MAGNETIC RECONNECTION IN NON-EQUILIBRIUM IONIZATION PLASMA

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ABSTRACT

We have studied the effect of time-dependent ionization and the recombination processes on magnetic reconnection in the solar corona. Petschek-type steady reconnection, in which the magnetic energy is mainly converted at the slow-mode shocks, was assumed. We carried out the time-dependent ionization calculation in the magnetic reconnection structure. We only calculated the transient ionization of iron; the other species were assumed to be in ionization equilibrium. The intensity of line emissions at specific wavelengths was also calculated for comparison with Hinode or other observations in future. We found the following: (1) iron is mostly in non-equilibrium ionization in the reconnection region; (2) the intensity of line emission estimated by the time-dependent ionization calculation is significantly different from that determined from the ionization equilibrium assumption; (3) the effect of time-dependent ionization is sensitive to the electron density in the case where the electron density is less than 1010 cm−3; (4) the effect of thermal conduction lessens the time-dependent ionization effect; and (5) the effect of radiative cooling is negligibly small even if we take into account time-dependent ionization.

Key words: magnetohydrodynamics (MHD) – plasmas – shock waves – Sun: corona – Sun: flares – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Magnetic reconnection has been discussed as one of the important mechanisms for heating and bulk acceleration in astrophysical plasma, because the magnetic field energy can be rapidly released to the plasma during reconnection. One of the major aspects of magnetic reconnection is the rapid energy conversion of stored free magnetic energy to kinetic energy, thermal energy, non-thermal particle energy, and wave/turbulence energy. This energy conversion is fundamental and essential to the understanding of the dynamical behavior of plasma (e.g., Zweibel & Yamada 2009), not only in the solar atmosphere (e.g., Pneuman 1981) but also in Earth’s magnetosphere (e.g., Hones 1979; Nagai et al. 1998, 2001; Baumjohann et al. 1999; Øieroset et al. 2002; Imada et al. 2007b, 2008b), in the laboratory (e.g., Baum & Bratenahl 1974; Ono et al. 1988; Yamada et al. 1997; Ji et al. 1998), or in other astronomical objects. One of the goals for studying magnetic reconnection is to understand how much energy is converted toward plasma and what happens afterward. To answer this question, it is essential to observe the entire energy conversion in magnetic reconnection on a large scale continuously. The solar atmosphere is an excellent space laboratory for magnetic reconnection because of the observability of its magnetic reconnection on a large scale.

One of the most famous phenomena associated with magnetic reconnection is the solar flare. Modern telescope observations have confirmed many typical features expected from the magnetic reconnection model. These include cusp-like structure in X-ray images (e.g., Tsuneta et al. 1992), non-thermal electron acceleration (e.g., Masuda et al. 1994), chromospheric evaporation (e.g., Teriaca et al. 2003), reconnection inflow and outflows (e.g., Yokoyama et al. 2001; Innes et al. 2003), and plasmoid ejection (e.g., Ohyama & Shibata 1998). Recently the Hinode spacecraft was launched (Kosugi et al. 2007), and after first light Hinode has been revealing many new solar flare aspects.

The recent observation of magnetic reconnection in solar corona can be summarized as follows. The stored magnetic field energy in the corona before magnetic reconnection (e.g., Kubo et al. 2007; Magara & Tsuneta 2008), the energy release rate (e.g., Jing et al. 2008), and most forms of energy after magnetic reconnection (e.g., Imada et al. 2007a, 2008a; Asai et al. 2008; Minoshima et al. 2008, and references therein) can be estimated in detail. On the other hand, there is not enough observational knowledge of the physical parameters in the reconnection region itself. The inflow into the reconnection region, the temperature of the plasma in the reconnection region, and the fast Alfvénic flows predicted by reconnection have not been quantitatively measured sufficiently. Hinode and/or the Solar Dynamics Observatory (SDO) may provide some answers if solar cycle 24 ever produces a solar maximum. However, it is important to discuss why most observations cannot detect the predicted flow or temperature in the reconnection region. One of the reasons why we cannot observe inside the magnetic reconnection region is its darkness. Generally we can see the bright cusp-like structure during the solar flare, although the reconnection region, which might be located above the cusp-like structure, is faint. Recently, Imada et al. (2011a) have pointed out that ionization cannot reach equilibrium in the magnetic reconnection region because of its fast flow and rapid heating. Actually, the timescale for ionization (∼100 s) is comparable to the Alfvén timescale (∼100 s) in the magnetic reconnection region. The reconnection region might be much fainter than we expected in some cases. Therefore, it is important to take into account the time-dependent ionization process when we interpret the observation of the magnetic reconnection region.

