COOLING OF A CORONAL FLARE LOOP THROUGH RADIATION AND CONDUCTION

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ABSTRACT. A simple method is proposed for a computation of the cooling of coronal flare loops by radiation and conduction, for various temperatures, densities, and lengths of the loops. The relative importance of conductive and radiative losses is briefly discussed.

1. INTRODUCTION

Recently, in several papers (Svestka and Martin, 1985; Svestka et al., 1986, 1987) we have estimated the cooling times of coronal loops by using a simple method which has never been explicitly explained. Since it may perhaps be used in some other studies as well, I describe it in this Letter, discuss briefly the approximations used and compare the resulting relative importance of the conductive and radiative losses.

2. METHOD

Let us consider a loop of length 2L and density n_e $(=n_i)$ which has been heated to temperature T and subsequently cools through radiation and conduction. Then energy loss per unit volume of the loop and per second is

$$3n_e k(dT/dt) = \varepsilon(T)n_e^2 + 1.1 \times 10^{-6}\ T^{5/2}\ \nabla T/L.$$

The radiative cooling coefficient $\varepsilon(T)$, as given by Raymond et al., (1976), can be approximated by the relation

$$\varepsilon(T) \simeq 1.2 \times 10^{-19}/T^{1/2} \qquad (1)$$

within $3 \times 10^5 < T < 3 \times 10^7$ K. The temperature gradient can be approximated by the relation suggested by Culhane et al. (1970),

$$\nabla T \simeq T/L. \qquad (2)$$

Then $dT/dt \simeq 2.9 \times 10^{-4}\ n_e T^{-1/2} + 2.66 \times 10^9\ T^{7/2} n_e^{-1} L^{-2}$.

Thus after time t, temperature T(0) falls to a value T(t) defined by

$$\int_{T(0)}^{T(t)} T^{1/2} dT/(a + bT^4) \simeq t, \qquad (3)$$

with $a = 2.9 \times 10^{-4}\ n_e$ and $b = 2.66 \times 10^9/n_e L^2$.

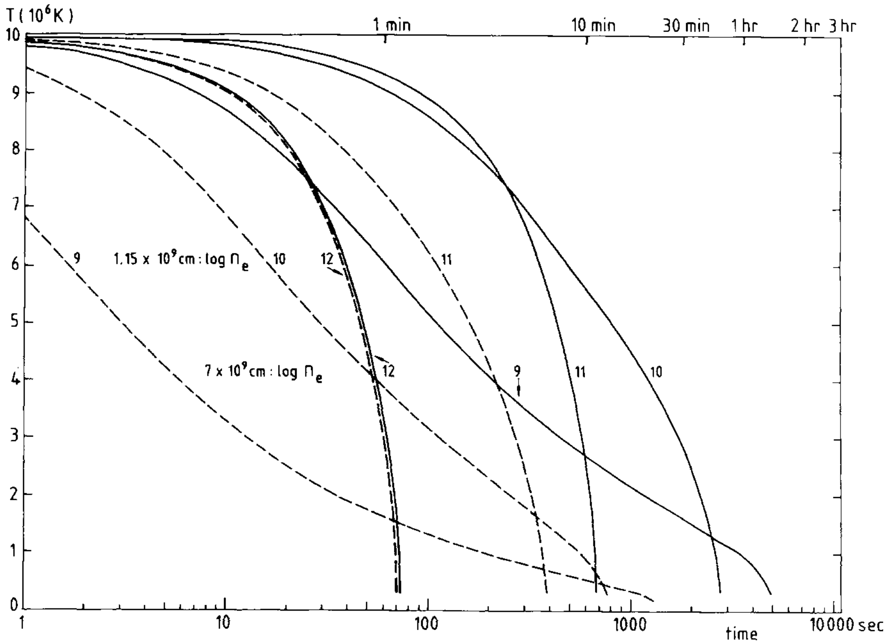

Fig. 1. Solutions of Equation (3).

Figure 1 shows the solution of (3) for two loops of widely different lengths heated to 10^7 K, with n_e between 10^9 and 10^{12} cm^{-3}. One length, L = 7 x 10^9 cm represents a typical (post-)flare loop about 50000 km high, the other one, L = 1.15 x 10^9 cm approximates a loop low in the corona, extending to about 8000 km. The curves do not proceed beyond the lower limit of T = 3 x 10^5 K, as the approximation (1) is no more valid below this limit; the low-temperature end of the cooling process needs a more detailed analysis.

3. A COMPARISON OF RADIATIVE AND CONDUCTIVE LOSSES

The ratio $b/a = 9.17 \times 10^{12}/n_e{}^2L^2$, in which b characterizes the conductive and a the radiative losses, is strongly dependent both on the density and the loop length. Table I summarizes this dependence for the two loop lengths considered before and for L = 3 x 10^9 cm which approximately corresponds to a loop height of 20000 km. One can see there, e.g., for L = 7 x 10^9 cm, that far the most energy is conducted to lower atmospheric layers at $n_e = 10^9$ cm^{-3} as long as T exceeds 1.5 x 10^6 K, whereas essentially all energy is radiated away at $n_e > 10^{11}$ cm^{-3}.

