Journal of The Korean Astronomical Society
36: S13 ∼ S20, 2003

OBSERVATIONAL TESTS OF CHROMOSPHERIC MAGNETIC RECONNECTION

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ABSTRACT

Observations have indicated that magnetic reconnection may occur frequently in the photosphere and chromosphere as well as in the solar corona. The observed features include cancelling magnetic features seen in photospheric magnetograms, and different kinds of small-scale activities such as UV explosive events and EUV jets. By integrating the observed parameters of these features with the Sweet-Parker reconnection theory, an attempt is made to clarify the nature of chromospheric magnetic reconnection. Our results suggest that magnetic reconnection may be occurring at many different levels of the photosphere and chromosphere without a preferred height and at a faster speed than is predicted by the Sweet-Parker reconnection model using the classical value of electric conductivity. Introducing an anomalous magnetic diffusivity 10-100 times the classical value is one of the possible ways of explaining the fast reconnection as inferred from observations.

Key words : sun: magnetic fields—sun: chromosphere—sun: corona — magnetic reconnection

I. INTRODUCTION

It is widely accepted that solar flares result from the reconnection of magnetic field lines in the corona. The corona, however, is not the only place where magnetic reconnection occurs. Magnetic reconnection may occur in the chromosphere, photosphere, and even below the surface only if oppositely directed field lines are put together to form current sheets. As a matter of fact, observations support that magnetic reconnection does occur in the chromosphere.

The most compelling observational evidence may be cancelling magnetic features (CMFs) that display "mutual apparent loss of magnetic flux in closely-spaced features of opposite polarity" (Martin et al. 1985). The rate of magnetic flux loss ranges from 10^{17} to 4×10^{18} Mx h^{-1} in the quiet Sun (Livi et al. 1985) and may be up to 10^{19} Mx h^{-1} in active regions. Zwaan (1987) proposed several different pictures to explain the observed CMFs. The first one is a simple submergence of an omega-shaped loop driven by converging motion. The next possibility is a simple emergence of a U-shaped loop. Zwaan speculated this kind of loops can be created by magnetic reconnection occurring below the solar surface. The final one is the submergence after reconnection occurring above the surface. If this is the case, it would be possible to observe chromospheric brightenings and jets resulting from such magnetic reconnection.

Various kinds of chromospheric activities have been observed in association with cancelling magnetic features, which include transition region explosive events (Dere et al. 1991; Chae et al. 1998a), Hα upflow events (Chae et al. 1998b; Lee et al. 2000), erupting mini-filaments (Hermans & Martin 1986; Wang et al. 2000; Lee et al. 2003), X-ray/EUV bright points (Webb et al. 1993) in the quiet Sun, Hα surges/jets (Chae et al. 1999; Litvinenko & Martin 1999; Chae et al. 2000), EUV jets (Chae et al. 1999; Chae 2003), pre-flare activities (Livi et al. 1989; Wang & Shi 1993; Moon et al. 2003) and filament formation/eruption (Chae et al. 2001; Kim et al. 2001; Zhang et al. 2001) in active regions. Thus, it is very likely that cancelling magnetic features represent a process of magnetic flux removal by the flux submergence following magnetic reconnection in the chromosphere. This explanation is also supported by the comparison of photospheric magnetograms and chromospheric magnetograms done by Harvey et al. (1999), and the finding that a pair of magnetic poles involved in flux cancellation are not connected to each other initially (Martin 1990; Wang & Shi 1993).

One of the curiosities we have about the magnetic reconnection that leads to observed CMFs is the atmospheric level where it proceeds. Priest et al. (1994) proposed a converging flux model to explain X-ray bright points that are associated with a CMF. In this model, the level of reconnection may be in the corona, chromosphere, and photosphere, depending on the evolutionary phase of the CMF. On the other hand, Sturrock (1999) and Litvinenko (1999) proposed that the low chromosphere near the temperature minimum is the most preferred height of chromospheric reconnection since the electric conductivity is the lowest there.

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Therefore, it would be interesting and may give us an insight on the physical nature of chromospheric reconnection to examine whether currently available observational data support that chromospheric reconnection preferentially occurs near the temperature minimum or not. This has motivated the present study.