So far, most of the solar observations are discussed with the assumption of ionization equilibrium. Non-equilibrium ionization was mainly discussed in the category of coronal heating or solar wind formation. Dupree et al. (1979) discussed the general characteristics of the ionization balance in the solar
transition region and corona when mass outflow is present. They found that the large temperature gradient within the flow can result in a departure from ionization equilibrium. Recently, Imada et al. (2011b) have also discussed the time-dependent ionization in the dimming region where the large mass flows were observed. They claimed that the ionization equilibrium assumption in the dimming region is violated especially in the higher temperature range (\sim 2 MK). Mariska et al. (1982) examined the hydrodynamic numerical modeling of an ionization state in nanoflare-heated loops and concluded that non-equilibrium ionization can significantly alter the relative ionic abundances in the quiet Sun. Hydrodynamic modeling of the ionization states in nanoflare-heated loops has been studied intensively during several decades, and most results indicate the importance of non-equilibrium ionization in the context of not only comparison with observations (e.g., Reale & Orlando 2008) but also plasma dynamics itself (e.g., Bradshaw & Mason 2003). Recently, modeling of time-dependent ionization in a post-coronal mass ejection current sheet has also been studied by Ko et al. (2010) and Murphy et al. (2011), and they discussed the consistency between the modeling results and the observation. As for the observation, non-equilibrium ionization was studied by using line spectroscopy. Kato et al. (1998) studied the time evolution of spectra of He-like Ca XII and Fe XXIV observed by Yohkoh/Bragg Crystal Spectrometer for a solar flare and found that the plasma is considered to be an ionizing plasma even in the decay phase of the flare. Imada et al. (2009) discussed the ion thermal temperature (not apparent ion temperature) in an active region from two emission lines of different atomic species (Fe XVI and S XIX) observed by the EUV Imaging Spectrometer (EIS) on board Hinode, and they found that the electron temperature estimated from ionization equilibrium assumption is different from ion thermal temperature in some parts. They claimed that the result may indicate the presence of ionizing plasma.

In this paper, we focus on the effect of time-dependent ionization processes on magnetic reconnection by numerically treating the ionization and recombination process in Petschek-type steady magnetic reconnection (Petschek 1964). This paper is organized as follows. In the next section, the models and assumptions that we used in our calculation are given. Section 3 is devoted to the results of the time-dependent ionization and its radiation under four of magnetic reconnection conditions. Summary and discussion are given in Section 4.

2. MODELING

2.1. Petschek Reconnection Model

We have studied the effect of the time-dependent ionization processes on magnetic reconnection. Petschek-type steady reconnection was assumed in our study (Figure 1). In this model, the magnetic energy is mainly converted at the slow-mode shocks which extend from the X-line. We defined the size of the calculation box as $200 \times 20 \times 200$ Mm$^3$, and the outside of the box was assumed to be vacant. The magnetic reconnection X-line is located at $(x,y) = (0,0)$, and the slow-mode shocks are extended from the X-line. We assumed that the upstream and downstream of the slow-mode shocks are uniform in temperature and density. We also assumed all ions and electron have the same flow speed and temperature at the same location. Further, the ion on the not-reconnected magnetic field is assumed to be in ionization equilibrium. The reconnection plane is in the $x-y$ plane, and the depth of reconnection is assumed to be 200 Mm.

Figure 1. Schematic illustration of Petschek-type steady magnetic reconnection. Dotted lines show magnetic fields and SS are slow-mode shocks. $\theta_1$ and $\theta_2$ show the shock angles of upstream and downstream, respectively. (a) Entire structure and (b) the relationship between the shock angle and the entire structure.

The reconnection structure is uniform in the $z$-direction. We calculated the shock jump condition using the following standard one-dimensional steady MHD conservation laws in the deHoffmann–Teller frame, in which the electric fields vanish outside the shock (e.g., Hau & Sonnerup 1989):

\[
[\rho v_n] = 0, \tag{1}
\]

\[
\left[ \rho v_n^2 + p + \frac{B_z^2}{2\mu_0} \right] = 0, \tag{2}
\]

\[
\left[ \rho v_n v_1 - \frac{B_n B_1}{\mu_0} \right] = 0, \tag{3}
\]

\[
\left[ \frac{\gamma}{\gamma - 1} \frac{p}{\rho} + \frac{1}{2} \left( v_n^2 + v_1^2 \right) \right] = 0, \tag{4}
\]

