JOURNAL OF THE KOREAN ASTRONOMICAL SOCIETY
29: S303 ~ S305, 1996

MAGNETIC RECONNECTION IN SHEARED SOLAR MAGNETIC ARCADES

G. S. CHOE
Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543-0451, U. S. A.

ABSTRACT

The evolution of solar magnetic arcades is investigated with the use of MHD simulations imposing resistivity on sheared magnetic fields. It is found that there is a critical amount of shear, over which magnetic reconnection can take place in an arcade-like field geometry to create a magnetic island. The process leading to reconnection cannot be solely attributed to a tearing instability, but rather to a reactive evolution of the magnetic arcade under resistivity. The natures of the arcade reconnection are governed by the spatial pattern of resistivity. A fast reconnection with a small shock angle can only be achieved when the diffusion region is localized. In this case, a highly collimated reconnection outflow can tear the plasmoid into a pair, and most of principal features in solar eruptive processes are reproduced.

Key Words : Sun: magnetic fields, Sun: flares, MHD

I. INTRODUCTION

It is widely believed that magnetic reconnection plays an important role in solar eruptive phenomena such as solar flares and coronal mass ejections. The occurrence of magnetic reconnection is conditioned by presence of a sufficiently thin current layer. The magnetic field in an active region can be simply depicted by a 2-D arcade, in which the axis of invariance lies along the polarity inversion line. A current layer is known to develop within a magnetic arcade when the field lines are sheared along the polarity inversion line (Choe & Lee 1996a). In an arcade-like geometry, however, there always exists a magnetic field component transverse to the current layer, which can inhibit development of tearing instability (see e.g., Somov & Verneta 1994). In this paper, we will address the question what physical process is most responsible for arcade reconnection. The natures of arcade reconnection depending on spatial patterns of resistivity are also investigated.

II. CRITICAL SHEAR FOR ARCADE RECONNECTION

To examine the critical behavior of arcade reconnection, we have applied different values of resistivity on magnetic arcades with different shears. Then the time duration between the outset of diffusion and the first appearance of an X-line is measured. As shown in Figure 1, magnetic reconnection does not take place for $\zeta_m \lesssim 6.7$, where ζ_m is the maximum shear in units of the distance between the normal magnetic field maxima, irrespective of the resistivity value. This indicates the existence of a critical shear for magnetic reconnection and reminds us of the proposition by Aly (1990) that there are more than one equilibrium field configuration with different topologies if the shear exceeds a certain value. Our results may not serve as a direct proof of Aly's assertion, but provide a convincing support for it.

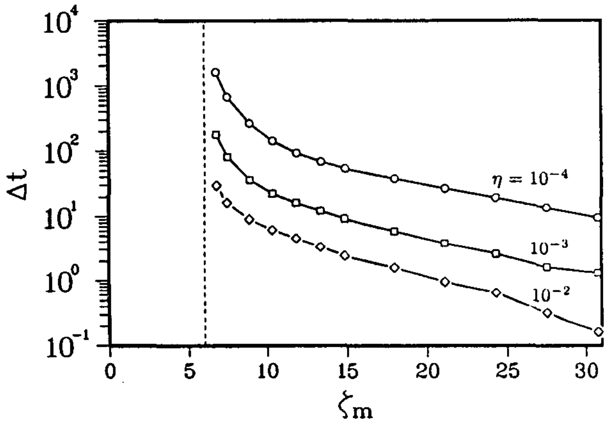

Fig. 1.— Time required for reconnection versus shear. The circles stand for $\eta = 10^{-4}$, the squares for $\eta = 10^{-3}$ and the diamonds for $\eta = 10^{-2}$.

The near parallelism of the three curves in Figure 1 may be interpreted as an indication of resistive tearing instabilities, the growth rate of which is proportional to a certain power of the resistivity, i.e., $\omega \propto \eta^{\alpha}$. (e.g., Furth, Killeen, & Rosenbluth 1963). The value of the exponent α obtained from the curves ranges between 0.6 and 0.8. The process leading to arcade reconnection here thus evolves slower than the fastest growing tearing modes. Furthermore, the tearing instability is known to be stabilized by the transverse field $B_\perp$ if the condition $|B_\perp/B_\parallel| \gg R_m^{-3/4}$ is satisfied, where R_m is the magnetic Reynolds number (Somov & Verneta 1994). For a considerable portion of Figure 1, this condition is met, but magnetic reconnection still takes place. Therefore, the arcade reconnection cannot be merely attributed to the tearing instability, but is caused by the reactive evolution of magnetic fields under resistivity. This can be seen in the fact that the field configuration evolves in the direction of increasing