In the following section, we will present some important relations obtained for a two-dimensional steady-state, adiabatic reconnection current sheet of Sweet-Parker type (Sweet 1958; Parker 1957). This current sheet model is similar to the one studied by Litvinenko (1999), except for the assumption that the energy transfer occurs in an adiabatic way, which is necessary to account for the temperature increase by the release of magnetic energy. Litvinenko (1999) assumed the equality of temperature between inside and outside the current sheet, which does not allow any increase in temperature. The real situation may be in the midway between these two extremes. In section III, we will present observed parameters of CMFs and their associated small-scale activities, and in section IV we will compare these observed parameters with the theory of the current sheet, and will attempt to answer to several important questions relevant to the nature of chromospheric reconnection. Finally, our conclusion will be given in section V.

II. PHYSICAL PARAMETERS OF ADIABATIC CURRENT SHEET

The geometry of a two-dimensional steady-state current sheet is characterized by the two lengths: thickness $2l$ and width $2L$. The length of the current sheet along the third direction is infinite theoretically, but should have a finite value L_z in a real situation. From now on, the subscripts $i,\ c,\ o$ will denote the inflow region, the current sheet, and the outflow region, respectively. For example, the magnetic field strength and flow speed in the inflowing region are denoted by B_i and v_i, respectively, and those in the outflow region, by B_o and v_o. The rate of magnetic flux loss is related to these quantities in the way

$$\frac{d\Phi}{dt} = v_o B_o L_z = v_i B_i L_z \tag{1}$$

and the electric field that characterize the reconnection rate is given by

$$E = \frac{1}{c} v_i B_i = \frac{1}{c L_z}\frac{d\Phi}{dt}\,. \tag{2}$$

Note that the electric field corresponds to the rate of flux loss per unit length of the cancellation interface. We emphasize that both the rate of flux loss $d\Phi/dt$ and the length L_z can be determined from observations of CMFs, so the electric field E is also an observable quantity.

We are going to derive several useful relations describing a two-dimensional steady-state reconnection current sheet. The results depend on the specific form of the energy equation. Usually the assumption of incompressible flow $\rho_i = \rho_o$ replaces the energy equation. Litvinenko (1999) relaxed this incompressibility condition assuming that temperature remains constant $T_i = T_o$. This isothermal assumption may be justified if cooling processes such as thermal conduction and radiation are very efficient. If cooling processes are not efficient enough, then reconnection leads to localized heating and temperature increases. In this case the adiabatic assumption may be better. In real situations, the energy process of reconnection flow may be in the midway between these two extremes. In the present work, we deal with an adiabatic reconnection current sheet. Note that our approach is more general than Litvinenko (1999) in that an isothermal reconnection current sheet can be restored from an adiabatic one if the specific heat ratio is forced to be equal to 1.

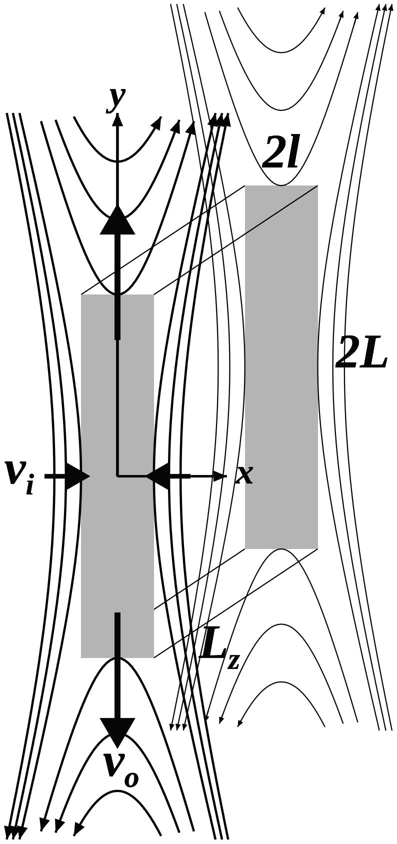

Fig. 1.— The geometry of a Sweet-Parker reconnection current sheet.