where $\rho$, $v$, $p$, $B$, and $\gamma$ are density, velocity, pressure, magnetic field, and specific heat ratio, respectively. The subscripts “1” and “n” denote tangential and normal to the shock, respectively. The square brackets are the usual notation for the difference between the two sides of the discontinuity. Once the conditions in the upstream and downstream of the slow-mode shock are determined, its location and reference frame are also determined in the reconnection region by $y = \pm \tan \theta_2 x$, where $\theta_2 (= \arctan(B_{z2}/B_{n2}))$ is the shock angle in the downstream (see Figure 1(b)). The subscripts 1 and 2 denote upstream and downstream, respectively. Afterward, the temperature, density, velocity, and magnetic field are also determined in the entire structure. We have examined the four cases of reconnection conditions to discuss the effect of time-dependent ionization. Table 1 shows the jump conditions of the slow-mode shocks in the reconnection region. The jump condition can be solved as follows: (1) assume the upstream density ($N_1$), temperature ($T_1$), shock angle ($\theta_1$), and plasma beta ($\beta_1$), and specific heat ratio ($\gamma$); and (2) define the inflow velocity by the assumption that the outflow velocity is equal to Alfvén velocity of upstream. Our assumptions about the upstream plasma condition are from past observations (e.g., Tsuneta 1996; Tsuneta et al. 1997). We will discuss the density dependence with Runs1–3 and the...
Inflow velocity, and specific heat ratio are 109 cm$^{-1}$. The upstream density, temperature, shock angle, plasma beta, thermal conduction effect with Run4. In Run1, we assumed that the upstream density, temperature, shock angle, plasma beta, inflow velocity (km s$^{-1}$), specific heat ratio, upstream magnetic field (G), downstream density (cm$^{-3}$), downstream temperature (MK), downstream shock angle (degree), and outflow velocity (km s$^{-1}$), respectively. These are normal values for ambient plasma in the solar corona. The other values in Run1 were derived from Rankine–Hugoniot relations. The electron densities in Run2 and Run3 are different from Run1. Most of the other values are the same as Run1. In Run4 we simulated the isothermal shock condition by setting $γ \sim 1$. The plasma beta in Run4 is 40 times larger than in Run1, because temperature in the upstream region is increased by thermal conduction. Although the other values in Run4 are also different from Run1, these values are normal values observed in solar flares.

### 2.2. Non-equilibrium of Ionization

To study the effect of transient ionization on magnetic reconnection, we have calculated the time evolution of ion charge states. There are many kinds of atomic species in solar corona, and they mainly radiate line emission in the ultraviolet wavelength range by the bound–bound process. The most dominant element for radiation is iron at coronal temperatures (a few MK); thus, most of the radiative energy loss is from iron line emission. Further, the recent space telescopes such as Hinode/EIS or SDO/Atmospheric Imaging Assembly mainly observe the emission lines from iron (e.g., Fe xi 171 Å or Fe xii 195 Å). Therefore, we concentrated on the time-dependent ionization of iron in this paper.

![Figure 2. Example of time-dependent ionization in magnetic reconnection (Run1). Time starts from shock crossing. The calculation was carried out in the plasma comoving frame.](image)

(A color version of this figure is available in the online journal.)

| Run | $N_1$ | $T_1$ | $θ_1$ | $β_1$ | $V_i$ | $γ$ | $B_1$ | $N_2$ | $T_2$ | $θ_2$ | $V_o$ |
|-----|-------|-------|-------|-------|------|-----|------|-------|------|-------|------|
| 1   | $10^9$ | 1.5   | 85    | 0.02  | 137  | 5/3 | 22.8 | $2.45 \times 10^9$ | 31.3 | 5.2   | 1560 |
| 2   | $10^{10}$ | 1.5   | 85    | 0.02  | 137  | 5/3 | 72.1 | $2.45 \times 10^{10}$ | 31.3 | 5.2   | 1560 |
| 3   | $10^8$  | 1.5   | 85    | 0.02  | 137  | 5/3 | 7.2  | $2.45 \times 10^8$  | 31.3 | 5.2   | 1560 |
| 4   | $10^9$  | 1.5   | 85    | 0.02  | 137  | 5/3 | 15.2 | $2.45 \times 10^9$  | 15.2 | 5.2   | 780  |

Notes. $N_1$, $T_1$, $θ_1$, $β_1$, $V_i$, $γ$, $B_1$, $N_2$, $T_2$, $θ_2$, and $V_o$ are upstream density (cm$^{-3}$), upstream temperature (MK), upstream shock angle (degree), upstream plasma beta, inflow velocity (km s$^{-1}$), specific heat ratio, upstream magnetic field (G), downstream density (cm$^{-3}$), downstream temperature (MK), downstream shock angle (degree), and outflow velocity (km s$^{-1}$), respectively.

