Chromospheric Magnetic Reconnection on the Sun

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ABSTRACT

Solar observations support that magnetic reconnection ubiquitously occurs in the chromosphere as well as in the corona. It is now widely accepted that coronal magnetic reconnection is fast reconnection of the Petschek type, and is the main driver of solar flares. On the other hand, it has been thought that the traditional Sweet-Parker model may describe chromospheric reconnection without difficulty, since the electric conductivity in the chromoshphere is much lower than that in the corona. However, recent observations of cancelling magnetic features have suggested that chromospheric reconnection might proceed at a faster rate than the Sweet-Parker model predicts. We have applied the Sweet-Parker model and Petschek model to a well-observed cancelling magnetic feature. As a result, we found that the inflow speed of the Sweet-Parker reconnection is too small to explain the observed converging speed of the feature. On the other hand, the inflow speeds and outflow speeds of the Petschek reconnection are well compatible with observations. Moreover, we found that the Sweet-Parker type current sheet is subject to the ion-acoustic instability in the chromosphere, implying the Petschek mechanism may operate there. Our results strongly suggest that chromospheric reconnection is of the Petschek type.

I. INTRODUCTION

Magnetic reconnection is a physical process that the connectivity of magnetic field lines changes due to the Ohmic dissipation of electric current in a localized volume. Magnetic reconnection is an attractive phenomenon since it provides a convenient way of changing topology of magnetic field lines, transporting mass across the field lines, and converting magnetic energy into thermal energy and kinetic energy (read the textbook of Priest and Forbes (2000) for a thorough study of this process). Many of various dynamic features on the Sun are believed to be driven by magnetic reconnection and the most well-known example is flares.

Flares have been extensively studied both observationally and theoretically. In Hα, big flares are usually observed as two-parallel bright lanes that are called “ribbons”. These two-ribbon flares are believed to originate from magnetic reconnection in the corona. As a result of magnetic reconnection, loop arcades are newly made below the site of reconnection. The loops are initially very hot, so they are visible only in X-ray and then in EUV (see Fig. 1). At this time, only the footpoints of the loops are observed in Hα, the two sets of footpoints at each side of the loop arcade appear as two-ribbons. As the loops cool down, the whole parts of the loops may be temporarily visible in Hα, being called Hα post-flare loops.

Even if magnetic reconnection has been regarded for a long time as the only plausible explanation of solar flares, it has been challenged by the enormous electric conductivity of the solar corona. Therefore, it has been expected that magnetic reconnection occurs too slowly to explain the rapid energy release in flares. A number of theoretical efforts have aimed to find a way of making fast magnetic reconnection, including the tearing instability (Sweet 1958; Parker 1957), the slow mode MHD shocks (Petschek 1964), and the anomalous resistivity

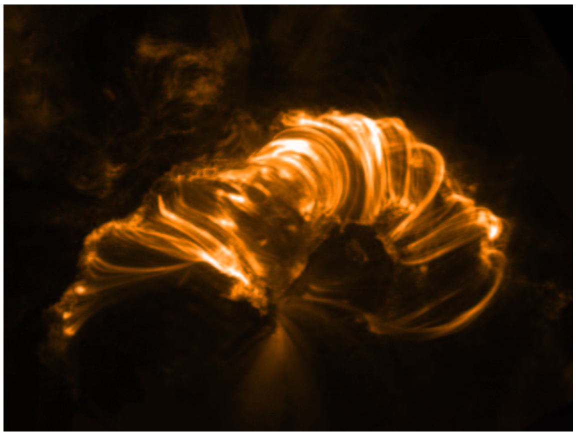

Fig. 1.— Arcade-like flare loops seen in a 171 Å image (characteristic of emission from gas at 10^6 K) that was taken by the Transition Region and Coronal Explorer (TRACE). The field of view is 232,000 by 174,000 km. These loops are the result of an X2.3 flare that occurred on 10 April 2001. The footpoints of the loops form a classic two ribbon structure as seen in Hα.

due to plasma turbulence (Scholer 1989; Ugai 1986). Recent numerical simulations (Yokoyama and Shibata 1994) showed that the coupling between the anomalous resistivity and the tearing instability leads to the rapid formation of and ejection of magnetic islands, which is found to be a key physical process leading to fast reconnection as proposed by Petschek (1964).

