Possible two-step solar energy release mechanism due to turbulent magnetic reconnection

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In this paper, a possible two-step solar magnetic energy release process attributed to turbulent magnetic reconnection is investigated by magnetohydrodynamic simulation for the purpose of accounting for the closely associated observational features including canceling magnetic features and different kinds of small-scale activities such as ultraviolet explosive events in the lower solar atmosphere. Numerical results based on realistic transition region physical parameters show that magnetic reconnections in a vertical turbulent current sheet consist of two stages, i.e., a first slow Sweet–Parker-like reconnection and a later rapid Petschek-like reconnection, where the latter fast reconnection phase seems a direct consequence of the initial slow reconnection phase when a critical state is reached. The formation of coherent plasmoid of various sizes and their coalescence play a central role in this complex nonlinear evolution. The “observed” values of the rate of cancellation flux as well as the approaching velocity of magnetic fragments of inverse polarity in present simulation are well consistent with the corresponding measurements in the latest observations. The difference between our turbulent magnetic reconnection two-step energy release model and other schematic two-step models is discussed and then possible application of present outcome to solar explosives is described. © 2005 American Institute of Physics. [DOI: 10.1063/1.1862249]

I. INTRODUCTION

Magnetic reconnection provides a convenient way of changing the topology of differently directed magnetic field lines, transporting mass across the field lines, and transferring the magnetic field energy to the energy of mass motions, heat, and plasma radiation on the Sun. The most well-known example is the solar flare, which has been believed to come from the fast magnetic reconnection in the corona. The corona, however, is far beyond the unique place where magnetic reconnection takes place. It has been realized that the lower solar atmosphere, i.e., the photosphere and chromosphere, is another region where magnetic reconnection may occur to generate observational consequences. The most compelling observational evidence may be the photospheric canceling magnetic features (CMFs), which display mutual apparent loss of magnetic flux of opposite sign at the polarity inversion line (PIL) as a common boundary. Moreover, efforts have been made to associate the low-lying magnetic reconnection processes with diverse energy release phenomena such as x-ray bright points, transition region explosive events, filament activation and eruption, flares, and coronal heating.

To achieve the relationship between photospheric magnetic reconnection and CMFs on the Sun, a Sweet–Parker-like reconnection model has been developed theoretically with parameters of the plasma in the neighborhood of the temperature minimum region about 600 km above the lower photospheric boundary. This local photospheric reconnection model combines the magnetic cancellation rate and the plasma inflow velocity in a current sheet with the magnetic field strength. However, an alternative possibility has also been suggested that the reconnection in the low atmosphere of the Sun is a Petschek-like fast type. The inflow and outflow speeds produced by the Petschek model are more compatible with the observational converging speed in the CMFs and the observed speeds of Hα/ extreme-ultraviolet (EUV) jets than those by the Sweet–Parker reconnection using the classical value of magnetic diffusivity. It is then argued that there is no preferred height for magnetic reconnection to take place and magnetic reconnection may occur at any different levels of the photosphere and chromosphere if an anomalously high resistivity is introduced.

On the other hand, parallel progresses have been made in the direction of reconciling the above conflicts. Many authors proposed schematic two-step magnetic reconnection models or concepts to explain the findings of close relationships among (1) magnetic flux cancellation seen from photospheric magnetograms, (2) chromospheric upflow events found in Hα line, and (3) transition region explosive events in UV lines. Consequently, these observations have been interpreted as a first low-lying, slow-mode reconnection taking place continuously in the photospheric atmosphere at a low temperature ($T \sim 10^4–10^5$ K), and a successive rapid reconnection occurring in the transition region or lower corona at higher temperature ($T \sim 10^6–10^7$ K) when a critical state is reached.