The following equations describe a two-dimensional steady-state current sheet:

1. steady-state induction equation (electric field should

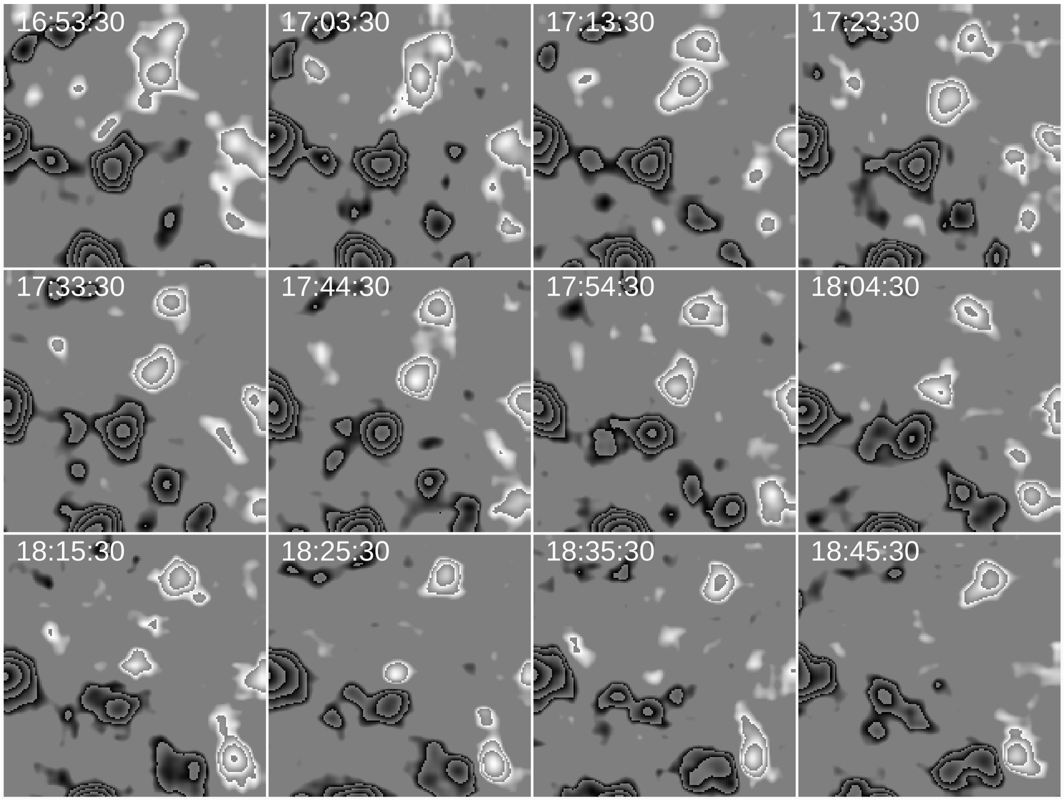

Fig. 2.— An example of cancelling magnetic feature observed by SOHO/MDI. The field of view is $24'' \times 24''$. The gray scale discontinuities represent the flux density levels of ±5, 10, 20 G and so on, and white refers to positive flux density, and black, negative one.

be spatially uniform)

$$cE = v_i B_i = v_o B_o = \eta_c \frac{B_i}{l} \tag{3}$$

2. mass conservation

$$\rho_i v_i L = \rho_o v_o l \tag{4}$$

3. momentum conservation across the current sheet

$$\frac{B_i^2}{8\pi} + \frac{1}{2}\rho_i v_i^2 + p_i = p_c \tag{5}$$

4. momentum conservation along the current sheet

$$\frac{1}{2}\rho_o v_o^2 + p_o = p_c + \frac{B_i B_o}{8\pi}\frac{L}{l} \tag{6}$$

5. adiabatic energy equation

$$\begin{aligned}\left(\frac{1}{2}\rho_i v_i^2 + \frac{\gamma}{\gamma-1}p_i + \frac{B_i^2}{4\pi}\right) v_i L = \\ \left(\frac{1}{2}\rho_o v_o^2 + \frac{\gamma}{\gamma-1}p_o + \frac{B_o^2}{4\pi}\right) v_o l\end{aligned} \tag{7}$$

