MAGNETIC FINE STRUCTURES IN CORONAL LOOPS

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Abstract. The formation of magnetic fine structures and associated electric currents is considered in the context of the coronal heating problem. The penetration of field-aligned electric currents into the lower atmosphere is discussed. It is argued that currents strong enough to heat the corona can persist only for short periods of time. The formation of thin current sheets is discussed. It is argued that photospheric magnetic structures (flux tubes) play an important role in the generation of coronal currents.

Key words: Sun – Corona

1. Introduction

One of the main goals of SOHO is to understand the physical processes responsible for the heating of the solar corona. Magnetic fields are known to play a crucial role in this process, but the details of the energy transport and dissipation are still unclear. Many theories of coronal heating have been proposed (for recent reviews see Zirker 1993 and references therein). Here I focus on one possible heating mechanism: the dissipation of DC electric currents. This mechanism is relevant only to closed magnetic structures such as coronal loops.

2. Field-Aligned Currents

Electric currents are generated in the corona as a result of fluid motions in the convection zone. Due to the high electrical conductivity of the solar plasma, convective flows interacting with the magnetic field at the two “ends” of a coronal loop cause twisting and braiding of the coronal field lines. If the time scale of the subsurface flows is long compared to the time for an Alfvén wave to travel back and forth along the loop, the magnetic field will evolve quasi-statically through a series of equilibrium states. The magnetic pressure in coronal loops is generally much larger than the gas pressure, hence these equilibria are nearly force free with electric currents flowing nearly parallel (or anti-parallel) to the magnetic field lines.

Random motions at the loop footpoints naturally lead to a configuration in which some field lines have current flowing parallel to the magnetic field and other field lines have current flowing anti-parallel. If the transverse length scale of the motions is less than the width of the coronal loop, the net current integrated over the loop cross-section vanishes. One coronal loop may contain a large number of counter-flowing current channels. The spa-
tial distribution of these currents will depend on the nature of the footpoint motions and on the dissipation mechanism.

An estimate of the typical size of the current channels can be obtained as follows. The average heating rate for resistive dissipation is given by \( f \eta J^2 \), where \( \eta \) is the resistivity, \( f \) is the filling factor of the electric currents and \( J \) is the current density. The heating rate must balance the observed radiative and conductive losses; for active region loops this rate is \( \sim 10^7 \) erg cm\(^{-2}\) s\(^{-1}\). The classical Spitzer resistivity of the coronal plasma is small, hence the required current density \( J \) is very large (\( \sim 10^7 \) [esu]). The change in the magnetic field across a coronal current layer must be less than the typical field strength (\( \sim 100 \) G). This implies that the width of the current layers must be very small (\( \sim 100 \) m).

One might suggest that this conclusion could be avoided if the resistivity is much larger than its classical value. However, most known processes for enhancement of the resistivity involve plasma microinstabilities (such as ion-acoustic and ion-cyclotron modes) which depend on the drift speed of the electrons relative to the protons. For typical coronal particle densities the threshold current density is \( \sim 10^7 \) [esu], similar to that required to heat the corona classically. Therefore, anomalous resistivity does not reduce the required electric current density, but rather reduces the required filling factor \( f \).

What happens at the ends of the coronal loop where the field-aligned coronal currents flow into (or out of) the lower atmosphere? The answer to this question depends on the life time of the electric currents. I first consider the case that the currents persist for a time long compared to the time for an Alfvén wave to travel from the corona down into the convection zone (\( \sim 100 \) seconds). Then inertial effects are unimportant, so that the currents can cross the magnetic field lines only in the convection zone where the dynamical forces of convection are able to balance Lorentz forces (\( j \times B \neq 0 \)). In the intermediate layers of the photosphere and chromosphere the currents must be field-aligned. The classical resistivity of the photosphere and chromosphere is much larger than that of the corona. Therefore, unless the resistivity of the corona is somehow enhanced relative to its classical value, most of the dissipation in the current circuit actually occurs in the lower atmosphere and does not contribute to coronal heating. Van Ballegooijen (1990b) showed that the coronal resistivity must be enhanced by a factor of at least 40, and to dissipate more than 50% of the available energy in the corona requires an enhancement factor \( \sim 10^5 \). The dissipation time of such currents is at most a few seconds, which is inconsistent with the assumed long lifetime of the currents. Therefore, it does not seem possible to heat the corona by dissipation of strong, long-lasting currents.

A more plausible scenario is that strong (\( 10^7 \) [esu]) currents persist in the corona only for a short periods of time. This scenario is consistent with the