As far as the magnetic reconnection model involved in the complex process of solar magnetic energy release is concerned, new lights might be shed by the numerical and theoretical efforts on turbulent magnetic reconnection. It has been found recently with high resolution magnetohydrodynamic (MHD) simulations that turbulent magnetic recon-
nean possesses a dual nature in its nonlinear evolutionary process, i.e., the presence of MHD turbulence in large-scale current sheets can lead the reconnection to transfer from a Sweet–Parker-like slow reconnection to a Petschek-like fast reconnection. Generally speaking, turbulence is ubiquitous in solar MHD systems where the flow Reynolds number and magnetic Reynolds number are large enough. In this context, turbulent magnetic reconnection in solar atmosphere may contribute to the understanding of the related observations of solar energy release processes through photospheric magnetic field changes, transition region explosive events, and flares above the canceling magnetic features.

The paper is organized as follows. In Sec. II, we present the turbulent reconnection model and its related parameters in the lower solar atmosphere. In Sec. III, the speed of plasma inflow to the current sheet and the magnetic flux cancellation rate are then determined. Comparisons with typical properties of observations are also conducted. The last section is devoted to some discussions.

II. DESCRIPTION OF THE TURBULENT RECONNECTION MODEL

To address the two-step solar magnetic energy release process mentioned above, we use the turbulent magnetic reconnection model established recently in Ref. 16. However, the nondimensional MHD simulations reported there need to be extended to cover the circumstances in the lower solar atmosphere.

Consider an antiparallel Harris neutral current sheet $\mathbf{B}_0 = B_0 \tanh(y/L_0) \mathbf{e}_z$ forming initially by the horizontal photospheric converging flows that transport roughly vertical magnetic fields to the PIL. For simplicity the spatial structure of the field is assumed to be two-dimensional (2D) on a plane perpendicular to the solar surface, and all variables depend on coordinates $x$ and $y$ only. The notation is as follows: $L_2$, $2L_0$, and $2L$ are the length, thickness, and width of the current sheet; $\rho_0$, $T_0$, $L$ are the plasma density and temperature at $x = 0$ and $|y| > L_0$ (far from the current sheet).

In what follows, we determine the numerical values of the current sheet parameters based on appropriate order of magnitude through observations. The length of the current sheet along the PIL is infinite theoretically, but should have a finite value $L_2$ in a real situation, on the order of the common boundary size of the canceling fragments as they are interacting. The vertical dimension $L$ of the current sheet should be comparable to the atmospheric pressure scale height $\Lambda(z)$ in order to avoid disruption of the flow and magnetic field patterns in different parts of the sheet.\footnote{In view of the low-atmosphere reconnection ($\leq 2 \times 10^4$ km) under discussion, we take account of the significant differences in the plasma temperature and density from the well-known coronal magnetic reconnection at a high altitude ($> 10^5$ km) and adopt the realistic VAL-C model\cite{19} at a height of 1600 km above the solar surface. At this height the low temperature $T < 10^4$ K means a small plasma ionization, however, the ion-neutral collision frequency is high enough to ensure that the ionized and neutral plasma components are well coupled and move as a whole.\cite{20} The local reconnection magnetic field near the sheet, which is hard to determine from observations, is estimated reasonably to be tens of Gausses. Though the observed initial magnetic field strength of CMFs are as high as hundreds of Gausses,\cite{11,21} it has been found that explosive events rarely occur in the interior of strong magnetic flux concentrations, but rather are preferentially found in regions with weak and mixed polarity displaying magnetic neutral lines.\cite{7} Table I synthesizes the parameters used for the simulation. Then the plasma $\beta$ defined as $\beta = 2 \mu_0 \rho_0 / B_0^2$ is approximately equal to 0.1 and the Alfvén speed $V_A = B_0 / \sqrt{\mu_0 \rho_0}$ is about $3.5 \times 10^6$ m s$^-1$. The seed-level magnetic field turbulences are excited in the same way as that in Ref. 16.}

Table I. Characteristic values of mentioned physical quantities.

