THE STRUCTURE OF RADIATIVE SLOW-MODE SHOCKS

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Abstract. We investigate the structure of slow-mode MHD shocks in a plasma where both radiation and thermal conduction are important. In such a plasma a slow shock dissociates into an extended foreshock, an isothermal subshock, and a downstream radiative cooling region. Our analysis, which is both numerical and analytical, focuses on the nearly switch-off shocks which are generated by magnetic reconnection in a strong magnetic field. These shocks convert magnetic energy into kinetic energy and heat, and we find that for typical flare conditions about 3 of the conversion occurs in the subshock while the remaining 1 occurs in the foreshock. We also find that no stable, steady-state solutions exist for radiative slow shocks unless the temperature in the radiative region downstream of the subshock falls below 10^5 K. These results suggest that about 3 of the magnetic energy released in flare loops is released at the top of the loop, while the remaining 1 is released in the legs of the loop.

1. Introduction

It has long been recognized that magnetic reconnection plays a very important role in solar flare phenomena (Giovanelli, 1947; Sweet, 1958; Parker, 1963; Petschek, 1964; Sonnerup, 1979, 1984; Priest, 1984, 1985), and magnetic reconnection has been used to explain the observed energy release in solar flares and the formation of the flare loops (Parker, 1984; Malherbe, Forbes, and Priest, 1984; Forbes, 1986; Priest and Forbes, 1986; Low and Wolfson, 1988; Forbes, Malherbe, and Priest, 1989). Solar flare loops, with their temperature ranging from 10^4 to 3 x 10^7 K, are unusually dense compared with the surrounding corona (Lin, Lin, and Kane, 1985; Withbroe, 1978; Zirin, 1986; Heinzel and Karlický, 1987), and they are long-lived features which may persist for 10 hours or more. An enormous amount of material – greater than the mass of the entire corona – flows through the flare loops system during its lifetime (Kleczek, 1964; Kopp and Pneuman, 1976). Thus, the evolution of the flare loops involves not only reconnection, but also the additional processes of chromospheric ablation and thermal condensation (Sturrock, 1972; Hirayama, 1974; Ohki, 1975; Schmieder et al., 1987; Forbes and Malherbe, 1986a, b).

MHD slow-mode shocks, which were first introduced in reconnection theory by Petschek (1964), are the key link between magnetic reconnection and chromospheric ablation (see, e.g., Cargill and Priest, 1982). To see why this is so, consider Figure 1 which shows the expected shock pattern in the reconnection model of flare loops by Forbes, Malherbe, and Priest (1989). According to this model reconnection occurs at a coronal x-line which lies at the intersection of two pairs of slow-mode shocks. These shocks convert magnetic energy into bulk flow kinetic energy and heat. Due to the strong thermal conduction along the field lines, the slow shocks dissociate into isothermal
subshocks and foreshocks (thermal conduction fronts) (Forbes and Malherbe, 1986b), but the jump conditions across the total shock transition, from upstream of the foreshock to downstream of the subshock, are given by the usual slow-mode jump conditions. The foreshocks and the subshocks annihilate the magnetic field in the plasma flowing through them, and the thermal energy released in the annihilation is spread out all along the field lines. Consequently the heat is conducted from the corona to the chromosphere and leads to extensive heating and ablation of chromospheric plasma, creating and sustaining the hot X-ray loops.

The thickness of the total shock transition is of the order of the scale-size of the loops. Therefore, the total transition can no longer be considered strictly as a shock since its thickness is not small compared to its extension in the other dimensions. However, the subshocks still exist as proper shocks, although strictly speaking they should no longer be thought of as subshocks.

The plasma which crosses the subshocks forms a pair of reconnection jets which are directed towards and away from the photosphere. Unlike the upward jet, the downward jet forms on field lines which are connected to the chromosphere. Consequently, evaporation injects dense chromospheric plasma into the lower jet but not into the upper one. Because the downward jet is supersonic with respect to the fast-mode wave speed, it terminated at a fast shock (termination shock) below which is region of