The continuity equations for iron are expressed as follows:

$$\frac{\partial n_i^{Fe}}{\partial t} + \nabla \cdot n_i^{Fe} \mathbf{v} = n_e \left[ n_i^{Fe} n_i^{Fe} + n_i^{Fe} n_{i-1}^{Fe} S_i^{Fe} - n_i^{Fe} \left( \alpha_i^{Fe} + S_i^{Fe} \right) \right],$$

where $n_i^{Fe}$ is the number density of the $i$th charge state of the iron, $\alpha_i^{Fe}$ represents the collisional and dielectronic recombination coefficients, and $S_i^{Fe}$ represents the collisional ionization coefficients. The ionization and recombination rates were calculated using the work of Arnaud & Rothenflug (1985), Arnaud & Raymond (1992), and Mazzotta et al. (1998). Here we assumed that all ions and electrons have the same flow speed and temperature in the same upstream location. Note that the ions just across the slow-mode shocks still have the charge state distributed at the coronal temperature, although the temperature has already jumped up to the downstream value ($T_2$). The ionization and recombination coefficients ($\alpha$ and $S$) strongly depend on temperature and weakly depend on density. The timescale for ionization and recombination is proportional to $n_i^{-1}$ (see Equation (5)).
the ionization equilibrium timescales are changed to $10^2$ and $10^3$ s, respectively (not shown here).

2.3. Thermal Conduction and Radiative Cooling

Thermal conduction and radiative cooling govern the evolution of the electron temperature in the downstream of the slow-mode shocks. It is generally believed that the thermal conduction effectively works in the reconnection region because of its nonlinearity (e.g., Yokoyama & Shibata 1997, 2001). Heat conductivity increases with increasing temperature nonlinearly ($\propto T^{3/2}$). The thermal conduction is anisotropic, working only along the magnetic field line. Therefore, the slow-mode shocks in the reconnection become isothermal shocks owing to the thermal conduction. Thermal conduction is a time-dependent process, and we need to solve the time-dependent energy equation. Actually, the thermal conduction front is propagating along the magnetic field with finite time. However the heating at the slow-mode shock is very strong, and the electron thermal velocity ($\sim 10,000$ km s$^{-1}$) is sufficiently faster than the typical velocity of reconnection outflow ($\sim 1000$ km s$^{-1}$) such that we can neglect the finite time of propagation of the thermal conduction front (see Figure 2 in Yokoyama & Shibata 1997). Thus, we simply solve the isothermal shock condition by setting $y \sim 1$ instead of solving the time-dependent energy equation directly. We will discuss the effect of thermal conduction in Section 3.2.

The radiative cooling timescale is relatively long compared with the dynamical timescale of a solar flare. Therefore, it is generally believed that radiative cooling does not affect the entire plasma dynamics of the solar flare. The radiative cooling process can contribute the dynamics of post flare loops. On the other hand, it is interesting to estimate to what extent time-dependent ionization can affect the radiative cooling process. Therefore, we assumed that the radiative cooling cannot affect the slow-mode shock condition or plasma dynamics in the downstream, but only that the electron temperature is changing by radiative cooling in the plasma comoving frame as described in the following equation:

$$\frac{\partial T_e}{\partial t} = -\frac{2}{3k_B} n_e \Lambda(T_e), \quad (6)$$

where $k_B$ is the Boltzmann constant and $\Lambda(T_e)$ is the radiative energy loss function. We neglected the energy exchange between ions and electrons. This process might calm down the cooling of electrons. In that sense, we might overestimate the effect of radiative cooling by a factor of $\sim 2$ in Equation (6). Note that we assumed all ions and electrons have the same temperature. We distinguish them only in the case of evaluating the radiative cooling effect with Equation (6). We calculate the radiative energy loss function by CHIANTI atomic database 6.0 (e.g., Dere et al. 2009), but with ionic fractions of iron calculated by Equation (5). Although $\Lambda(T_e)$ also depends weakly on the electron density, we neglect the density dependence and assumed the electron density is $10^{10}$ cm$^{-3}$. The radiative cooling includes bound–bound, bound–free, and free–free processes. The dominant radiative process in the solar corona is bound–bound emission, which we have already mentioned above. Because bound–bound emissions are heavily affected by the ionic fraction, the radiative cooling may be sensitive to the time-dependent ionization process. The ions are most likely in non-equilibrium ionization in the downstream of the slow-mode shocks (Figure 2). We assumed all the elements except iron are in ionization equilibrium, because most radiative energy loss is from iron in coronal plasma. We used the usual coronal abundance in Feldman (1992) to estimate the line emissions. We will discuss the effect of time-dependent ionization on the radiative cooling process in Section 3.3.