Assuming $p_n = p_o$ and $l << L$, we obtain the useful expressions of the density factor

$$f \equiv \frac{\rho_o}{\rho_i} = 1 + \frac{1}{(\gamma - 1 + \gamma\beta_i)}\,, \tag{8}$$

the outflow speed

$$v_o = v_{Ai} \equiv \frac{B_i}{\sqrt{4\pi\rho_i}}\,, \tag{9}$$

the inflow speed

$$v_i = \left(\frac{\eta_c B_i}{L\sqrt{4\pi\rho_i}}\right)^{1/2} f^{1/2}\,, \tag{10}$$

and the temperature increase

$$\Delta T \equiv T_o - T_i = \frac{1}{2}\frac{\gamma-1}{\gamma}\frac{\mu m_H}{k_B} v_o^2\,. \tag{11}$$

where β_i is the plasma beta given by $\beta_i \equiv 8\pi p_i / B_i^2$, γ, the specific heat ratio, and μ is the mean molecular weight.

In these equations the inflow field strength B_i is considered as a free parameter. But B_i is hard to determine from observations. What can be better determined from observations are the flux loss rate $d\Phi/dt$

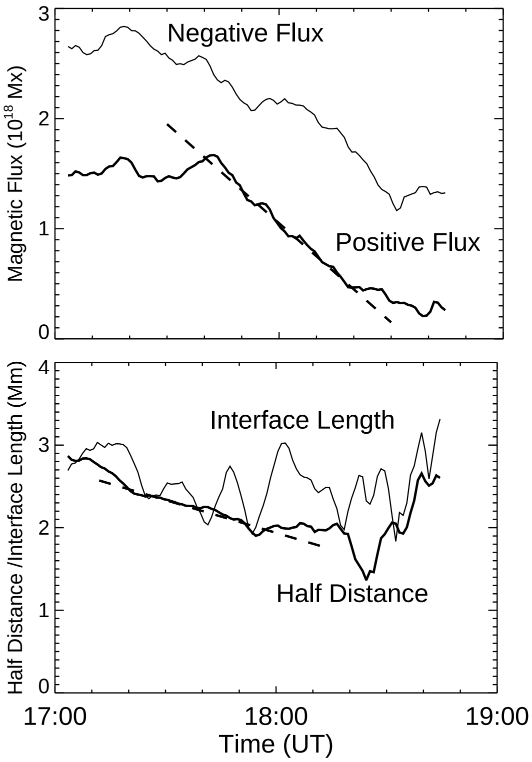

Fig. 3.— Temporal variations of positive and negative magnetic fluxes, half distance, and interface length. The slopes of the dashed straight lines in the magnetic flux plot and the distance plot are -1.8×10^{18} Mx h^{-1} and -0.22 km s^{-1}, respectively.

and the cancellation interface length L_z. Therefore, we express the field strength and the inflow speed in terms of the observable parameters with the help of Eq.(2) and Eq.(10),

$$B_i = \left(\frac{L\sqrt{4\pi\rho_i}}{\eta_c} \left(\frac{1}{L_z} \frac{d\Phi}{dt} \right)^2 \right)^{1/3} f^{-1/3} , \tag{12}$$

$$v_i = \left(\frac{\eta_c}{L\sqrt{4\pi\rho_i}} \frac{1}{L_z} \frac{d\Phi}{dt} \right)^{1/3} f^{1/3} . \tag{13}$$

Litivinenko (1999) argued that the width of the current sheet L should be comparable to the pressure scale height. Once the atmospheric height of reconnection is specified, it is possible to choose parameters ρ_i, p_i, η and L from an appropriate atmospheric model, such as the VAL C model (Vernazza et al. 1981).

The most uncertain parameter in Eq.(12) and Eq.(13) is the magnetic diffusivity of the current sheet η_c. There is a good possibility that η_c much differs from that of the inflow region because of different thermodynamic properties. Moreover, if microinstabilities occur inside the current sheet, η_c may be anomalously higher than the value inferred from the classical electric conductivity. For the moment, we set η_c to be equal to the value in the inflow region η_i mainly because we do not have a good knowledge of η_c. Later we will evaluate whether this choice is physically reasonable or not. Kubat & Karlicky (1986) calculated the electric conductivity as a function of height based on the VAL C model, which will be used to determine η_i. Once ρ_i, p_i, L, and η_i are specified as functions of height, it is possible to determine B_i and v_i if the parameters $d\Phi/dt$ and L_z are determined from observations.