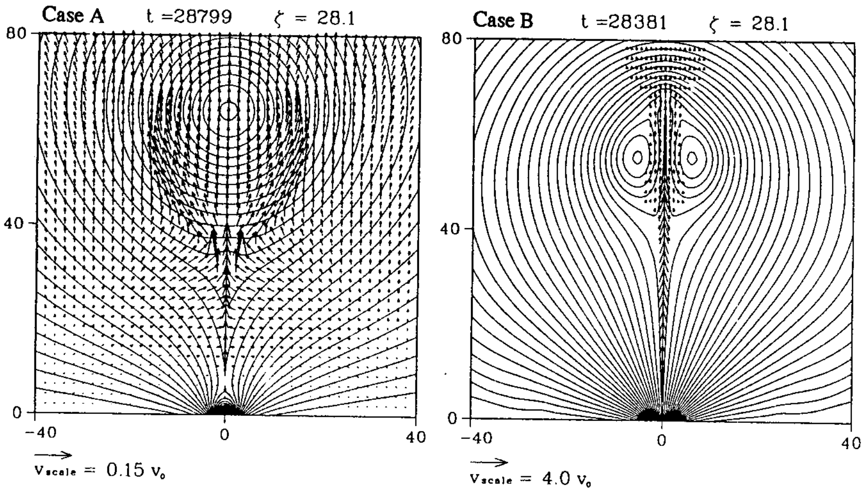

Fig. 2.— Velocity fields superimposed on field lines for Case A (uniform resistivity) and Case B (localized resistivity).

the current density if and only if the shear exceeds the critical value. This critical behavior is related to the transport of toroidal flux during the resistive evolution (see Choe & Lee 1996b for more details).

III. RECONNECTION CHARACTERISTICS DEPENDING ON RESISTIVITY PROFILES

In magnetic reconnection processes in an arcade-like geometry, the extension of the reconnection system is limited by the size of the magnetic island. There is thus no big difference in the external and internal reconnection rates unless the size of the diffusion region is very small compared to the plasmoid size. The internal reconnection rate is found to be scaled with the Sweet-Parker rate (Sweet 1958; Parker 1963). To increase the reconnection rate, either resistivity needs to be raised or the length of the diffusion region must be reduced.

Under uniform resistivity, the relative length of the diffusion region compared to the plasmoid height grows and the width of the diffusion region decreases with the increasing magnetic Reynolds number ($\eta = 10^{-5}$, 10^{-4}, 10^{-3}). In the case with a highest uniform resistivity ($\eta = 10^{-3}$) we tried (Case A), the Sweet-Parker rate is comparable to the Petschek rate (Petschek 1964) and the diffusion region length is relatively small (see Figure 2a). The presence of a large plasmoid, however, creates a large separatrix angle and diverts the flows along field lines as shown in Figure 2a. After the plasmoid is completely ejected out of the computational domain, not much flux remains unreconnected.

We have also tried a current-dependent resistivity to confine the diffusion region. In this case (Case B), the reconnection rate is smaller, but the reconnection flux rate is almost the same as in the former case. As shown in Figure 2b, the reconnection outflows are highly collimated to cause magnetic reconnection within the magnetic island. Owing to the flow channel thus created, the shock angle is kept small and a high conversion rate of magnetic energy into kinetic energy is achieved. The fast shock front generated by the super-fast motion of the plasmoid tip resembles the observed CME loops, which propagate ahead of a prominence of a broken shape. After the ejection of the plasmoid, a considerable portion of the flux still remains unreconnected forming a partially open configuration.

IV. DISCUSSION

Recently Uchida (1996) has reported that soft X-ray images obtained by Yohkoh SXT reveal CME structures resembling a spine and ribs. The density distribution within the plasmoid system in our model B has three peaks and a 3-D view of this structure would be similar to what is observed by Yohkoh SXT.

The launch time of CMEs inferred from coronal observations usually falls about 10 minutes before the flare onset characterized by hard X-ray bursts (Hundhausen 1996). If the reconnection is triggered in a rather static corona as in our model, the launch of a CME and the onset of a hard X-ray flare must be simultaneous. For the reconnection model to survive that inconsistency, the magnetic field needs to rise a little before the magnetic reconnection. In this regard, Livi et al. (1989) have reported that flux cancellation is often observed before the flare onset. The flux cancellation can be best described as emergence of an island-like structure which was dipped in the photosphere and pushed up by subphotospheric reconnection. Whether the subsequent rising of the arcade is fast or slow, the current layer is stretched and becomes more vulnerable to reconnection than before the rising. The rest scenario would be just the same as our model.

ACKNOWLEDGEMENTS

This work was supported by NSF Grant No. ATM-9531711 and U. S. Department of Energy Contract No. DE-AC02-76-CHO-3073. The author would like to thank L. C. Lee and C. Z. Cheng for helpful discussions.

REFERENCES

Aly, J. J. 1990, Comput. Phys. Comm., 59, 13

Choe, G. S., & Lee, L. C. 1996a, ApJ, in press

Choe, G. S., & Lee, L. C. 1996b, ApJ, in press

Furth, H. P., Killeen, J., & Rosenbluth, M. N. 1963, Phys. Fluids, 6, 459

Hundhausen, A. J. 1996, in The Many Faces of the Sun, ed. K. Strong, J. Saba, & B. Haisch (New York: Springer), in press

Livi, S. B., Martin, S., Wang, H., & Ai, G. 1989, Solar Phys., 121, 197

Parker, E. N. 1963, ApJS, 8, 177

Petschek, H. E. 1964, in AAS-NASA Symposium on the Physics of Solar Flares, ed. W. N. Hess (Washington, DC: NASA SP-50), 425

Somov, B. V., & Verneta, A. I. 1994, Space Sci. Rev., 65, 253

Sweet, P. A. 1958, Nuovo Cimento Suppl., Ser. X, 8, 188

Uchida, Y. 1996, in Magnetodynamic Phenomena in the Solar Atmosphere, ed. Y. Uchida, T. Kosugi, & H. S. Hudson (Dordrecht: Kluwer), in press