2.4. Line Emissions in Ultraviolet

It is useful to calculate the intensity of line emission at specific wavelengths for comparison with the recent modern observations. We selected the strong emission lines, which are sensitive to the hot component such as solar flare plasma in ultraviolet wavelength. Table 2 shows the lines used in our study. We also calculated Fe xii to monitor the plasma in the upstream of the slow-mode shocks. In a low-density plasma such as the solar corona, the processes that populate and depopulate the excited levels of an ion are generally much faster than the processes that are responsible for ionization and recombination. Thus, we assumed that level populations are always in equilibrium in each plasma condition. We calculated each line emission by CHIANTI atomic database 6.0 with ionic fraction estimated by Equation (5). Further we assumed that the contribution functions do not depend on density, because the dependences are very small in our situations.

3. RESULTS

3.1. Standard Petschek-type Magnetic Reconnection

Figure 3 shows the intensities of the specific wavelength in the magnetic reconnection region (Run 1). The horizontal axis shows $x$, and the vertical axis shows $y$ in Figure 1. The colors show the intensities of Fe xii, Fe xviii, Fe xix, Fe xx, Fe xxi, Fe xxii, and Fe xxiv (Table 2). We show the results only in $x > 0$. The magnetic reconnection X-line is located at $(x, y) = (0, 0)$ and the pair of slow-mode shocks is extended from the X-line. The results of time-dependent ionization are shown in $y > 0$. We also show the results of ionization equilibrium in $y < 0$ for comparison. The line-of-sight (LOS) depth is assumed to be 200 Mm, and the intensities linearly depend on LOS depth. Note that the thermal conduction or radiative cooling effects are not included in this calculation.

We can clearly see that there are typically two regions, which are bright and dark, in the result of Fe xii. The boundaries for bright and dark regions correspond to the location of the slow-mode shocks. The ionization timescale for Fe xii at $T_e = 31.3$ MK is very short (see Figure 2). Therefore, the difference between equilibrium ($y < 0$) and non-equilibrium ($y > 0$) is not clear. The bright broad linear structures can be seen from Fe xviii to Fe xxii only in non-equilibrium results. These linear structures are parallel to the slow-mode shocks. The ionization timescales for those ions are longer than that for Fe xii. Therefore, the ions, which are still ionizing, are advected

| Table 2 |
|---|
| **Emission Lines** |
| Line | Wavelength (Å) | $\log_{10} T_{\text{em}}$ (K) | Transition |
| Fe xii | 195.12 | 6.2 | 3s2 3p3 4S3/2 → 3s2 3p2 3P3/2 |
| Fe xviii | 974.86 | 6.9 | 2s2 2p5 2P3/2 → 2s2 2p5 2P1/2 |
| Fe xix | 592.24 | 7.0 | 2s2 2p4 3P2 → 2s2 2p4 1D2 |
| Fe xx | 721.56 | 7.1 | 2s2 2p3 4S3/2 → 2s2 2p3 2D3/2 |
| Fe xxi | 786.16 | 7.1 | 2s2 2p2 3P2 → 2s2 2p2 1D2 |
| Fe xxii | 135.79 | 7.1 | 2s2 2p 4P3/2 → 2s2 2p 2P3/2 |
| Fe xxiii | 132.91 | 7.2 | 2s2 1S0 → 2s 1P1 |
| Fe xxiv | 192.03 | 7.2 | 1s2 2s 2S1/2 → 1s2 2p 2P3/2 |
by the fast outflow (\(\sim 1500 \text{ km s}^{-1}\)) toward the deep downstream of the slow-mode shocks. For example, in Figure 2 the Fe\textsubscript{XIX} population can achieve a peak in 10 s (15 Mm) and reduce down to less than 0.1% within 100 s (100 Mm). On the other hand, we cannot see any line emissions in the case of ionization equilibrium results. The electrons are heated by crossing the slow-mode shocks, and at the same time and place the ions are ionized and achieve ionization equilibrium in \(y < 0\) of Figure 3. In the ionization equilibrium condition, the population of Fe\textsubscript{XVIII} to Fe\textsubscript{XXII} is less than 1%. Thus the emissions from those ions are negligibly small. For Fe\textsubscript{XXIII} and Fe\textsubscript{XXIV} emissions in non-equilibrium conditions are stronger than they are in equilibrium conditions. The peak ionic population for those ions is achieved in \(\sim 50\) s. The flow transit timescale of our calculation box is also \(\sim 50\) s. Therefore, the ionic fractions of Fe\textsubscript{XXIII} and Fe\textsubscript{XXIV} are almost at the peak, and the emissions are very strong.