Corona is not the only place in the Sun where magnetic reconnection takes place. In principle, magnetic reconnection may also occur in the low atmosphere — the chromosphere and photosphere — and even below the solar surface. In fact, there is increasing observational evidence that magnetic reconnection does occur in the low atmosphere of the Sun. The most compelling observational evidence is that photospheric magnetic fluxes of opposite polarities often collide each other and disappear (Martin et al. 1985; Livi et al. 1985). Flux cancellation is believed to be a consequence of retraction of field lines that are newly created from magnetic reconnection in the low atmosphere, since the two poles are found to be initially unconnected (Martin 1990; Wang and Shi 1993; Harvey et al. 1999). Moreover, its occurrence is often associated with diverse energy release phenomena such as flares (Livi et al. 1989; Wang and Shi 1993), microflares/surges/jets (Chae et al. 1999); X-ray bright points (Webb et al. 1993), erupting mini-filaments (Hermans and Martin 1986), transition region explosive events (Dere et al. 1991; Chae et al. 1998), filament eruption (Kim et al. 2001), and coronal mass ejections.

Compared with the coronal magnetic reconnection that is in charge of flares, reconnection in the low atmosphere is very poorly understood at present. We do not know how the low atmosphere reconnection is different from the coronal magnetic reconnection. We do not understand how flux cancellation observed in the photosphere is physically connected to the different kinds of energy release processes observed in the transition region and corona. An obvious thing is that the chromosphere and photosphere are much cooler and denser than the corona. As a result, most hydrogens remain neutral without being ionized and hence electric conductivity in the low atmosphere becomes much lower than that of the corona, without the need to introduce anomalous resistivity. For this reason, it has been suggested that the traditional Sweet-Parker type reconnection model may work in the low atmosphere.

Litvinenko (1999) developed a Sweet-Parker type reconnection model for flux cancellation and applied it to a cancelling magnetic feature that is associated with mass flows in a filament (Litvinenko and Martin 1999). The model satisfactorily explained for the converging speed of the cancelling feature and the Hα jet speed.

Very recently, Chae et al. (2002a) extended this kind of study. They investigated the time-variation of two cancelling magnetic features and carefully determined the rates of flux cancellation and the speeds of flux convergence. The measured converging speeds were 0.27 km s^{-1} and 0.35 km s^{-1}. These values are significantly bigger than the theoretical value 0.076 km s^{-1} expected from the observed flux cancellation rate based on Litvinenko's (1999) model. They conjectured that the discrepancy may be resolved in the framework of Sweet-Parker type reconnection, if uncertainty factors such as low filling factor of magnetic flux and very low electric conductivity are taken into account.

In the present paper, we examine an alternative possibility. The observed big values of converging speed may support that reconnection occurring the low atmosphere of the Sun is of Petschek-type, too, like coronal magnetic reconnection. In the following section,