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<th>Notation</th>
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<tr>
<td>$L$</td>
<td>$1.0 \times 10^5$ m</td>
<td>$L_2$</td>
<td>$5.0 \times 10^6$ m</td>
</tr>
<tr>
<td>$T_0$</td>
<td>$6.5 \times 10^4$ K</td>
<td>$\rho_0$</td>
<td>$1.49 \times 10^{-9}$ kg m$^{-3}$</td>
</tr>
<tr>
<td>$\rho_0$</td>
<td>$9.33 \times 10^{-2}$ Pa</td>
<td>$B_0$</td>
<td>$1.5 \times 10^{-1}$ T</td>
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Afterwards, an improved high order Lax–Friedrichs total variation diminishing (TVD) finite difference model is used to solve the conservative compressible MHD equations.\cite{22} The rectangular computation box is $0 \leq x \leq 2L$, $-L/3 \leq y \leq L/3$ with uniform grids $N_x = 601$ and $N_y = 401$. Here we have prescribed that the ratio of the current-sheet width to thickness is equal to $L/l_0 = 15$. Such an assignment results in 6.7 km half thickness of the current sheet, almost comparable with the corresponding parameter about 1 km obtained in former analysis.\cite{10,11} There is no necessity to further reduce the current sheet thickness to the scale of the ion Larmor radius or the ion inertial length, both of which are on the order of 1 m in typical corona environment.\cite{23,24} Since the present turbulent magnetic reconnection model is free of the so-called spatially confined anomalous resistivity. In practice, all the calculations are carried out in dimensionless form. The uniformly distributed dimensionless resistivity is assigned 0.001. The calculation time is measured in units of the Alfvén time $\tau_A = l_0 / V_A$ and the interval of turbulent energy supply $\tau_f = 10$.

III. MODELING RESULTS AND APPLICATION TO EXPLOSIVE ENERGY RELEASE

With the turbulent magnetic reconnection model and the current sheet parameters described above, we are now in a position to address the possible two-step solar magnetic energy release process from the point of view of turbulent reconnections.

First of all, we examine some significant parameters characterizing the 2D MHD reconnection system, which can provide possible comparison with the latest observations. Figure 1 presents the temporal evolution of the magnetic reconnection rate, the reconnection outflow speed, and the rate of flux cancellation. The mean plasma bulk inflow speed in the top panel of Fig. 1 reads a small speed of hundreds of meters per second in the initial stage of the nonlinear evolution and a large one of several kilometers per second in the later development process. This latter large inflow speed in-
The jet speed of the Alfvén velocity of 35 km s\(^{-1}\) indicates a typical Petschek-like reconnection rate, about 0.08, if nondimensionalized with the local Alfvén speed specified. The maximum outflow velocity recorded in the +x direction in the mediate panel of Fig. 1 also illustrates two distinct ranges of values, a reading smaller than 10 km s\(^{-1}\) and a higher jet speed of the Alfvén velocity of 35 km s\(^{-1}\). The bottom panel of Fig. 1 demonstrates that the “observed” magnetic flux cancellation rate defined by \(d\Phi/dt = u_B L_x\) in the simulations first falls into a range of from \(4.0 \times 10^{12}\) to \(5.0 \times 10^{18}\) Mx h\(^{-1}\) and then increases to the order of \(1.0 \times 10^{19}\) Mx h\(^{-1}\).