The ionization timescale is proportional to the electron density. Therefore the high-density condition causes the lessening of the time-dependent ionization effect. Figure 4 shows the emissions under relatively high-density conditions (Run2). The figure format is the same as Figure 3. Note that the color scale is 100 times higher than that in Figure 2, because the intensity itself is proportional to \(n_e^2\). The bright linear structures in Figure 4, from Fe\textsubscript{XVIII} to Fe\textsubscript{XXII}, become narrower than that in the case of \(N_1 \sim 10^9 \text{ cm}^{-3}\). The ionization timescale in the high-density plasma (\(N_1 = 10^{10} \text{ cm}^{-3}\)) is one-tenth of that in Run1, although the dynamical timescale does not change. Therefore, the ions can achieve ionization equilibrium on a shorter spatial scale than the ions in Run1. We can clearly see that most of the intensity is the same between \(y > 0\) and \(y < 0\). This indicates that the ionization timescale is very short compared with the dynamical timescale in Run2. The difference between \(y > 0\) and \(y < 0\) can be seen only around the slow-mode shocks.

It is plausible that the low-density condition causes the strengthening of the time-dependent ionization effect. Figure 5 shows the result of transient ionization in the low-density plasma (\(N_1 = 10^8 \text{ cm}^{-3}\), Run3). In the low-density condition, the emissions from Fe\textsubscript{XXI} to Fe\textsubscript{XXIV} are quite small in the time-dependent ionization results. The emissions from Fe\textsubscript{XVIII} to Fe\textsubscript{XX} are strong, because the ionic fraction is roughly around the peak in our calculation box. Further, we can clearly see the enhancement of Fe\textsubscript{XII} emissions in the result of time-dependent ionization, which cannot be seen in Runs 1 and 2. This enhancement is caused by the compression at the slow-mode shock. The density in the downstream of the slow-mode shocks is \(\sim 2.5\) times as much as the density in the upstream. The same enhancement should occur even in Runs 1 and 2, though the ionization timescale is too short to detect the enhancement of Fe\textsubscript{XII}.

We discussed the time-dependent ionization effect in the \(x-y\) plane (reconnection plane, Figure 1(a)) with Figures 3–5. It is useful to change the LOS direction to be parallel to the \(x\)-axis. We assumed all physical values are uniform in the

Figure 3. Intensities of Fe\textsubscript{XII}, Fe\textsubscript{XVIII}, Fe\textsubscript{XIX}, Fe\textsubscript{XX}, Fe\textsubscript{XXI}, Fe\textsubscript{XXII}, Fe\textsubscript{XXIII}, and Fe\textsubscript{XXIV} from the magnetic reconnection region (Run1). The time-dependent ionization results are shown in \(y > 0\), and the results with ionization equilibrium are shown in \(y < 0\). Note that the aspect ratio of the figure is different from the real scale.

(A color version of this figure is available in the online journal.)
Figure 4. Result of Run2 (high-density condition, $N_1 = 10^{10} \text{ cm}^{-3}$). The figure format is the same as Figure 3.
(A color version of this figure is available in the online journal.)

Figure 5. Result of Run3 (low-density condition, $N_1 = 10^8 \text{ cm}^{-3}$). The figure format is the same as Figure 3.
(A color version of this figure is available in the online journal.)
Figure 6. Spatial variations of intensity in the \( y \)-direction. The horizontal axis shows \( y \), and the vertical axis shows the intensity of each line emission integrated along the LOS (\(-100 < x < 100\)). The LOS direction is parallel to the \( x \)-axis. The time-dependent ionization results are shown in \( y > 0 \), and the results with ionization equilibrium are shown in \( y < 0 \). The spatial distribution of Fe \( x \text{ii} \) is not much different between non-equilibrium and equilibrium ionization, because the ionization timescale is very short. On the other hand, from Fe \( x \text{viii} \) to Fe \( x \text{xxiii} \), the intensity calculated from our time-dependent ionization is stronger than that calculated with the ionization equilibrium assumption for the most part. The intensity of Fe \( x \text{xiv} \) is roughly the same in both cases, although the gradient decreasing from the peak is much steeper in the non-equilibrium ionization results.

It is useful to display the line spectrum radiated from the reconnection region to compare with recent flare observations. Figure 7 shows the line spectrum of Fe \( x \text{xiv} \) along \( y = 0 \) in Figure 6. The horizontal axis shows the wavelength, and the vertical axis shows the spectral intensity. The line center position for stationary Fe \( x \text{xiv} \) is represented by dashed lines. The line width is determined only by the thermal velocity of the ions. Although in actual observation the instrumental or non-thermal width can contribute to broadening the line spectrum, we neglect them for simplicity. The two line components of Fe \( x \text{xiv} \) can be seen around 191 and 193 Å, because of the bi-directional fast reconnection outflows (1500 km s\(^{-1}\)). The line components are completely separated, because the thermal velocity is sufficiently small compared with the reconnection outflow.

