SELF-SIMILAR MAGNETOHYDRODYNAMIC SOLUTION FOR THE
DYNAMICS OF MAGNETIC FLUX EMERGENCE

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Abstract. A model based on a self-similar magnetohydrodynamic (MHD) solution is presented which accounts for the dynamic behavior of the birth of an active region due to the emergence of magnetic flux. The constraints of this model are deduced from observations. Specifically, this self-similar MHD solution explains the observation that plasma flow ascends in one leg and descends in the other leg of an arch filament system (AFS). Furthermore, the solution accounts for the formation of a current sheet in which a slow reconnection may occur that may explain the appearance of bright plages in the neighborhood of an AFS.

1. Introduction

We know from observations, that the formation of active regions is associated with the emergence of magnetic flux from sub-photospheric layers (convective zone). Bruzek (1967, 1969) discovered that magnetic flux emergence is always accompanied by an AFS connecting plages of opposite polarities, and that an upward velocity of 10 km s$^{-1}$ exists at the top of the AFS, while downdrafts occur at both legs of the AFS with a velocity of 50 km s$^{-1}$. Zwaan (1985, 1987) summarized the process of the birth of a new active region as first revealing the appearance of a small, compact, and very bright bipolar plage. Soon thereafter, an AFS is observed which connects faculae of bipolar plages. With new magnetic flux emerging near the neutral line ($B|| = 0$), the faculae of opposite polarities separate and move apart with an expansion velocity of 0.5–2 km s$^{-1}$.

Then, pores and sunspots may form near the leading and following edges of the expanding plages. During the flux emergence such plages are amorphous and very bright. When the emergence stops, the brightness decreases sharply (Zirin, 1974). In addition to the strong downflows in the chromosphere at the feet of the AFS, downward flows with velocities of up to 1 km s$^{-1}$ are found in the photosphere of the emerging flux region (EFR). These downdrafts occur over large parts of the EFR, while maximum velocities are found over or close to rapidly growing sunspots. Downflows often occur shortly before the birth of sunspots and
throughout the phase of rapid sunspot growth (Gopasyuk, 1967, 1969; Bachmann, 1978; Kawaguchi and Kitai, 1976). Also, Howard (1971) found upward flows over small portions of young active regions, and some AFSs have both ascending and descending motions in the loops. Bruzek (1968) attributed these phenomena to the ejection of mass at one leg and return of the mass to the chromosphere via the other leg, rooted in the opposite polarity. Recently obtained simultaneous vector magnetograms and Dopplergrams indicate that there are both descending and ascending plasma flows of $0.5-5 \text{ km s}^{-1}$ near a neutral line (Zhang and Song, 1992).

In this study we utilize a self-similar, time-dependent MHD solution to describe the dynamic behavior of the formation of an active region due to magnetic flux emergence based on the scenario given by observations (Zwaan, 1985, 1987; Bruzek, 1967, 1968, 1969). In order to apply these self-similar, time-dependent MHD solutions to the problem described above, we need to assume that the flux emergence is slow (compared to the Alfvén time) and can be regarded to be self-similar in a regime far from the influence of initial and boundary conditions. In addition, we need to replace the constant gravitational force with a slowly decreasing force as a function of $r^{-1}$ (radial distance) and with a $\theta$-component of gravity that is negligible because the scale height is negligibly small. In addition to using observations to guide us to select parameters for the self-similar MHD solutions, numerical simulation results (Zhang and Song, 1992) are also used. On the basis of the knowledge gained from observations and numerical simulations, we divide the whole domain of our interest into two regions; one being the pre-existing field-plasma region and the other the newly emerging flux region. It is known that these two regions have quite different field strengths and orientations. Hence, there must exist a transition layer separating these two regions where a current occurs and where the plasma flow changes its direction. Assuming that ascending flows (with different magnitudes of the velocities) appear in these two regions (old and new), we can use the same type of self-similar solutions to describe the behavior of the plasma flows in these regions. To assure self-consistency, we observe the conjunction conditions of these two regions. It was found that when the direction of the flow was deflected through an angle of $90^\circ$, an interface could be determined exactly. These two self-similar solutions were matched at the transition layer which consists of this interface and a current sheet. Physically, we identify this transition layer with the observed AFS. It is worthwhile to point out here that, the self-similar solutions we used for this study, in principle, are similar to those given by Low (1982), but they are different in two aspects: (i) the present solutions are defined in cylindrical coordinates with a polytropic index $\gamma = 1$ (i.e., isothermal plasma) and Low's solution is defined in spherical coordinates with polytropic index $\gamma = \frac{4}{3}$; and (ii) a matching technique (Van Dyke, 1975) is employed for the present study by matching two self-similar solutions across a current sheet to describe the present physical system. Self-similar solutions relevant to the flux emergence dynamics are presented in Section 2. A