III. OBSERVED PARAMETERS

(a) Cancelling Magnetic Features

Fig. 2 illustrates the time evolution of a typical cancelling magnetic feature in the quiet Sun. The magnetic flux patch of positive polarity is split into two, one of which moves toward the magnetic flux of negative polarity. This convergence results in flux cancellation. Three important parameters of cancelling magnetic features can be obtained from observations: the rate of flux loss $d\Phi/dt$, the converging speed of each pole toward the flux cancellation interface v_c, and the length of the interface L_c, following the procedures described by Chae et al. (2002a). Note that if the cancellation is a result of Sweet-Parker reconnection, v_c and L_c could be identified with v_i and L_z in Fig. 1.

Fig. 3 shows the temporal variations of positive and negative magnetic fluxes, half distance between the two poles, and the length of the interface. From this figure we obtain

$$\begin{aligned} \frac{d\Phi}{dt} &= 1.8 \times 10^{18} \text{ Mx h}^{-1} && (14) \\ v_c &= 0.22 \text{ km s}^{-1} && (15) \\ L_c &= 2.5 \text{ Mm.} && (16) \end{aligned}$$

These values yield a value of 2×10^6 G cm s^{-1} for the rate of flux loss per unit length of the interface. Chae et al. (2002a) obtained somewhat lower, but the same-order values of 1.1×10^6 G cm s^{-1} and 1.2×10^6 G cm s^{-1}.

(b) Uv Explosive Events And Euv Jets

Explosive events are short-lived, small-scale dynamic features that are characterized by very broad UV line profiles. They ubiquitously occur in the quiet Sun as well as in active regions. The spectral characteristics indicate the existence of both a highly red-shifted component and highly blue-shifted component in an explosive event (see Fig. 4). This bi-directional jet nature is the reason why explosive events are often considered to be magnetic reconnection outflows. In support of this interpretation, Chae et al. (1998a) found that the majority of explosive events occur as bursts during magnetic flux cancellation.

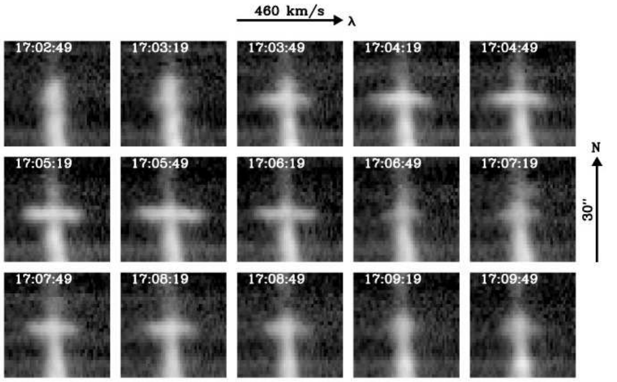

Fig. 4.— An explosive event observed in a time series of Si IV 1402 line spectrograms taken by SOHO/SUMER.

The previously reported physical parameters of explosive events (e.g., Dere 1994) include bulk motion speed (about 100 km s^{-1}), temperature (10^5 K), electron density (7×10^{10} cm^{-3}), size (1500 km), lifetime (one to a few minutes). The rate of magnetic flux loss associated with explosive events was reported to be $d\Phi/dt = 2\times10^{17}$ Mx h^{-1} (Chae et al. 1998a). This is one order of magnitude smaller than the value for a typical cancelling magnetic feature obtained above. The interface of flux cancellation is roughly estimated to be 3 Mm from Figure 3 of Chae et al. (1998). Therefore, the rate of flux per unit length is about 2×10^5 G cm s^{-1}.

In active regions, jets are often observed at different wavelengths in association with cancelling magnetic features. These events are big enough to be spatially well resolved. Fig. 5 shows an event studied in detail by Chae (2003) based on EUV images taken by TRACE. The transverse component of the bulk motion across the plane of sky was determined from the displacements of EUV-emitting blobs. It ranged from 150 to 250 km. These values may be close to the magnitudes of the velocity vectors, since the dominant direction of motion appears to be horizontal. The temperature of the jet plasma was inferred to be about 2.5×10^5 K based on the method using two filter ratios (Chae et al. 2002b). The electron density was inferred from the analysis of emission measure and was found to be about 1.5×10^{10} cm s^{-1}.