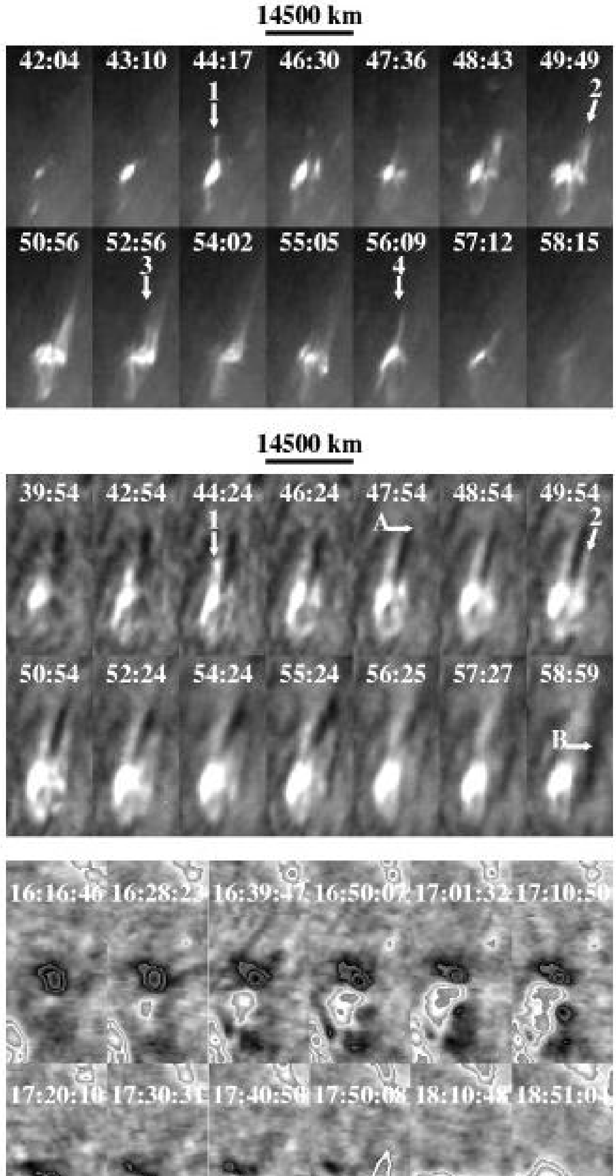

Fig. 2.— Different kinds of associated features in an active region that are believed to be the observable consequences of magnetic reconnection in the low atmosphere of the sun: *cancelling magnetic feature* seen in photospheric magnetograms (low panel), *chromospheric surges and jets* as seen in Hα center-line images (middle panel), and *EUV jets* as seen in *TRACE* 195 images (upper panel).

we briefly review major observational characteristics of cancelling magnetic features as previously reported by Chae et al. (1999, 2002a). Then, we compare the physical concepts of the two types of steady magnetic reconnection: Sweet-Parker type and Petschek-type.

II. OBSERVATIONAL CHARACTERISTICS

Figure 2 shows three kinds of associated observable features of a small event in an active region. This event was studied in detail by Chae et al. (1999). The major difference between this event and the flare event as shown in Figure 1 lies in the size of the system, with that being at least ten times smaller than this. The flare must be associated with coronal magnetic reconnection at a high altitude ($> 10^5$ km). On the other hand, the event in Figure 2 appears to be associated magnetic reconnection at a low altitude ($< 10^4$ km), and very probably at a chromospheric height($\leq 2 \times 10^4$ km). This difference in the height implies the differences in temperature and density, and therefore the differences in physical properties of magnetic reconnection.

The time series of photospheric magnetograms in the lower panel clearly show that pre-existing magnetic flux was cancelled by newly emerging flux of opposite polarity. The rate of flux loss due to this flux cancellation was estimated to be 7×10^{14} Mx s^{-1}. The middle and upper panels show the response of the plasma to the reconnection in the chromosphere and transition region. In Hα, we see a series of dark surges (A and B) and a series of bright jets (1 and 2) that repeatedly occur in parallel to each other. The transverse velocities of the Hα jets perpendicular to the line of sight were estimated to be 30 and 75 km s^{-1}, respectively. In EUV, we see a series of transient brightenings — often called microflares — and a series of EUV jets. The EUV jets are short-lived for 2 to 4 minutes, and have transverse velocities in the range of 50-100 km s^{-1}.

Low-atmosphere reconnection is distinguished from coronal reconnection in plasma temperature, too. The Hα features require the existence of significant amount of neutral hydrogen. Thus, the Hα plasma temperature may be lower than 10^5, and, most likely, around 10^4 K. Chae et al. (2002b) used two filter ratios (195/171 ratio and 284/195 ratio) and found that EUV jets have temperatures of about 0.25 MK. Therefore, plasma involved in low-atmosphere reconnection appears to be much cooler than 1 MK whereas plasma involved in coronal magnetic reconnection is known to reach up to 20 MK, much hotter than 1 MK.

