A THERMAL CATASTROPHE IN A RESONANTLY HEATED CORONAL LOOP

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ABSTRACT

A theory for the thermal stability of hot coronal loops is presented, which is based on the resonant electrodynamic heating theory of Ionson (1982) and the evaporation/condensation scenario of Krall and Antiochos (1980). The theory predicts that gradual changes in the length of a loop or in its magnetic field strength can trigger catastrophic changes in the X-ray visibility of the loop, without the need for a change in the magnetic field topology.

A natural explanation is thereby given for the observations of X-ray brightenings in loops and loop evacuations with coronal rain.

1. THERMAL BALANCE OF A RESONANTLY HEATED LOOP

The electrodynamic coupling of a coronal loop to the photosphere has been described by Ionson (1982) in terms of an equivalent electric circuit with a high quality factor and resonance frequency $\nu = v_A/4L$, where v_A is the Alfvén velocity and L is the halflength of the loop. The amount of heat the loop absorbs per unit volume from the available photospheric power spectrum $S(\nu)$ is given by

$$E_H(\nu) = 9.06 \times 10^{12} \frac{S(\nu)}{L^2} \text{ erg cm}^{-3} \text{ sec}^{-1}. \tag{1}$$

In thermal equilibrium this heat input is lost by radiation since the loops are thermally insulated. The radiative losses can be expressed in terms of the resonance frequency, the loop length and the magnetic field strength B (see Martens and Kuperus (1982) for a detailed description) and are given to a good approximation by

$$E_R \approx \frac{7.26 \times 10^2 \, B^{7/2}}{L^{15/4} \, \nu^{7/2}} \text{ erg cm}^{-3} \text{ sec}^{-1} \tag{2}$$

provided the loops are short compared with the coronal scale height. For loops comparable to the scale height a correction is needed. Figure 1 gives the heating and the radiative losses (multiplied by L^2 for reasons of convenience (see Equation 1)) as a function of ν, with L and B as parameters for the radiative loss function.

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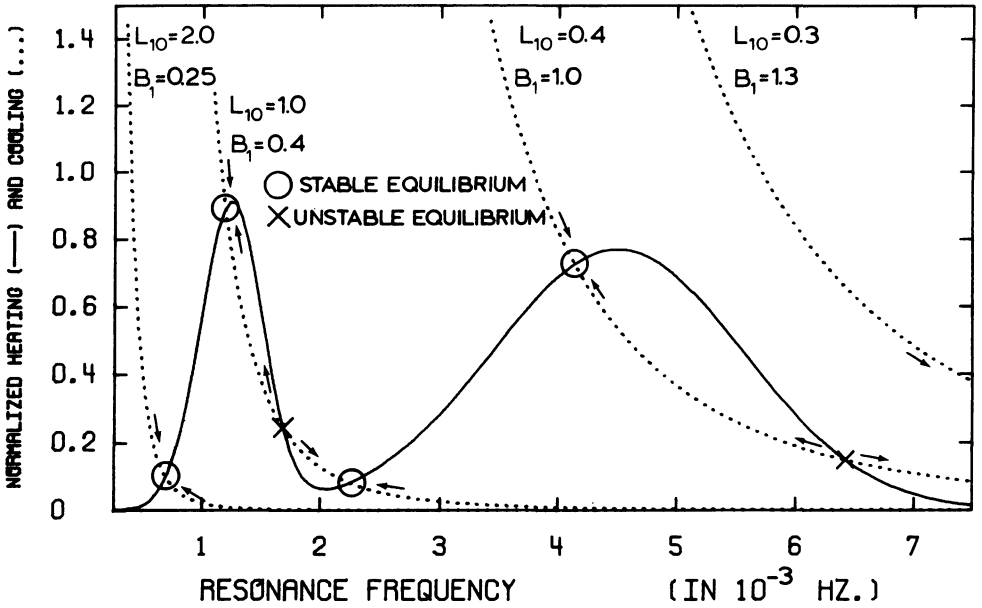

Figure 1. The heating and cooling of a coronal loop as a function of resonance frequency. The unity along the vertical axis is 10^{16} erg cm^{-1} sec^{-1}.

The heating function in Figure 1 is exactly the power spectrum that Ionson used. He found a satisfactory agreement between the heating theory and the observations of hot loops. For a given loop length and a given field strength equilibrium ($E_H = E_R$) is found when the heating and cooling curves intersect. As can be seen from Figure 1 multiple solutions are possible.

