Nonlinear Evolution of Parker Instability of Isolated Magnetic Flux Sheet and Its Application to Emerging Magnetic Flux in the Solar Atmosphere

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ABSTRACT: A two dimensional MHD code is used to study the nonlinear evolution of the Parker instability in isolated horizontal magnetic flux imbedded in (or below) the solar photosphere. It is found that the magnetic loop expands self-similarly in the nonlinear stage. Numerical results explain many features observed in emerging flux regions.

1. Introduction

It is now well established that sunspots and active regions are formed by the emergence of magnetic flux tubes from below the photosphere (e.g. Zwaan 1985). There are several observational evidences showing the rise motion of emerging magnetic flux. The rise velocity of the loops (or filaments) is 10 - 15 km/s in the upper chromosphere (Bruzek 1967, 1969, Chou and Zirin 1988), while it is less than about 1 km/s in the photosphere (Kawaguchi and Kitai 1976, Brants 1985, Chou and Wang 1987). Downflow with about 50 km/s is observed along rising filaments (Bruzek 1969) in the upper chromosphere, and this is probably due to gravity. Similar downflow with much smaller velocity (1 – 2 km/s) is also observed in the photosphere (Kawaguchi and Kitai 1976), and Shibata (1980) interpreted it as the downflow due to gravity along a rising magnetic flux tube.

In spite of these observations of emerging flux, no one has theoretically studied the nonlinear magnetohydrodynamics of emerging magnetic flux in the solar *photosphere* and *chromosphere*. Hence, we have developed a two-dimensional MHD model of emerging flux based on the 2D MHD numerical simulation of the nonlinear Parker instability (Shibata *et al.* 1989). This kind of study may also be important to understand the physics of energy storage and the trigger of solar and stellar flares (e.g. Kundu and Woodgate 1986, Kurokawa 1988).

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2. Results and Comparison with Observations

We assume initially an isolated magnetic flux sheet with $\beta = 1$ in (or just below) the photosphere. This magnetized gas layer is unstable for undular mode of magnetic buoyancy (Parker) instability (Parker 1966). Ideal 2D MHD equations with polytropic index $\gamma = 1.05$ are solved numerically (Matsumoto *et al.* 1988, Shibata *et al.* 1989). Fig. 1 shows numerical results on the nonlinear evolution of the instability. The units of the length and time are the scale height $H(\simeq 200$ km/s) and the sound travel time across the scale height $\tau = H/C_s(\simeq 20$ sec) in the chromosphere. As the instability develops, the gas slides down the expanding loop, and the evacuated loop rises due to enhanced magnetic buoyancy. In the nonlinear regime of the instability, the expansion of magnetic loop tube (arch) shows self-similar behavior; the rise velocity of a magnetic loop and the local Alfven speed at the top of the loop increase linearly with distance. Self-similar solution is also found from analytical study, and it well explains the numerical results (Shibata *et al.* 1989).

The rise velocity of magnetic loop in the high chromosphere ($h \simeq 4000$ - 6000 km) is about 10 15 km/s, and the velocity of downflow along the loop is about 30 50 km/s, both of which are consistent with observed values for Arch filament system (Bruzek 1967, 1969, Chou and Zirin 1988). Numerical results also explain some observed features of emerging magnetic flux in the photosphere; such as strong downdrafts associated with the birth of sunspot pores, and the small rise velocity of emerging magnetic flux tubes in the photosphere (Kawaguchi and Kitai 1976, Chou and Wang 1987).

Fig. 2 shows results in the final stage ($t = 58.5\tau \simeq 20$ min). We see that MHD shock waves are formed near the footpoints of the loop, because the downflow speed exceeds the local sound and Alfven speeds. The shocks consist of fast and intermediate MHD shocks (Steinolfson and Hundhausen 1988). The energy flux dissipated in the shocks due to downflow is estimated to be about 6×10^6 erg/cm^2/s, which may explain a part of chromospheric heating in bright plages in emerging flux regions. The kinetic energy of downflow originates from magnetic energy stored in the initial magnetic flux sheet in (or below) the photosphere. The release rate of magnetic energy is $\sim 4 \times 10^9$ erg/cm^2/s, which is sufficient to explain enhanced activities in emerging flux regions.