3.2. Thermal Conduction

In Section 3.1, we neglect thermal conduction along the magnetic fields in the reconnection region. It is generally believed that the slow-mode shocks in the reconnection become isothermal shocks owing to the thermal conduction (Yokoyama & Shibata 1997, 2001). Thermal conduction is a time-dependent process, and we need to solve the time-dependent energy equation. We simply solve the isothermal shock condition by setting \( \gamma \sim 1 \) instead of solving the energy equation directly. The shock jump conditions are those shown for Run4 in Table 1. In this calculation, the outflow velocity is relatively slow (780 km s\(^{-1}\)), because the Alfvén velocity in upstream is slower than that in Runs1–3.

Figure 8 shows the emissions from the magnetic reconnection region, which includes the thermal conduction effect. We also take into account the time-dependent ionization process in this figure. We can also see that there are bright and dark regions in Fe \( x \text{ii} \). The boundary for bright and dark regions corresponds to the magnetic field, which connects to the magnetic reconnection X-line (magnetic separatrix). The electrons upstream of the slow-mode shock are also heated up to 15 MK, the ionization process can proceed even in the upstream. The slow-mode shock in Figure 8 is located in the same position in Figure 3. We can clearly see the hot plasma between the magnetic separatrix and the slow-mode shock, the so-called thermal halo, from Fe \( x \text{viii} \).
Imada et al.

Figure 8. Result of time-dependent ionization in the magnetic reconnection region with the thermal conduction effect (Run4).

(A color version of this figure is available in the online journal.)

Figure 9. Spectral intensity of Fe\textsuperscript{xxiv} along $y = 8.5$ in Figure 8.

to Fe\textsuperscript{xxiv}. The intensity downstream of the slow-mode shock
is strong and the ionization proceeds much faster owing to the
density compression at the slow-mode shock.

It is useful to display the line spectrum from the reconnection
with thermal conduction. Figure 9 shows the line spectrum of
Fe\textsuperscript{xxiv} along $y = 8.5$ in Figure 8. The figure format is the
same as Figure 7. The two line emissions of Fe\textsuperscript{xxiv} can be
seen around 191.5 and 192.5 Å, because of the bi-directional
fast reconnection outflows (780 km s\textsuperscript{-1}) in Run4. The emissions
from the “thermal halo” also can contribute to the line profile,
and we can clearly see the stationary component in Fe\textsuperscript{xxiv}.
Even in Run4 the line components are completely separated,
because the thermal velocity is sufficiently small compared with
the reconnection outflow.

3.3. Radiative Cooling

To understand to what extent time-dependent ionization
can affect the radiative cooling process, we calculate the
time evolution of the radiative energy loss rate and electron
temperature with the time-dependent ionization in the magnetic
reconnection region. Figure 10 shows the radiative energy
loss rate and electron temperature along $y = 0$ in Run1.
The horizontal axis shows the distance from the X-line, and
the vertical axis shows the radiative energy loss rate and
electron temperature. The solid lines show the results with
the time-dependent ionization process, and the dashed lines
show the results with the ionization equilibrium assumption.
In this calculation, electron temperature varies with time even
after crossing the slow-mode shock. This naturally causes
the ionization and recombination coefficients ($\alpha$ and $S$) to
vary with time. Therefore, in this calculation we need to
solve the time-dependent ionization coupled with radiative cooling.

The radiative energy loss rate estimated by the time-dependent ionization calculation is much larger than that calculated with the ionization equilibrium assumption everywhere in the reconnection region. In the non-equilibrium ionization case, the radiative energy loss rate is peaked around $x = 5 \text{ Mm}$ and the absolute value is $1.4 \times 10^{-22} \text{ erg s}^{-1} \text{ cm}^{-3}$. On the other hand, in the ionization equilibrium case, the radiative energy loss rate is almost flat and the absolute value is $2.8 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-3}$. Therefore, the effect of radiative cooling can be stronger in the case that time-dependent ionization is taken into account; however, the cooling itself is very weak. The cooling timescale (for example, $\delta t = 3k_B T_e/2n_e\Lambda \sim 6 \text{ hr}$ at $T_e \sim 30 \text{ MK}$, $n_e = 3 \times 10^9 \text{ cm}^{-3}$, $\Lambda = 10^{-22} \text{ erg s}^{-1} \text{ cm}^{-3}$) is still much longer than the Alfvén timescale ($100 \text{ s}$). Therefore, the cooling of electron temperature is negligibly small even in the case of non-equilibrium conditions. One may think that the radiative cooling effectively works in the high-density condition, such as $N_1 \sim 10^{10} \text{ cm}^{-3}$; however, even under such a condition the radiative cooling effect is still weak. We will discuss this point later.