Figure 3 presents an example of a cancelling magnetic feature in which the rate of flux loss and converging speed were well determined from observation (Chae et al. 2002a). The rate of magnetic flux decrease is about 3.4×10^{18} Mx h^{-1}, being more or less constant throughout the observing time. The contact length is 7.8 Mm, so the specific rate of flux loss per unit length is estimated to be 1.2×10^6 G cm s^{-1}. The figure also shows that the converging speed of each polarity is about 0.27 km s^{-1}. These two values are important observational parameters to be used for comparison with reconnection theories in the next section.

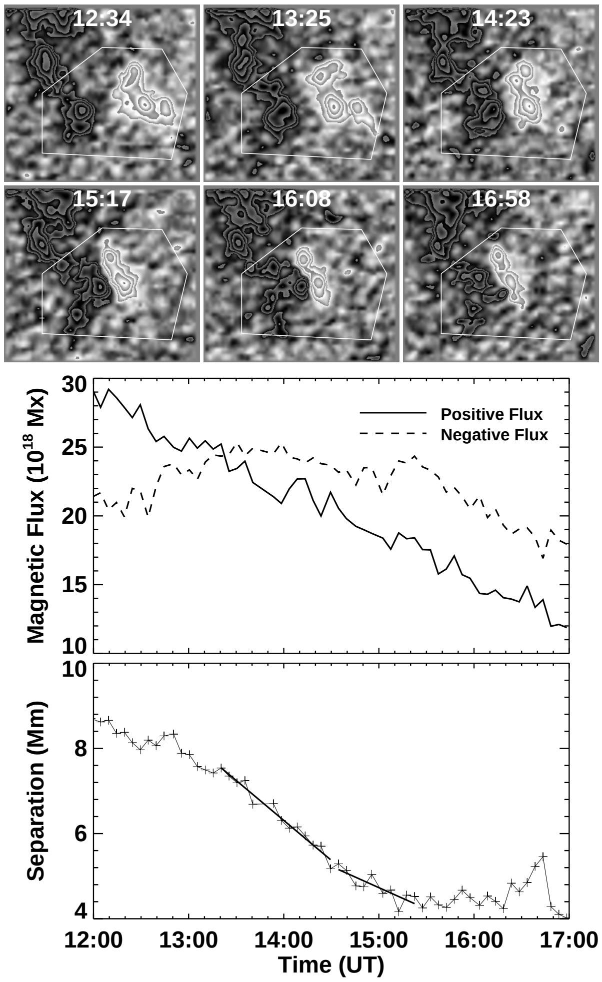

Fig. 3.— A cancelling magnetic feature seen in a time series of photospheric magnetograms (upper panel) with the time-variations of magnetic flux of each polarity and the distance between the two polarities being shown in the middle and low panels, respectively.

III. RECONNECTION MODELS

One of the goals of magnetic reconnection theories is to predict how fast reconnection can occur. The speed of magnetic reconnection is usually defined by the speed of inflow v_i or its ratio to the Alfven speed at the inflow region

$$M_i \equiv v_i/V_{Ai} \quad (1)$$

with the definition

$$V_{Ai} = B_i/\sqrt{4\pi\rho}. \quad (2)$$

Most reconnection theories assume that plasma is incompressible. We regard density ρ as a free parameter to be chosen from solar atmospheric models. Then, the unknown field strength in the inflow region B_i is related to the observed specific rate of cancellation by the equation

$$r = v_i B_i. \tag{3}$$

Our strategy is as follows. Using the observed r and expressions of M_i derived in different reconnection models, we determine B_i and v_i. We will compare this value v_i with the observed converging speed v_c to see which model is better applicable to magnetic reconnection in the low atmosphere of the Sun.