In view of the features given above, it is interesting to note that some related observations supply solid evidences for the present MHD numerical results. For instance, in the study of the time evolution of two CMFs in the active region NOAA 8011 using the high resolution magnetograms taken by the Michelson–Doppler Imager (MDI) on board the Solar and Heliospheric Observatory,\(^{21}\) the observed rate and converging speed of flux cancellation in each feature are \(1.3 \times 10^{10}\) Mx h\(^{-1}\) and 350 m s\(^{-1}\) in the smaller case, and \(3.5 \times 10^{10}\) Mx h\(^{-1}\) and 270 m s\(^{-1}\) in the bigger one, respectively. These measured values could be easily associated with the first phase of the turbulent magnetic reconnection process in Fig. 1. Furthermore, analytical estimate results obtained by the Sweet–Parker-like model\(^{10,11}\) are well covered by the present simulation outcomes. Besides these two observational parameters, i.e., the magnetic cancellation rate and the inflow velocity in a current sheet, which have been focused on in previous theoretical models\(^{10,11}\) and data analysis,\(^{21}\) the simulated outflow speed first characterizes a motion around 15 km s\(^{-1}\), which is very close to the observed typical velocity of Hα upflow events, 20 km s\(^{-1}\),\(^{25}\) then accelerates up to the Alfvén velocity 35 km s\(^{-1}\). The latter value obtained in the second evolutionary phase of the turbulent reconnection is compatible with the observed speeds of Hα jets, in the range of 30–75 km s\(^{-1}\). Such observational evidences have been resorted to support the idea that low-lying reconnection might be of the Petschek-type in the theoretical analysis on chromospheric magnetic reconnection.\(^{12}\) Recall the duality of turbulent magnetic reconnection discovered before,\(^{16}\) i.e., the presence of MHD turbulence in large-scale current sheets can make the reconnection transfer from a Sweet–Parker-like slow reconnection to a Petschek-like fast reconnection, it is thus believed reasonably that the profiles in Fig. 1 suggest two stages of magnetic energy release during the evolution, corresponding to an initial slow reconnection phase and a later fast reconnection stage, though the identification of the exact boundary between the two stages is slightly arbitrary, as shown by \(t=100\tau_A\).

What accounts for the two-step magnetic energy release scenarios? Let us check the evolution of the magnetic field. Figure 2 shows three typical snapshots of the corresponding configuration, assuming that the magnetic field is derived from \(\varphi(x,y)\) by \(\mathbf{B} = \mathbf{V} \times \varphi \mathbf{z}\). The presence of turbulent magnetic field components has initiated many independent microreconnection events simultaneously. A set of magnetic coherent structures of different sizes, which are roughly centered along the background neutral sheet, have evolved at \(t=10\) (Fig. 2, the top panel). A fluctuation-induced, nonlinear instability makes contributions towards such kind of development with the preexisting finite fluctuations.\(^{26}\) Moreover, the system is intrinsically unstable because of the coalescence instability, as reported before.\(^{27}\) Magnetic island coalescences proceed slowly and steadily without any obvious deformation of the global configuration (Fig. 2, middle), responsible for the slow reconnection phase till then. After tens of Alfvén time, the persisting multiple coalescences enhance the reconnection. With the coalescence of another two islands in its embrace, a major plasmoid has been accelerated and ejected outwards at the speed of a substantial fraction of the Alfvén velocity, leading to an asymmetric Petschek-like fast reconnection configuration on account of a localization mechanism\(^{28}\) in this phase (see \(t=120\) in Fig. 2, the last
panel). It is then understandable that the transition from the initial slow reconnection to the later drastic fast reconnection development contributes to the establishment of a two-step magnetic energy release process, where the first slow phase is an essential stage that gives rise to the second rapid phase. The key point that should be stressed here is that the self-consistent interactions (positive feedback) between plasmoids of various sizes play the central role in such a complex evolution. This process may sometimes be related to the self-organized criticality reconnection or fractal reconnection\(^{29}\) and back part of the proposed scenario for fast reconnection through plasmoid-induced reconnection.\(^{30}\)