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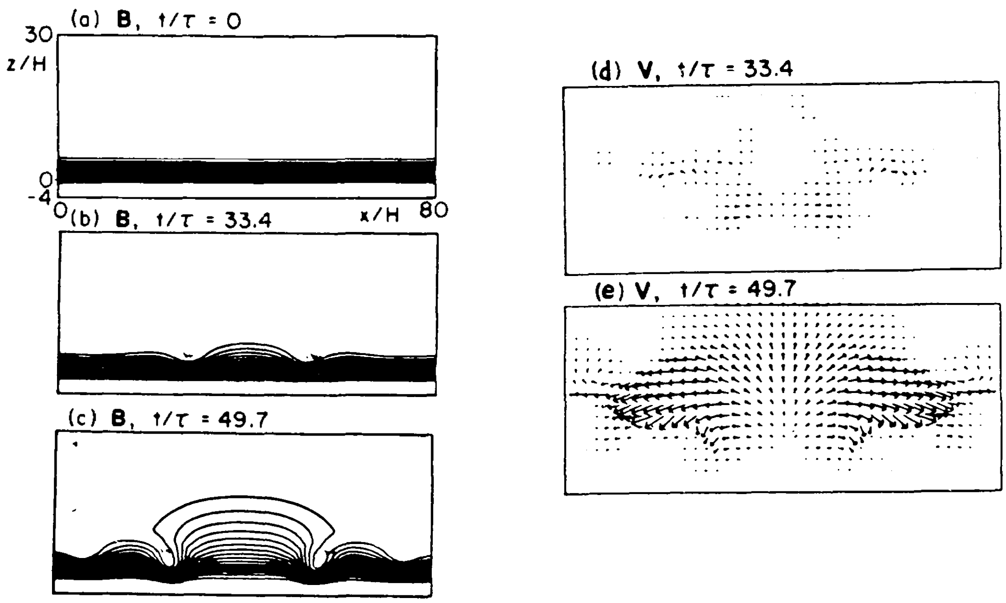

Fig. 1 Numerical results for two-dimensional MHD model of emerging magnetic flux. (a) – (c) magnetic field lines (**B**), (d) – (e) velocity vectors (**V**).

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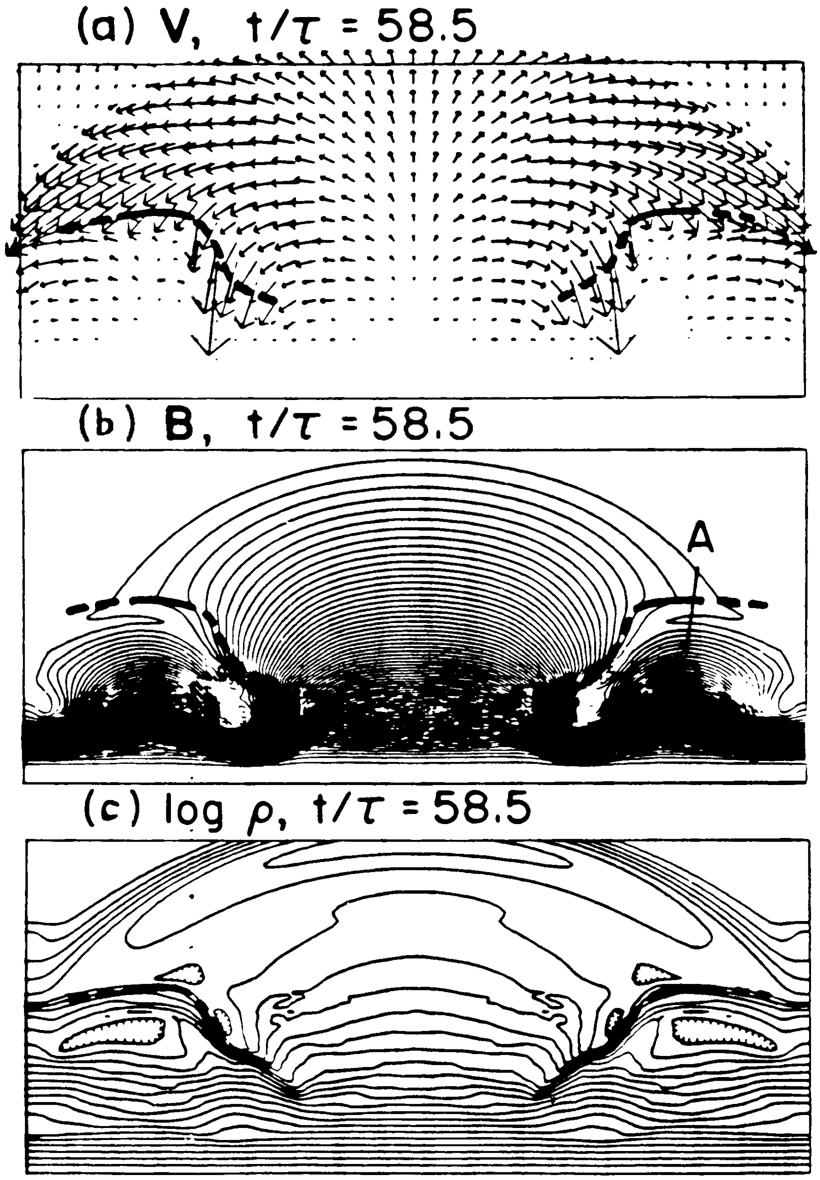

Fig. 2 The results for final stage of the model shown in Fig. 1. (a) velocity vectors, (b) magnetic field lines, (c) density contours. The dashed and solid curves show the positions of fast and intermediate MHD shocks.