THERMAL EQUILIBRIA OF ISOBARIC CORONAL MAGNETIC ARCADES

C. D. C. STEELE and E. R. PRIEST

Department of Mathematical Sciences, University of St. Andrews, North Haugh, St. Andrews, Fife, KY16 9SS, Scotland

(Received 8 February, 1990; in revised form 29 November, 1990)

Abstract. A coronal magnetic arcade can be thought of as consisting of an assembly of coronal loops. By solving equations of isobaric thermal equilibrium along each loop and assuming a base temperature of $2 \times 10^4$ K, the thermal structure of the arcade can be found. The possible thermal equilibria can be shown to depend on two parameters $L^p_p$ and $h^p_p$ representing the ratios of cooling (radiation) to conduction, and heating to cooling, respectively. Arcades can contain four types of loops: hot loops with summits hotter than 400 000 K; cool loops at temperatures less than 80 000 K along their lengths; hot-cool loops with cool summits and cool footpoints but hotter intermediate portions; and warm loops, cooler than 80 000 K along most of their lengths but with summits as hot as 400 000 K. Two possibilities for coronal heating are considered, namely a heating that is independent of magnetic field and a heating that is proportional to the square of the local magnetic field. When the arcade is sheared the thermal structure of the arcade may change, leading in some cases to non-equilibrium or in other cases to the formation of a cool core.

1. Introduction

Instead of being homogeneous and uniform, it is now known that the solar corona consists of a large number of loops probably outlining the coronal magnetic field. There has been considerable work on the equilibrium profiles of the temperature along these loops as reviewed in (Priest, 1978, 1981), the following authors being representative rather than exhaustive. One facet of particular interest is the existence of cool loops (with temperatures less than about $10^5$ K) since these may form elementary structures of a solar prominence (Tandberg-Hanssen, 1974; Priest, 1989) and they may explain the excess plasma in differential emission curves at low temperature (Hood and Priest, 1979; Antiochos and Noci, 1986), which has long represented a major puzzle (Athay, 1966).

Rosner, Tucker, and Vaiana (1978) using an order of magnitude analysis, derived a relation between the loop length, the plasma pressure, and the maximum temperature along the loop. Hood and Priest (1979) solved the equations of thermal equilibrium along a coronal loop in the absence of gravity. They discovered cool solutions with summit temperatures below $10^5$ K and suggested that they may explain the existence of active-region prominences. Hood and Priest also considered the transverse structure across a coronal loop and Craig, McClymont, and Underwood (1978) considered loops at constant pressure. Gravitational effects were included by Wragg and Priest (1981) and Landini and Monsignori (1975) who applied the results to stars other than the Sun.

A great deal of work has been done on the stability of these loops (e.g., Antiochos, 1979; Habbal and Rosner, 1979; Craig, Robb, and Rollo, 1982).

She, Malherbe, and Raadu (1986) suggested that the corona should not be considered in isolation from the lower atmosphere and that a more realistic footpoint temperature for the models is $2 \times 10^4$ K. Solutions have been found for loops with footpoints at such temperatures (e.g., Landini and Monsignori Fossi, 1981), where the heating term was assumed to obey a simple power law function of temperature.

Observations show that the differential emission measure has a strong minimum at temperatures around $10^5$ K (Athay, 1966; Dupree and Goldberg, 1967). Several explanations have been put forward to explain the cooler material at lower temperatures. Athay (1984) and Rabin and Moore (1984) suggested spicules and electric currents, respectively. Antiochos and Noci (1986) proposed that the high emission measure at low temperatures is caused by the cool loop solutions discovered by Hood and Priest (1979) with temperatures between $2 \times 10^4$ K and $10^5$ K.

Craig, McClymont, and Underwood (1978) showed that the observed differential emission measure cannot be produced by a single loop and that an assembly of loops of some form must be present. Loops are known to form arcades in the corona (Vaiana, Krieger, and Timothy, 1973; Serio et al., 1978).

Loops at coronal temperatures have often been observed (e.g., Sheeley et al., 1975). Such loops are observed to form hot arcades (Davies and Krieger, 1982).

Cool loops and larger volumes as cool as about $6 \times 10^3$ K have been observed in the solar corona (Foukal, 1975, 1976, 1978, 1981). An extreme example of a cool loop is a solar prominence, often observed inside a magnetic arcade. The temperature is of the order of $10^4$ K, much less than the surrounding corona. In or near an active region the magnetic field is aligned along the prominence and it may be modelled by a loop that is cool along its length. A quiescent prominence consists of many threads inclined to the prominence axis. Each thread may be modelled by a magnetic loop with a cool summit and with hot legs either side of the prominence (Ballester and Priest, 1989). Such an assembly of loops forms the shape of an arcade.

Hood and Anzer (1988) reconsidered in detail the equations of thermal equilibrium with footpoint temperatures of $2 \times 10^4$ K (i.e., much lower than Hood and Priest (1979)). They used a phase plane analysis to identify the form of certain types of solution for low coronal heating. Steele and Priest (1990a) found numerical solutions to the equations studied by Hood and Anzer and identified further forms of solution. They considered the case of zero gravity and loops of constant cross-sectional area in which case the governing equation for the temperature as a function of position along the loop is

$$\frac{d}{ds^*} \left( T^* \frac{dT^*}{ds^*} \right) = \left( L^* p^* \right)^2 \left[ X^* T^* - \frac{h^*}{p^* T^*} \right].$$

They found that loops may be divided into several categories, depending on their position in a two-dimensional parameter space. Such loops, when fitted together, could form a cylindrical arcade with zero shear.

Steele and Priest showed that the thermal structure of a loop depends on two