The energy conducted away from a unit volume at the top of the loop during time τ is

$$E_{cond}(\tau) \simeq 1.1 \times 10^{-6}\ L^{-2} \int_0^{\tau} T(t)^{7/2}\ dt.$$

TABLE I: Relative importance of conductive and radiative cooling in loops of various lengths (2.3×10^9 - 1.4×10^{10} cm) and densities (10^9 - 10^{12} cm^{-3}). Initial temperature $T(0) = 10^7$ K.

n_e (cm^{-3}) L (cm):	7×10^9	3×10^9	1.15×10^9
$bT(0)^4/a$ for $T(0) = 10^7$ K			
10^9	1.9×10^3	1.0×10^4	6.9×10^4
4.3×10^{10}	1.0	5.5	37
10^{11}	0.19	1.0	6.8
2.6×10^{11}	2.8×10^{-2}	0.15	1.0
10^{12}	1.9×10^{-3}	1.0×10^{-2}	6.9×10^{-2}
T(K) when $bT^4/a = 1$			
10^9	1.5×10^6	1.0×10^6	6.2×10^5
10^{10}	4.8×10^6	3.2×10^6	2.0×10^6
4.3×10^{10}	1.0×10^7	5.4×10^6	4.0×10^6
10^{11}	---	1.0×10^7	6.2×10^6
2.6×10^{11}	---	---	1.0×10^7

Since the conduction is not effective at low temperatures, we can take for τ the total cooling time down to chromospheric temperatures and compare the conducted energy with the total energy contents in a unit volume of the loop, $E_{tot} = 3n_ekT(0)$. Both E_{cond} and the ratio E_{cond}/E_{tot} (% cond) are plotted in Figure 2 as functions of n_e for the same two values of L that we used in Figure 1.

4. DISCUSSION

According to Figure 1, the cooling time of flaring loops in the corona (loop prominences) can vary between an hour and a few minutes, mainly depending on the loop density. In loops with $n_e > 10^{11}$ cm^{-3} the radiative cooling prevails and cools the loop in minutes. At low densities loops cool through conduction very fast from their top temperature to a few million degrees, but the subsequent cooling, after the conduction loses its efficiency, proceeds very slowly (cf. Figure 1 and take properly into account that the time scale is logarithmic).

Apart from a short period of the impulsive phase it is the conduction that heats the chromosphere, e.g. producing the two bright ribbons in dynamic flares. Figure 2 shows that, for a given loop lenght, there is a relatively narrow range of densities at which the conduction is most effective: the optimum values are $n_e = 2\text{-}3 \times 10^{10}$ cm^{-3} for $L = 7 \times 10^9$ cm and $2\text{-}3 \times 10^{11}$ cm^{-3} for $L = 1.15 \times 10^9$ cm. For lower n_e values the duration of an efficient conductive transfer of energy is very short (cf. Figure 1), whereas for higher n_e far the most energy is radiated away (cf. % cond in Figure 2).

Of course, the computations in Sections 2 and 3 have assumed that

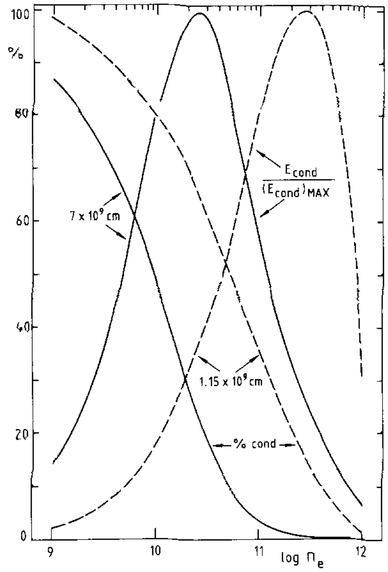

Fig. 2. The total energy conducted from a unit volume at the top of the loop for the two loop lengths of Figure 1 (in percent of $(E_{cond})_{MAX}$) and the percent of the energy conducted downwards (% cond), in dependence on the density. The remaining energy is radiated away.

the loop density is independent of position and time. Whereas the first assumption may be true (cf. Jefferies and Orrall (1961) and Fritzova and Svestka (1967)), the loop density most likely increases with time (cf. Svestka et al., 1987). The reason for it is chromospheric evaporation possibly combined with a compression of the loop. Thus, during the process of cooling, a flare loop probably does not follow any of the curves in Figure 1 but, as time proceeds, sequentially follows curves corresponding to increasing density.

It is also important to realize that in some cases conduction can behave differently from our basic assumptions: it can be inhibited, or the temperature gradient, at least during the earliest period of the loop development, can be much steeper than in (2); the conduction may be non-classical if the initial release of energy is very impulsive. In contrast to that, the radiative cooling is always approximated well. Thus one can suppose that the presented simple method yields a reasonably good approximation to the process of cooling at least in the later part of the development of coronal flare loops, and throughout their whole life if their density is high enough.

REFERENCES

Culhane, J.L., Vesecky, J.F., and Phillips, K.S.H.: Solar Phys. **15**, 394.
Fritzova, L and Svestka, Z.: 1967, Solar Phys. **2**, 87.
Jefferies, J.T. an Orrall, F.Q.: 1961, Astrophys. J. **133**, 963.
Raymond, J.C., Cox, D.P., and Smith, B.W.: 1976, Astrophys. J. **204**, 290.
Svestka, Z. and Martin, S.F.: 1985, Bull. Amer. Astron. Soc. **17**, 628.
Svestka, Z., Fontenla, J.M., Machado, M.E., Martin, S.F., Neidig, D.F., and Poletto, G.: 1986, Adv. Space Res., in press.
Svestka, Z. and same authors: 1987, Solar Phys., in press.