According to the evaporation/condensation scenario (Krall and Antiochos, 1980) a rise in coronal temperature results in an increased conductive flux into the transition region. The response to the increased energy input in the chromospheric upper level is an impulsive heating and subsequent expansion of the atmosphere redistributing the matter over the loop, thus increasing the average coronal density $\bar{\rho}$. As $\bar{\rho}$ increases the radiative losses increase and this continues until heating and radiative losses are balanced. The opposite ("condensation") occurs when the temperature drops below its equilibrium value. This scenario may be formalized by the expression

$$\frac{d\bar{\rho}}{dt} \sim E_H - E_R \ . \tag{3}$$

But a change in $\bar{\rho}$ is accompanied with a change in the resonance frequency ν. Hence

$$\frac{d\nu}{dt} \sim E_R(\nu) - E_H(\nu) \ . \tag{4}$$

Thus, the equilibrium at some equilibrium resonance frequency ν_0 is stable when

$$\frac{d}{d\nu}(E_R - E_H)\Big|_{\nu_0} < 0 \; . \tag{5}$$

Stable and unstable branches are indicated in Figure 1.

2. CATASTROPHIC BEHAVIOUR

Consider a loop with a slowly increasing loop length or a slowly decreasing magnetic field. Then, as can be deduced from Figure 1, the equilibrium resonance frequency slowly decreases and so do the radiative losses.

At some point in the loop development two new intersections, one stable and one unstable, will emerge. As the loop evolves further, the radiative loss curve becomes tangent to the heating curve at some point (in Figure 1 close to 2×10^{-3} Hz resp. 8.2×10^{-3} Hz). From that moment on the stable solution disappears and the loop will evolve in a thermal time scale towards the other equilibrium near 1.3×10^{-3} Hz resp. 3.2×10^{-3} Hz. The radiation losses are about eight resp. more than ten times larger than in the original situation, which must be clearly visible as a sudden X-ray brightening. Note that we propose here that a sudden brightening is a purely thermal process without the need of any magnetic reconnection. Howard and Švestka (1977) report these X-brightenings from Skylab movies.

When the length of the loop decreases or the field increases the reverse occurs. Now the loop finds a new stable equilibrium at much smaller radiative losses. This must be visible as a sudden loop evacuation and coronal rain because the cooling matter must fall down. Such observations are reported by Levine and Withbroe (1977).

It thus seems that the temporal behaviour of coronal loops can be understood as catastrophic changes in the thermal properties. The critical point in this theory is the vital importance of the photospheric power spectrum, which determines the total heating of the loop. The resonance frequency couples the heating to the power spectrum, but through the Alfvèn velocity the heating has a feedback to the resonance frequency and this determines the thermal equilibrium and its stability. Since the photospheric power spectrum, the loop length and the magnetic field strength are external parameters, any change in these may trigger the sudden loop transitions. Similar catastrophes are found numerically in an extension of the dynamical loop approach of Kuin and Martens (1982) which includes resonant heating (Martens and Kuin, 1982).

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DISCUSSION

SPRUIT: The existence and number of the thermal "catastrophes" depend mostly on the assumed frequency spectrum, is that correct?

MARTENS: The existence of the catastrophes depends on the existence of peaks in the spectrum, but not specifically on those peaks that are assumed. I think that these catastrophes will occur for any narrow-band resonant heating mechanism.

MULLAN: The power spectrum of solar velocity fields has been measured by Fossat et al. (1980). It does *not* resemble the double-peaked power spectrum used by the authors. There *is* a main peak around 3 mHz, but there is *no* peak around 1 mHz.

MARTENS: We have merely used the power spectrum used by Ionson as a *demonstration* of our mechanism. Our mechanism will work for *any* power spectrum as long as the peaks have slopes that are steep enough. Only for a *flat* "shot noise" spectrum there will be no catastrophes.

CRAM: I would like to make some comments on the shape of the power spectrum used in these calculations. Unfortunately, observers cannot provide at present an accurate velocity power spectrum of the kind needed for these models, and we must assemble several different components. The short period power (3 - 5 min) is due to well-understood photospheric and chromospheric oscillations. These oscillations are temporally phase coherent for many periods; they also tend to be spatially phase coherent on a large scale (>10 Mm). The long period power (>10 min) is meant to represent the evolution of solar convective structures (granules, mesogranules, supergranules, giant granules, etc.). These structures are not spatially or temporally phase coherent. There is also some evidence for slow, quasi-periodic velocity variations in plages and near sunspots (Woods and Cram; Harvey; Lites). More work must be done to delineate the power spectrum of this phenomenon, and of the "long-period" structures in general.

KUPERUS: I would like to stress here that any power spectrum that shows a definite maximum ultimately leads to this type of catastrophic transition provided that one uses a resonance theory such as the one proposed by Ionson (1982). This very behaviour of coronal loops is actually another observational support of Ionson's LRC equivalent circuit theory.