IV. OBSERVATIONAL TESTS OF MAGNETIC RECONNECTION SCENARIOS

With the observed parameters of cancelling magnetic features, UV explosive events and EUV jets, we are now in a position to address a few questions about the physical nature of chromospheric reconnection.

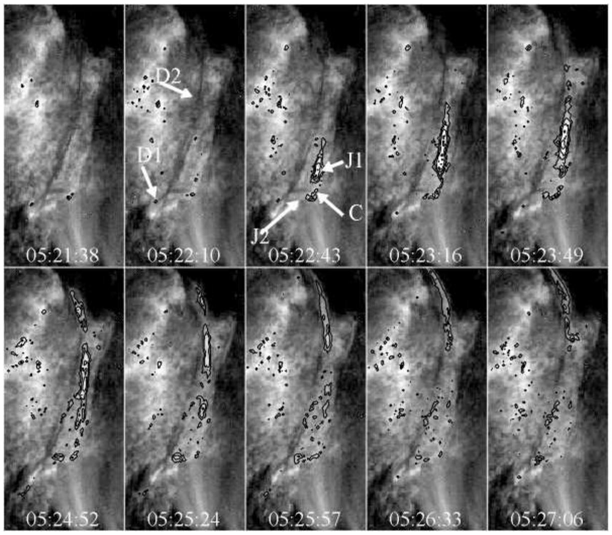

Fig. 5.— An EUV jet observed in EUV 171 Å by TRACE.

(a) Are UV explosive events and EUV jets produced by magnetic reconnection?

Our answer is probably yes. Suppose these events are reconnection outflows. Then the observed speed of explosive events can regarded as the speed of reconnection outflow $v_o = 100$ km s^{-1}. According to Eq.(11), the temperature increase corresponding to this value of outflow speed is $\Delta T = 1.5\times10^5$ K. This value is very comparable to the observed temperature of explosive events 10^5 K. Similarly, for EUV jets, we have $v_o = 200$ km s^{-1} from observations, and obtain a theoretical estimate $\Delta T = 6\times10^5$ K with $\gamma = 5/3$. This value is significantly higher than the observed temperature 2.5×10^5 K. The discrepancy, however, might be removed if the neglected effect of radiative cooling could be taken into account in the theoretical estimate. If we choose, for example, $\gamma = 4/3$, to simulate the effect of radiative cooling, we obtain a new theoretical estimate of $\Delta T = 3.7\times10^5$ K, a value closer to the observed value than for the case of $\gamma = 5/3$. Therefore, we conclude that the observed speeds and temperatures are consistent with the reconnection origin of of explosive events and EUV jets.

If observed flows are the reconnection outflows, it is possible to infer the inflow magnetic field strength B_i using Eq.(9). The measured densities of outflow are $\rho_o = 1.2\times10^{-13}$ and 2.5×10^{-14} g cm^{-3} for explosive events and EUV jets, respectively. These values of density suggest that it is in the upper chromosphere where magnetic reconnection occurs. In this level, β_i may be much less than 1, so it follows $f \approx 2.5$ and $\rho_i = 5\times10^{-14}$ and 1×10^{-14} g cm^{-3}, respectively. From the observed speeds and these inflow densities, we obtain $B_i = 8$ G for explosive events and 7 G for EUV jets, which happen to be about the same.

(b) Are cancelling magnetic features produced by the same magnetic reconnection that also produces explosive events and EUV jets?

Suppose yes. Then we have $B_i = 8$ G from above. Using this value and the observed value $v_i B_i = 2 \times 10^5$ G cm s^{-1} for explosive events, we estimate the inflow speed to be 0.25 km s^{-1}. On the other hand, we obtain a theoretical value of 0.10 km s^{-1} from Eq.(13) for the Sweet-Parker inflow speed, using the already inferred values of $\rho_i = 5 \times 10^{-14}$ g cm^{-3} and $f = 2.5$, and the typical values of $\eta_i = 2 \times 10^7$ cm^2 s^{-1} (Kubat & Karlicky 1986) and $L = 200$ km in the upper chromosphere. This theoretical value is significantly lower than the above value 0.25 km s^{-1} that was inferred from observed parameters of explosive events and cancelling magnetic features. In other words, observations suggest that magnetic reconnection is faster than the Sweet-Parker type reconnection using $\eta_c = \eta_i$.

