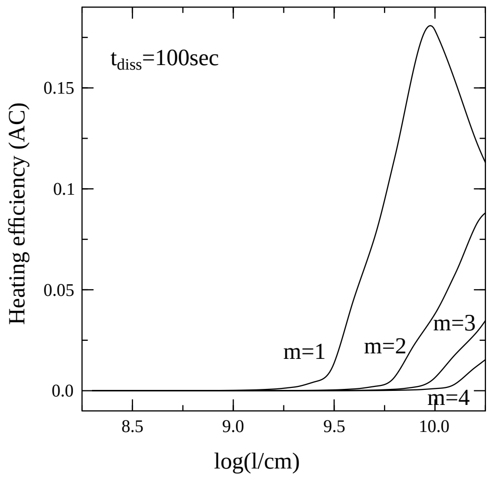

Figure 2. Variation of ϵ_m ($m = 1$, 2, 3 and 4) with loop length l for dissipation time $t_{diss} = 10^2$ sec.

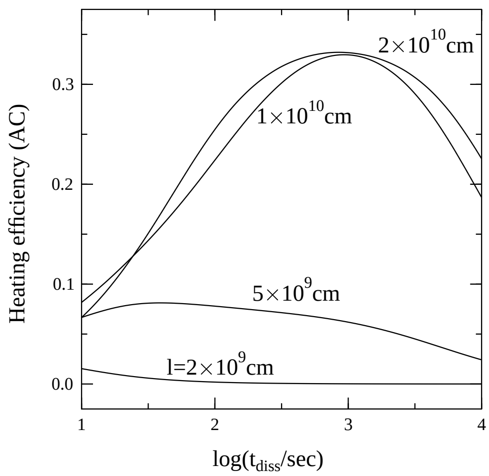

Figure 3. Variation of A.C. heating efficiency ϵ_{AC} with dissipation time t_{diss} for four different loop lengths.

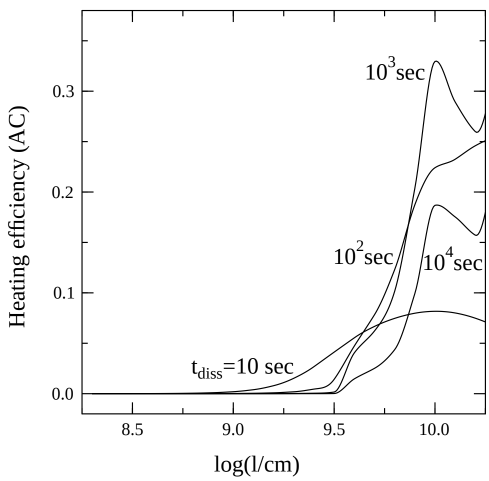

Figure 4. Variation of A.C. heating efficiency ϵ_{AC} with loop length l for four different dissipation times.

In the present Fig. 4, besides the decrease in the heating efficiency, for large values of l, the variations are not so steep and large in the amount as shown by Narain and Kumar (1995) in their Fig. 5. Further, for $t_{diss} > 10$ s, there is only one peak in each graph whereas Narain and Kumar (1995) found two peaks.

Since we have used the same set of mathematical formulation as well as data as used by Narain and Kumar (1995), the differences in the corresponding figures indicate towards the mistakes in their calculations, and it tempted us to reinvestigate the work of Narain and Kumar (1995)

4. Present investigation

In our work, we have used the formulation given in Section 2, where the factor $(t_{wi}/t_{pi})^2$ does not exist. Further we used the same set of data given in Section 3, except the values of t_{wi} which we have taken as (Ionson, 1985a)

$$t_{w1} = 750 \text{ s} \qquad\qquad t_{w2} = 250 \text{ s}$$

and obviously, we do not need the values of t_{pi}. For these data the results obtained are given in Figs. 5, 6, 7 and 8.

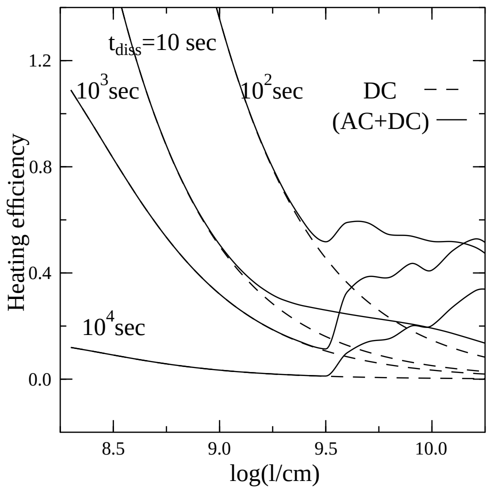

Figure 5. Variation of total electrodynamic coupling efficiency ϵ and its D.C. component with loop length l for four different dissipation times.