(a) Sweet-Parker Model

This model considers steady reconnection occurring in a thin current layer with a thickness l and width L. The basic features of this model are summarized as follows:

1. The speed of outflow is equal to the Alfven speed in the inflow region: $v_o = V_{Ai}$
2. The plasma carry the field lines toward the current sheet at the same speed as they are trying to diffuse outward: $v_i = \eta/l$
3. The incoming flow of matter must balance the outgoing flow $Lv_i = lv_o$

These relations result in the famous Sweet-Parker rate of reconnection

$$M_i = S^{-1/2} \tag{4}$$

where

$$S \equiv LV_{Ai}/\eta \tag{5}$$

is the Ludquist number of the current sheet. Combining Equations1 through 5 leads to the expression

$$v_i = \left[\frac{\eta r}{L\sqrt{4\pi\rho}}\right]^{1/3} \tag{6}$$

(b) Petschek Model

In Petschek model, the conversion of magnetic energy into thermal energy and kinetic energy actively occurs in slow-mode shocks as well as in the current layer, so the magnetic reconnection may proceed at a faster rate than in the Sweet-Parker model. The slow-mode shocks are located at the external region of the current layer whose spatial extent L_e is much larger than L. The reconnection rate is now measured in the speed of inflow into the shocks v_e. The maximum rate of reconnection rate M_e was found to be (see Priest 1982),

$$M_e = \frac{\pi}{8\ln(8S_e M_e^2)} \tag{7}$$

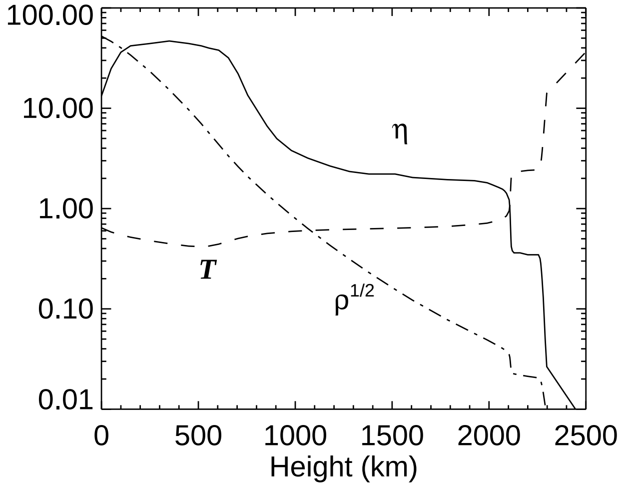

Fig. 4.— The height variations of temperature, density and magnetic diffusivity, which have been normalized by 10^4 K, 10^{-10} g cm^{-3}, and 10^7 cm^2 s^{-1}, respectively.

with the auxiliary relations:

$$M_e = \frac{v_e}{V_{Ae}} \tag{8}$$

$$V_{Ae} = \frac{B_e}{\sqrt{4\pi\rho}} \tag{9}$$

$$S_e = \frac{L_e V_{Ae}}{\eta} \tag{10}$$

$$r = v_e B_e. \tag{11}$$

Combining these equations lead to the following non-linear equation for v_e

$$v_e = \left[\frac{\pi r}{8\sqrt{4\pi\rho}\ln[8(v_e/v^*)^3]}\right]^{1/2}, \tag{12}$$

where

$$v^* = \left[\frac{\eta r}{L_e\sqrt{4\pi\rho}}\right]^{1/3} \tag{13}$$

is similar to the Sweet-Parker inflow speed in Equation 6, with L being replaced by L_e.

(c) Comparisons with Observation

For the application of the Sweet-Parker and Petschek models with an observed value of r, the parameters L, L_e, ρ and η need to be specified. We assume that both L, used in the Sweet-Parker model, and L_e, used in the Petschek model, are equal to the local pressure scale height. Then, we have computed v_i in the Sweet-Parker model and v_e in the Petschek model as functions of height using the atmospheric model C of Vernazza et

