MAGNETIC AND BOUNDARY EFFECTS ON THERMAL INSTABILITIES IN SOLAR MAGNETIC FIELDS: LOCALIZED MODES IN A SLAB GEOMETRY

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Abstract. The coupling of thermal and ideal MHD effects in a sheared magnetic field is investigated. A slab geometry is considered so that the Alfvén mode can be decoupled from the system. With the total perturbed pressure approximately zero, the fast mode is eliminated and a system of linearized equations describing magnetic effects on the slow mode and thermal mode is derived. These modes evolve independently on individual fieldlines. One of the main features of this approach is that the influence of the dense photosphere can be included. A variety of different conditions that simulate the photospheric boundary are presented and the different results are discussed. A choice of field geometry and boundary conditions is made which removes mode rational surfaces so that there are no regions in which parallel thermal conduction can be neglected. This provides a stabilizing mechanism for the thermal mode. Growth rates are reduced by 30–40% and there is complete stabilization for sufficiently short fieldlines. The influence of dynamic and thermal boundary conditions on the formation of prominences is discussed.

1. Introduction

Thermal instabilities in astrophysical plasmas have been a subject of study for over 30 years. Ever since Parker (1953) and Field (1965) pointed out that a radiative energy-loss rate that decreased with increasing temperature would give rise to instabilities, such a process has been perceived to have a significant role to play in both solar physics and astrophysics. In particular, the formation of solar prominences has been widely attributed to the occurrence of such a thermal instability in a hot coronal plasma (e.g., Tandberg-Hanssen, 1974; Priest, 1988). Solar prominences are still something of a challenge to theorists, since one must explain how a cool ($10^4$ K), dense ($10^{12}$ cm$^{-3}$) plasma can exist in the immediate vicinity of a hot ($10^6$ K), diffuse ($10^{10}$ cm$^{-3}$) coronal plasma, especially since the stabilizing effect of field-aligned electron heat conduction is such an efficient process for these parameters. The answer clearly lies in the ability of the coronal magnetic field to insulate the cool plasma, but precisely what the multidimensional topology of such a field is must await more powerful computational facilities.

Thermal instabilities are also of interest in astrophysical situations such as planetary nebulae and the galactic corona (e.g., Field, 1965) as well as possibly being responsible for the clumpy structure in the winds of O and B stars (Lucy, 1981; Owocki and Rybicki, 1984), although the latter results may depend on optically thick radiative effects. Still,
it is possible that the results calculated in the course of prominence studies are likely to be of interest in other fields.

While the initial studies of, for example, Field (1965) emphasized thermal instability in a uniform medium, the solar corona introduces two new features that should be taken into account. These are the global structuring of the magnetic field and plasma, and the finite extent of the medium, since magnetic field lines permeating the corona generally emerge from the very dense photosphere. Both effects contribute significantly to the precise nature of thermal instability in the solar corona. While they have been discussed in the literature in recent years (see Section 2), much of this discussion is incomplete in its treatment of the effect of the boundaries on the instability. The inclusion of boundary conditions will influence the modifications due to the magnetic field structuring on the nature of thermal instabilities.

This paper is one of a series which aim to carry out a more rigorous analysis of thermal instability relevant to the solar corona. As indicated above, our aim is to treat both the effect of the photospheric boundary conditions and the structure of the coronal plasma on thermal instability. In particular, we shall stress that the two issues are in fact intimately connected. In the present paper, we study the thermal stability of the plasma to localized modes in a slab (Cartesian) geometry: complementary analyses of such modes in a cylindrical geometry are also being carried out by Hood et al. (1990). We subsequently will analyse the thermal stability of global modes (i.e., without restriction on the structure of the perturbation). In Section 2, we discuss the relevant issues of line-tied thermal instability, Section 3 outlines the basic linearized equations and boundary conditions, Section 4 presents the results of the stability analysis, and Section 5 contains a discussion of our results.

2. Thermal Instability in Structured Magnetic Fields

The studies of Parker (1953) and Field (1965) mainly discussed thermal modes in a uniform magnetized medium. Even in this simple case, they found a wide variety of possible solutions to the coupled thermal/magnetohydrodynamic (MHD) equations. Of the 3 MHD wave modes, the Alfvén mode decoupled since it did not involve perturbations of the thermodynamic quantities. Both the fast and slow waves are able to couple to the radiative modes and, depending on the precise location in parameter space, one has either overstable or damped magnetosonic modes. In addition, there is a fourth mode, which is a pure thermal mode corresponding to an absolute instability (no oscillatory part of the frequency). Of course, in the uniform medium that these workers assumed and in the absences of dissipation, all the MHD modes are stable, since there is no free energy source to drive instabilities.

However, it is widely accepted that the plasma and magnetic field in the solar atmosphere are structured, so it is of interest to study thermal instability in such a structured medium. Introducing plasma structuring has two clear physical effects. First, currents or plasma pressure gradients can drive ideal MHD instabilities (e.g., Bateman, 1978). Such instabilities will grow on a characteristic MHD time-scale, which may be