However, there are still some differences that are worth clarifying between the present model and the other schematic two-step magnetic reconnection models. On one hand, all models have attributed flux cancellation to a slow Sweet–Parker-like reconnection, which seems to be reasonable for their coincidence with the observations and measurements. On the other hand, in the proposed picture\(^{13}\) the second step fast magnetic reconnection takes places in the overlying field lines owing to the collision driven by the upward moving magnetic island. Our simulation results show that the second fast magnetic reconnection is a definite consequence of the turbulent magnetic reconnection in the original vertical current sheet when a critical state of the system is reached. Such a critical state is found to be mainly dependent on the initially added turbulence and insensitive to the variations of plasma \(\beta\) and resistivity in the previous parameter studies on turbulent magnetic reconnections.\(^{16}\) Nevertheless, it is of interest to point out that the vital role of the plasmoid ejection in the setup of the fast reconnection phase is essentially identical in both our model and the schematic model.\(^{13}\) The plasmoid outflow speed of 20 km s\(^{-1}\) mentioned above seems to support the \(\text{H}\alpha\) upflow events argued before,\(^{13,23}\) but we would rather consider the plasmoid ejections as bidirectional jets since they leave the computational box in both +\(x\) and −\(x\) directions. As the Alfvén velocity increases with atmosphere height due to the rapid decrease of plasma density, the final plasmoid ejection will coincide with the reported bidirectional jet structure with a speed of 100 km s\(^{-1}\).\(^{31}\) If the solar atmosphere stratified structure\(^{32}\) is taken into consideration for a bit longer vertical dimension than the present choice of 100 km, this conclusion will be more convincing. The present model does show fast Petschek-like reconnection to occur at many different levels of the lower atmosphere without any anomalous resistivity added, by avoiding not only the obligatory choice of the temperature minimum region as the preferential atmospheric height for magnetic reconnection\(^{4,10,11}\) but also the compulsory introduction of anomalously high value of magnetic diffusivity to model the fast magnetic reconnection in the chromosphere by early theoretical attempt.\(^{5}\)

Additionally, the present turbulent magnetic reconnection model provides a possible answer to the dilemma of the diffusion region size estimation. It is generally accepted that the steady Petschek model is a promising mechanism to explain the rapid energy release occurring in solar explosions, the estimated size of the diffusion region in this model would be extremely small whatever type resistivity (e.g., the classical Spitzer-type collision resistivity or anomalous resistivity caused by various plasma microscopic processes) is adopted. It is therefore speculated that there must be a mesosize scale where the MHD turbulence functions.\(^{33}\) A global current sheet less than the flare scale (but not extremely small) lies in the diffusion region of a flare. The global sheet contains many small magnetic islands and small thin current sheets of fractal natures exist between these structures. Magnetic reconnections may first arise in the smallest scale and then the size of islands expands. Finally the reconnection process grows up rapidly in the large scale. It is interesting to notice that the turbulent reconnection evolutions presented here also support this schematic model.\(^{33}\)

**IV. SUMMARY**

In this paper we have investigated a possible mechanism for the two-step solar magnetic energy release process on the basis of turbulent magnetic reconnection with realistic lower atmospheric parameters. The simulated results are found compatible with some important observational values including the canceling magnetic flux rate and the fragment approaching velocity. The dual nature of turbulent magnetic reconnection might account for the cancellation magnetic feature seen in lower atmosphere level and \(\text{H}\alpha/\text{EUV}\) jets observed at the transitional region height.

The present 2D MHD simulation with a simplified solar structure is satisfactory in that it provides a convincing picture of two-step solar magnetic energy release. Some remarks should be pointed out. First, the 3D effect of turbulence needs to be considered, since turbulent anomalous electron viscosity or hyperresistivity produced by tearing mode turbulence in 3D sheared magnetic fields may contribute to the interpretation of both fast reconnection and the heating of corona.\(^{34}\) Second, the present efforts have neglected the effect of thermal conduction and radiation, which will be necessary in the study of heating solar corona. Finally, it is of importance to identify the contribution of anomalous resistivity to the turbulent reconnection with thinner current sheet thickness, since it is conventionally convinced that microscopic plasma instability such as the lower hybrid drift instability, the electrostatic ion cyclotron instability, and the ion-acoustic instability might be excited among the numerous tiny current sheets during the system evolution.\(^{12,23,24}\) These considerations will be left in future work.

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