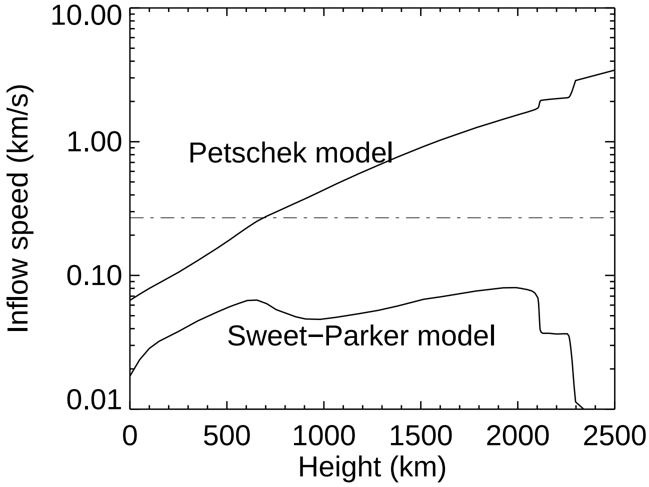

Fig. 5.— Theoretical inflow speeds of magnetic reconnection in the Sweet-Parker model and the Petschek model, given the observed specific cancellation rate of 1.2×10^6 G cm s^{-1}.

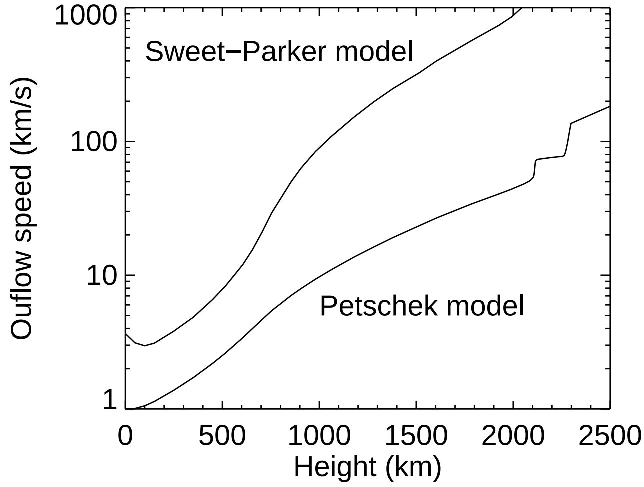

Fig. 6.— Theoretical outflow speeds of magnetic reconnection in the Sweet-Parker model and the Petschek model, given the observed specific cancellation rate of 1.2×10^6 G cm s^{-1}.

al. (1981) and the electric conductivity of Kubat and Karlicky (1986), as shown in Figure 4.

Figure 5 presents the calculated inflow speeds. It shows that the inflow speed in the Sweet-Parker model is lower than 0.1 km s^{-1} throughout the photosphere and chromosphere. Thus, it appears hard to explain the observed converging speed of 0.27 km s^{-1} using the Sweet-Parker model without invoking other effects as discussed by Chae et al. (2002).

The Petschek model produces faster rates of reconnection ranging from 0.1 km s^{-1} near the photosphere to a few km s^{-1} at the upper chromosphere. The theoretical inflow speed is equal to the observed one at the altitude of about 700 km, which is just above the temperature minimum. This height is low enough to ensure retraction of field lines after reconnection. Therefore, the Petschek-type magnetic reconnection better explains the observed converging speed of the cancelling magnetic feature than the Sweet-Parker model.

Figure 6 compares the calculated outflow speeds between the two models. Note the outflow speed of the Sweet-Parker model is too high to match the observed speeds of Hα jets and EUV jets shown in Figure 2. On the other hand, the Petschek model predicts chromospheric outflow speed in the range between 10 and 100 km s^{-1}, which is in close agreement with the observed speeds of 30-75 km s^{-1} for Hα jets and 50-100 km s^{-1} for EUV jets.

(d) Applicability of Petschek mechanism

It has been clear that the Petschek mechanism operates when micro-instabilities develop inside the current sheet, which results in spatially confined anomalous resistivity. The ion-acoustic instability sets in when the drift speed of ions relative to electrons, u_d, exceeds the ion sound speed c_{is} (e.g., Priest and Forbes 2000)

$$u_d > c_{is} \tag{14}$$

where u_d is the drift speed of ions relative to electrons, and is related to the current density by the equation