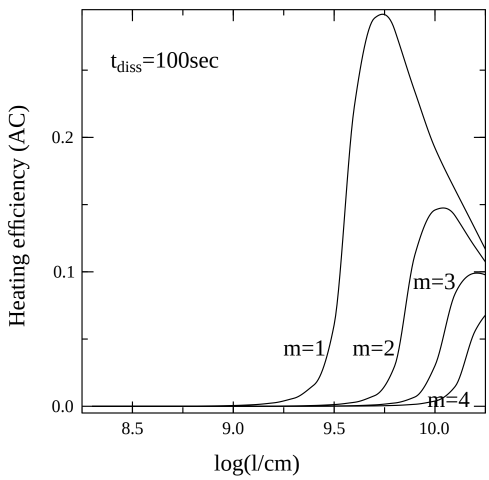

Figure 6. Variation of ϵ_m ($m = 1$, 2, 3 and 4) with loop length l for dissipation time $t_{diss} = 10^2$ sec.

Figure 5 shows that A.C. component of heating efficiency plays important role for loops of length $l > 10^{9.25}$. With the increase of the dissipation time t_{diss}, the lower limit of the length where A.C. component increases significantly.

Figure 6 shows that the A.C. component for $m = 1$ is the most effective for the loop length $l \approx 10^{9.7}$ cm and the components for $m = 2$, $m = 3$ and $m = 4$ show peak for larger value of l.

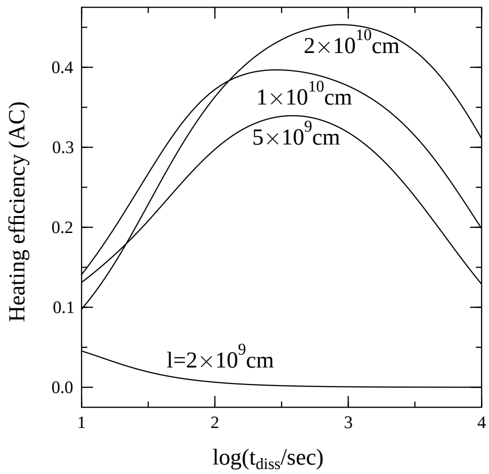

Figure 7. Variation of A.C. heating efficiency ϵ_{AC} with dissipation time t_{diss} for four different loop lengths.

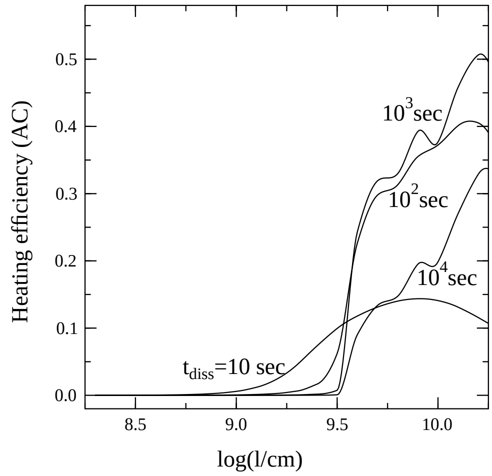

Figure 8. Variation of A.C. heating efficiency ϵ_{AC} with loop length l for four different dissipation times.

Figure 7 shows again that the A.C. component of the efficiency becomes significant for the loops of length $l > 10^{9.25}$ cm. Further, the effect is the optimum for $t_{diss} \approx 10^{2.7}$ sec.

Figure 8 shows that for large l, the A.C. heating efficiency shows three small kinks for $t_{diss} > 10$ sec whereas the corresponding Fig. 4 showed one large peak.

In Figures 5 and 6 the coronal heat efficiency exceeds the value 1, which is unphysical. However, Figure 2 of Ionson(1985a) as well as Figures 5 and 6 of Ionson(1985b) show the total efficiency (DC+AC) to be greater than 1.

5. Conclusions

It can be easily found that the calculations of Narain and Kumar (1995) have some inconsistencies. Further, the factor $(t_{wi}/t_{pi})^2$ introduced by Narain and Kumar (1995) in equation (4) produced some features in the graphs for heating efficiency. From the results, the following conclusions are to be drawn:

(i) A.C. component of heating efficiency becomes significant for long coronal loops.

(ii) With the increase of the length of loop, higher order components of A.C. efficiency also contribute.

(iii) The A.C. efficiency optimises for the dissipation time around $10^{2.7}$ s.

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