One way of resolving the discrepancy is to theoretically model faster reconnection by introducing anomalously high value of electric resistivity or magnetic diffusivity. If we use, for example, the anomalous resistivity $\eta_c = 20\eta_i$ instead of $\eta_c = \eta_i$, then we obtain the new theoretical estimate 0.26 km s^{-1} that is consistent with observations.

(c) Are cancelling magnetic features produced by magnetic reconnection occurring in the temperature minimum?

Since magnetic diffusivity is the highest, the temperature minimum region might be preferred to the upper chromosphere as a place where magnetic reconnection of Sweet-Parker type can proceed. Here, however, we will demonstrate that the Sweet-Parker reconnection with $\eta_c = \eta_i$ may be still too slow to explain observed parameters.

Let's consider the cancelling magnetic feature presented in Figs. 2 and 3. Using the observed parameters of the cancelling magnetic feature $d\Phi/dt = 1.8 \times 10^{18}$ Mx g^{-1} and $L_z = L_c = 2.5$ Mm, and the parameters of the temperature minimum: $\rho_i = 5 \times 10^{-9}$ g cm^{-3}, $p_i = 1.3 \times 10^3$ erg cm^{-3}, $L = 100$ km, and $\eta = 7 \times 10^8$ cm^2 s^{-1}, we obtain the theoretical value of the inflow speed $v_i = 0.10$ km s^{-1} from Eq.(13). This is only half the observed converging speed $v_c = 0.22$ km s^{-1}. This means that the theoretical speed of reconnection is too slow. Chae et al. (2002a) also found a similar discrepancy between the theoretical inflow speed and the observed converging speed. They proposed several possible ways to explain the discrepancy, which include slowing-down of inflow speed by flux pile-up, unresolved fine structure of flux tubes, anomalous resistivity and so on. Like the case discussed above, a simple way is to introduce the anomalously high resistivity $\eta_c = 10\eta$ instead of $\eta_c = \eta$, which yields a new estimate of inflow speed 0.21 km s^{-1} that is about the same as the observed converging speed.

(d) Are cancelling magnetic features produced by magnetic reconnection occurring in the upper chromosphere?

We use the same parameters of cancelling magnetic features in the above, but now we suppose that reconnection occurs not in the temperature minimum, but in the upper chromosphere. We choose the values $\rho_i = 5 \times 10^{-13}$ g cm^{-3}, $p_i = 0.3$ erg cm^{-3}, $L = 200$ km, and $\eta = 2 \times 10^7$ to represent the physical conditions of the upper chromosphere. Then from Eq.(8) and Eq.(9), and Eq.(12), we obtain the theoretical estimate of the outflow speed $v_o = 600$ km s^{-1}. This value appears much higher than the commonly observed speeds of chromospheric features (usually less than 200 km s^{-1}). A better estimate can be done if anomalously high value of magnetic diffusivity is adopted. If we adopt, for example, $\eta_c = 100\eta$ instead of $\eta_c = \eta$, we have a new estimate $v_o = 130$ km s^{-1}.

V. CONCLUSION

We have compared the observed parameters of cancelling magnetic features and their associated activities (explosive events and EUV jets) with a theory of an adiabatic reconnection current sheet of Sweet-Parker type, and have obtained the following results:

1. Chromospheric activities such as UV explosive events and EUV jets may be produced magnetic reconnection occurring in the upper chromosphere.
2. Sweet-Parker type magnetic reconnection with the classical value of magnetic diffusivity is too slow to explain the observed parameters, irrespective of the specific atmospheric level of the chromosphere where reconnection occurs. In other words, observations suggest that reconnection occurs at a faster speed than the Sweet-Parker reconnection.
3. If anomalously high value of magnetic diffusivity (that is enhanced by a factor of 10 or 100 compared with the undisturbed surrounding medium) is adopted, it is possible to explain the observed parameters of cancelling magnetic features in terms of Sweet-Parker type reconnection occurring either in the temperature minimum or in the upper chromosphere.