$$j = q_i n_i u_d = e n_e u_d. \tag{15}$$

The ion sound speed is given by

$$c_{is} = \sqrt{\frac{kT_e}{m_i}}. \tag{16}$$

In the solar chromosphere, we have $T_e \approx T_i = T$. Thus, the condition for the ion-acoustic instability is rewritten as $q \equiv u_d/c_{is} > 1$. Meanwhile, The current density is determined by the thickness of the current layer

$$j = \frac{cB_i}{4\pi l} \tag{17}$$

We identify l with the thickness of the Sweet-Parker current sheet

$$l = \frac{\eta}{v_i}. \tag{18}$$

By combining all of these equations and Equation 3, we obtain the expression for q, given r,

$$q = \frac{cr}{4\pi e \eta n_e}\left(\frac{m_i}{kT}\right)^{1/2} \tag{19}$$

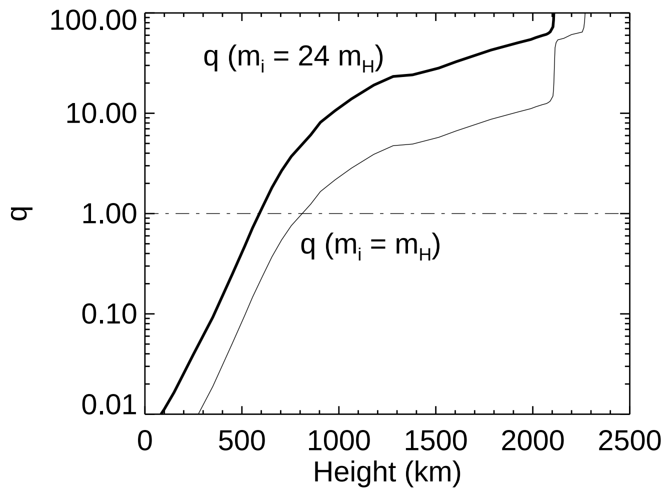

Fig. 7.— The ratio q of the ion drift speed in the Sweet-Parker current sheet to the ion sound speed, calculated as a function of height in the cases of two different ion masses based on the observed specific cancellation rate $r = 1.2 \times 10^6$ G cm s^{-1}.

Figure 7 presents q as a function of height, which was calculated using the observed r. We consider the cases of two different ion masses, to take into account the fact that most hydrogens remain neutral without being ionized at temperatures lower than 10^4 K, especially around the temperature minimum. At these temperatures, metals with low first ionization potentials are important electron suppliers, which include Si, Fe, Mg and so on (Feldman 1993). The mass of these elements are 28, 56, and 24 hydrogen mass, respectively. This is why we consider the case of ion mass $24m_H$. Note that heavier ions are more subject to the ion-acoustic instability.

Figure 7 shows that the Sweet-Parker current sheet constructed using the observed rate of flux cancellation is subject to the ion-acoustic instability if the sheet is located above 600 km. Therefore, it is likely that the Petschek mechanism works in the chromosphere above the temperature minimum.

IV. CONCLUSION

We have calculated the inflow speeds and outflow speeds based on the observed rate of flux cancellation 1.2×10^6 G cm s^{-1}, using the Sweet-Parker reconnection model and the Petschek reconnection model, and obtained the following results:

1. The Petschek model produced inflow speeds in the range 0.1 - 1 km s^{-1} whereas the Sweet-Parker model produced inflow speeds lower than 0.1 km s^{-1}. Therefore, the Petchek model is better compatible with the conversing speed of 0.27 km observed in the cancelling magnetic feature than the Sweet-Parker model.

2. The Petchek model produced outflow speeds in the range 10-100 km s^{-1}, which is compatible with the observed speeds of Hα/EUV jets. The Sweet-Parker model produced much higher values.

3. It is found that the Sweet-Parker current sheet is subject to the ion-acoustic instability if the sheet is located above 600 km.

Our results strongly suggest that chromospheric magnetic reconnection may be of the Petschek type like coronal magnetic reconnection, especially when reconnection occurs at heights above 500 km. Photospheric reconnection occurring below 500 km may be of the Sweet-Parker type, but cancelling magnetic features and associated activities seem to result from reconnection in the chromosphere.

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