MODELS FOR THE MOTIONS OF FLARE LOOPS AND RIBBONS

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Abstract. We have found a conformal mapping which is valid for any magnetic boundary condition at the photosphere and which can be used to determine the evolution of an open, two-dimensional magnetic field configuration as it relaxes to a closed one. Solutions obtained with this mapping are in quasi-static equilibrium, and they contain a vertical current sheet and have line-tied boundary conditions. As a specific example, we determine the solution for a boundary condition corresponding to a submerged, two-dimensional dipole below the photosphere. We assume that the outer edges of the hottest X-ray loops correspond to field lines mapping from the outer edges of the Hα ribbon to the lower tip of the current sheet where field lines reconnect at a Y-type neutral line which rises with time. The cooler Hα loops are assumed to lie along the field lines mapping to the inner edges of the flare ribbons. With this correspondence between the plasma structures and the magnetic field we determine the shrinkage that field lines are observed to undergo as they are disconnected from the neutral line. During the early phase of the flare, we predict that shrinkage inferred from the height of the Hα and X-ray loops is close to 100% of the loop height. However, the shrinkage should rapidly decrease with time to values on the order of 20% by the late phase. We also predict that the shrinkage in very large loops obeys a universal scaling law which is independent of the boundary condition, provided that the field becomes self-similar (i.e., all field lines have the same shape) at large distances. Specifically, for any self-similar field containing a Y-type neutral line, the observed shrinkage at large distances should decrease as \((AX/X_R)^{-2/3}\), where \(AX\) is the ribbon width and \(X_R\) is the ribbon separation. Finally, we discuss the relation between the electric field at the neutral line and the motions of the flare loops and ribbons.

1. Introduction

Solar flares are high-energy active phenomena which release large amounts of energy in the solar atmosphere. The energy involved varies from flare to flare, but for a major flare the energy release can amount to more than \(10^{32}\) ergs. It is generally accepted that flares derive their energy from the coronal magnetic field above active regions, but how the magnetic energy is converted into particle, thermal and kinetic energy is still an open question. At the present time, it is widely believed that magnetic field line reconnection plays an important role in the process of energy conversion. Theoretical studies show that the detailed physics of reconnection depends in an important way on the associated magnetic field configuration (e.g.,

Priest and Forbes, 1986). Therefore, for a better understanding of flare mechanisms, it is necessary to deduce from observations the magnetic field configuration involved in a flare process. Pallavicini, Serio, and Vaiana (1977) have classified solar flares into two classes according to their morphological characteristics: the first class consists of compact events with small size (< 30") and short duration (≈ 10–20 min), while the second class consists of two-ribbon flares with large size (> 60") and long duration (> 1 hr). In this work, we concentrate on the latter.

Large two-ribbon flares show a close association with filament eruptions and coronal mass ejections, and the most conspicuous features of these flares are the two bright Hα ribbons on the solar disc, which move away from the neutral line of the magnetic field of an active region. The Hα ribbons are accompanied by loop systems in soft X-rays and Hα, and these loops expand upwards in a motion that is synchronous with the ribbons.

A well-known and well-studied example of this kind of flare is the one which appeared on 29 July, 1973. This flare developed along a single magnetic neutral line in an old spotless region, which had a simple, bipolar magnetic field pattern in the photosphere. It started with the eruption of a large quiescent filament and it developed a pair of nearly parallel Hα ribbons on the disc along with a system of soft X-ray and Hα loops. Moore et al. (1980), Pneuman (1981), and Švestka et al. (1982) have studied this flare in its different aspects. In the present work, we theoretically investigate the basic principles which govern the evolution of the positions and shapes of the flare ribbons and loops.

There is extensive evidence (see Švestka and Cliver, 1992 for a review) that an open or quasi-open field is created before a large two-ribbon flare. The open field contains a current sheet where the open field lines reconnect. It is now widely accepted that the expansion motion of the ribbons and the loops is due to the formation of new closed magnetic field lines by the reconnection (Carmichael, 1964 and Kopp and Pneuman, 1976).

The basic requirements for a reconnection model of this type are, first, an open magnetic configuration with a current sheet, and, second, a configuration whose footpoints are fixed to the photosphere. These two requirements, in fact, form the boundary conditions for all the configurations we consider here. In addition, we add an assumption that the magnetic configuration is potential everywhere except at the current sheet.

This paper has three purposes: first of all, in Section 2 it presents a new general procedure for determining the quasi-equilibrium solution of any two-dimensional configuration with a detached, semi-infinite, vertical current sheet; secondly, in Section 3 the paper shows how shrinkage inferred from the altitude of hot and cool flare loops varies with the size of the loops; thirdly, in Section 4 the paper discusses the relation between the loop and ribbon motions and the reconnection electric field.