These results strongly suggest that there may be no preferential chromospheric height for magnetic reconnection to occur. This is against the argument of Sturrock (1999) and Litvinenko (1999) that the temperature minimum region is the most likely atmospheric level for reconnection to occur since the classical electric conductivity at that level is the lowest. We found that the classical value of magnetic diffusivity is still too low to explain the observed parameters. Observations suggest that reconnection proceeds at a significantly faster speed.

One way of modelling fast reconnection is to introduce the anomalously high value of magnetic diffusiv-

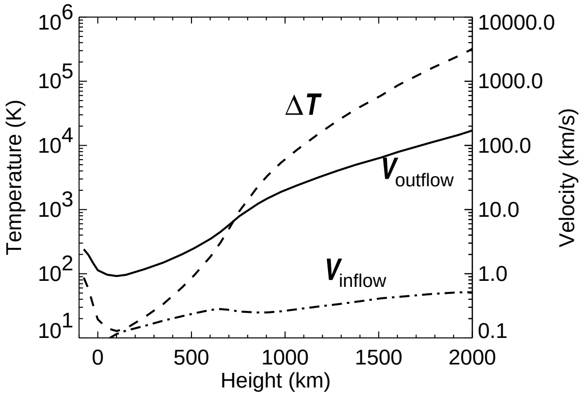

Fig. 6.— Theoretical height variations of inflow speed, outflow speed, and temperature increase for reconnection occurring in the photosphere and chromosphere, calculated with the input parameters $v_i B_i = 1.5 \times 10^6$ G cm s^{-1}, $\eta_c = 50\eta$, and $\gamma = 4/3$, where η is the classical value of magnetic diffusivity of the undisturbed surrounding medium.

ity. The physical origin of the anomalous magnetic diffusivity is now poorly understood, but it may be an outcome of the dynamical evolution of the current sheet like plasma microinstibilities. If this is the case, it is not the physical condition of the surrounding medium, but the dynamical evolution of the current sheet itself that determines the speed of reconnection. Of course, introducing anomalous magnetic diffusivity is not the only way of theoretically explaining fast reconnection. For example, Chae et al. (2002c) showed that Petschek's mechanism (Petschek 1964) is a viable explanation for the fast speed of chromospheric reconnection as inferred from observations. It is interesting to note that a necessary condition for reconnection of Petschek type to occur is the development of anomalous resistivity inside the current sheet (e.g., Yokoyama & Shibata 1994)

Since there is no preferred height, magnetic reconnection in charge of cancelling magnetic features, in principle, may occur at any level of the photosphere and chromosphere. As a matter of fact, this possibility is strongly supported by the great diversity of dynamic features observed in association with cancelling magnetic features. Generally speaking, the speed of outflow increases with height since density rapidly decreases. Therefore, dynamical features produced by reconnection in the low level will be cool and slowly moving, whereas those produced by reconnection in the high level will be hot and fast moving. Fig. 6 clearly illustrates this characteristic. Cool and slowly moving features associated with cancelling magnetic features are usually observed in Hα. Hα jets and surges, erupting mini-filaments, and chromospheric upflow events belong to this category. Hot and fast moving features associated with cancelling magnetic features are well observed in UV and EUV, which include UV explosive events and EUV jets.

In conclusion, observations support that magnetic reconnection occurs at many different levels of the photosphere and chromosphere, and at a faster speed than the Sweet-Parker reconnection using the classical value of magnetic diffusivity. If an anomalous magnetic diffusivity equal to 10 to 100 times the classical value of the surrounding medium develops inside the current sheet, the fast speed of reconnection as inferred from observations can be explained event with the Sweet-Parker reconnection.

ACKNOWLEDGEMENTS

J. Chae and Y.-J. Moon are grateful to Professor Hong Sik Yun who has enthusiastically taught and kindly guided his students including them. This paper is dedicated to him in honor of his retirement from the professorship at Seoul National University in February, 2003. This work was supported by the NASA grant NAG5-10894 and by KOSEF grant R14-2002-043-01000-0. Y.-J.M. has been supported by a MURI grant of AFOSR and by National Research Laboratory M10104000059 - 01J000002500 of the Korean government.

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