HEATING OF CORONAL LOOPS BY FAST MODE MHD WAVES

SHADIA RIFAI HABBAL*, EGIL LEER**, and THOMAS E. HOLZER

High Altitude Observatory, National Center for Atmospheric Research†, Boulder, Colo. 80307, U.S.A.

(Received 21 May, 1979)

Abstract. A possible mechanism for the formation and heating of coronal loops through the propagation and damping of fast mode waves is proposed and studied in detail. Loop-like field structures are represented by a dipole field with the point dipole at a given distance below the solar surface. The density of the medium is determined by hydrostatic equilibrium along the field lines in an isothermal atmosphere. The fast mode waves propagating outward from the coronal base are refracted into regions with a low Alfvén speed and suffer collisionless damping when the gas pressure becomes comparable to the magnetic pressure. The propagation and damping of these waves are studied for three different cases: a uniform density at the coronal base, a density depletion within a given flux tube, and a density enhancement within a given flux tube. The fast mode waves are found to be important in the formation and heating of the loops if the wave energy flux density is of the order 10^5 ergs cm^{-2} s^{-1} at the coronal base.

1. Introduction

When observed at X-ray and EUV wavelengths, the solar corona above both quiet and active regions appears as a collection of distinct arch-like structures, often referrred to as loops, which are thought to be aligned with the coronal magnetic field (e.g., Vaiana *et al.*, 1976; Levine and Withbroe, 1977). These loops range in height from a few hundredths of a solar radius in active regions to a few tenths of a solar radius in quiet regions, and their thickness seems to be about one tenth of their apparent height (e.g., Priest, 1978). The temperatures of those loops which have been studied carefully are generally reported to lie between 2×10^6 K and 3×10^6 K (e.g., Krieger, 1977), although cooler loops and hot loops with cool cores have been observed (Foukal, 1975, 1978).

Several mechanisms have been suggested for heating the coronal loops that emit strongly in X-rays, XUV, and EUV (e.g., review by Withbroe and Noyes, 1977). In general, these mechanisms involve heating either by Alfvén waves (Uchida and Kaburaki, 1974; Wentzel, 1974, 1978; Ionson, 1978) or by anomalous current dissipation (Rosner *et al.*, 1978). (We do not include here models of so-called transient post-flare loops.) Because both the coronal Alfvén waves and the coronal currents invoked tend to transport energy along magnetic field lines, a rather large energy flux density at the coronal base footpoint of the loop is required to supply the energy needed to heat the loop. The magnitude of the energy flux density required is increased still further in most of these mechanisms, since the energy is dissipated only

* Present address: Center for Astrophysics, Cambridge, Mass. 02138, U.S.A.

** Permanent address: University of Tromsø, The Auroral Observatory, Tromsø, Norway.

† The National Center for Atmospheric Research is sponsored by the National Science Foundation.

in a thin surface layer surrounding the loop. Of course, dissipation of the energy in a thin surface layer provides another, as yet unresolved problem – namely, the transport of heat across the magnetic field toward the center of the loop.

Our treatment in the present paper of the formation and heating of coronal loops by fast-mode waves eases the requirements on the outward energy flux density at the coronal base, because the waves that are dissipated in the loop can originate from anywhere underneath the loop, not just from its footpoints. In contrast to Alfvén waves, which tend to be guided along magnetic field lines and are rather difficult to damp, fast mode waves can propagate across magnetic field lines and are refracted into regions of low Alfvén speed where they undergo collisionless damping if the plasma β (i.e., the ratio of the gas pressure to the magnetic pressure) is sufficiently large. Of course, the propagation and damping characteristics of fast mode waves allow for the deposition of energy in a large volume, in contrast to the thin surface layer in which energy is deposited in several loop heating mechanisms.

The energy flux density of fast mode waves at the coronal base that is required for significant heating effects is of the order 10^5 erg cm^{-2} s^{-1}. This value is not inconsistent with the upper limit on acoustic waves of 10^4 erg cm^{-2} s^{-1} (Athay and White, 1978), provided the coronal base magnetic field is sufficiently large (i.e., $\gtrsim 10$ G). However, it must be kept in mind that there have as yet been no direct observations of fast mode waves in the solar corona.

In the present study we shall consider a loop to be a distinct magnetic flux tube characterized by a density and/or temperature enhancement or depletion relative to the ambient medium. The magnetic field defining the loop geometry is taken to be that of a dipole situated at some distance below the solar surface (cf. Antiochos and Sturrock, 1976). Each magnetic flux tube is assumed to contain an isolated atmosphere with uniform temperature, so that the variation of density above the coronal base is determined by hydrostatic equilibrium along each magnetic field line.

In Section 2, we discuss the general characteristics of the propagation and damping of fast mode waves in a magnetized plasma. This discussion is applied specifically to magnetically closed regions of the solar corona in Section 3, where a uniform coronal base density, a low density loop, and a high density loop are studied. In Section 4 the results of our two-dimensional model are critically examined, and their implications for a three-dimensional corona are considered. Finally, the important conclusions drawn from this work are briefly restated in Section 5.

2. Propagation and Damping Properties of Fast Mode Waves

2.1. Propagation

In regions with closed magnetic fields where the field at the coronal base varies from 10 to 100 G (Dulk and McLean, 1978), fast mode waves are only weakly damped near the coronal base, and they propagate up into the corona. The propagation properties of these waves in a stationary medium can be derived from the dispersion