4. SUMMARY AND DISCUSSION

We have studied the effect of time-dependent ionization and recombination on magnetic reconnection in the solar corona. We assumed the Petschek-type steady reconnection and calculated the time-dependent ionization in the magnetic reconnection structure. We found that ion is mostly still ionizing downstream of the slow-mode shocks. The intensity of line emissions estimated by the time-dependent ionization calculation is significantly different from that estimated by the ionization equilibrium assumption. We also found that the effect of time-dependent ionization is sensitive to the electron density in the case that the electron density is less than $10^{10} \text{ cm}^{-3}$. We also studied the effect of thermal conduction on the ionization process in the reconnection region. We found that thermal conduction caused the lessening of the time-dependent ionization effect, because the ionization process can proceed even upstream of the slow-mode shocks. The faint “thermal halo” can also be observed in the calculation with the thermal conduction, and the observed entire structure is significantly different from that without thermal conduction. The radiative energy loss in the non-equilibrium ionization plasma is also discussed. The effect of radiative cooling is negligibly small even if we take into account time-dependent ionization.

Recently, much work has been done about the atomic database. One of the main advances is the updating of recombination rate coefficients for bare through Na-like ions (e.g., Bryans et al. 2006). The ionization rate coefficients are also updated in part (e.g., Dere 2007). The update of the atomic database may affect our results to some extent. The ionic abundances in the ionization equilibrium might be changed. However, in our situation, the ionization rate coefficients are significantly larger than the recombination rate coefficients. Thus the effect of the recent update of the atomic database is limited in our case.

Let us discuss the difference between the time-dependent ionization calculation results with and without thermal conduction. In Figure 3 (without thermal conduction) we can clearly observe the linear structure which is parallel to the slow-mode shocks. Because the density and temperature can only vary when the plasma crosses the slow-mode shocks, the same ionization degree is parallel to the slow-mode shocks. On the other hand, in Figure 8 (with thermal conduction), the ionization can proceed even in the upstream. Thus, the same ionization degree is no longer parallel to the slow-mode shocks. To discuss the difference between the calculation results with and without thermal conduction quantitatively, we define the ionization degree as follows,

$$
\tau_{(x,y)} \equiv \sum_i \frac{L_i}{v_i n_i} \frac{n_1}{n_1}.
$$

where $\tau$, $L_i$, $v_i$, and $n_i$ are ionization degree, length along the streaming line, velocity, and density in the i-th region, respectively. Note that our definition can only apply in the case where the temperature is uniform in every i-th region. Only the density can be different in each region. The duration of ions staying in the i-th region is represented by $L_i/v_i$ in Equation (7). Because the ionization timescale is proportional to $n^{-1}$, we normalized i-th density by the upstream density. The schematic illustration of our variables in Petschek reconnection configuration is at the top of Figure 11. We also defined the inclination of the magnetic separatrix and the slow-mode shock as $\phi_1$ and $\phi_2$, respectively. We can derive $L_i$ from the simple geometrical information in Figure 11(a). By using Equation (7), we can simply derive the contour of the same ionization degree ($\tau_{(x,y)}$) in the downstream of the slow-mode shock (without thermal conduction) as follows:

$$
y = \tan \phi_2 \left(x - \frac{n_1}{n_2} \tau \right).
$$

The slope in Equation (8) is the same as the inclination of the slow-mode shock ($\tan \phi_2$). Thus, the same ionization degree is parallel to the slow-mode shocks (Figure 11(b)). Let us move to the result with the thermal conduction. In the same way as Equation (8), we can also derive the contour as follows:

$$
y = \left( \frac{1}{\tan \phi_2} - \frac{n_1}{n_2} \sin \phi_1 \right)^{-1} \left( x - \frac{n_1}{n_2} \tau \right)
$$

for downstream

$$
y = \tan (\phi_1 + \phi_2) \left(x - \frac{1}{\sin(\phi_1 + \phi_2)} \frac{n_1}{n_2} \tau \right)
$$

for thermal halo.

We can find that the slope in Equation (9) for the downstream of the slow-mode shock is much steeper than that in Equation (8). For the “thermal halo,” the slope in Equation (9) is the same as that of the magnetic separatrix ($\tan \phi_2$). Although the slope for the downstream is slightly steeper than that for the “thermal halo,” the difference between them is negligibly small. Thus, the same ionization degree is roughly parallel to the magnetic separatrix both downstream and in the “thermal halo” (Figure 11(c)). We assumed $\gamma \sim 1$ instead of solving the energy equation directly to include the thermal conduction effect. The inclination angle of “thermal halo” might be slightly modified when we solve the energy equation directly. Because the thermal conduction front is propagating with finite time, the boundary of “thermal halo” will be slightly moved from the magnetic separatrix toward the slow-mode shock.

In Section 3.3, we discussed the radiative cooling effect with time-dependent ionization in the magnetic reconnection region. We concluded that the effect is negligibly small in the coronal magnetic reconnection ($n_1 = 10^9 \text{ cm}^{-3}$) even if we take account
Figure 11. Schematic illustration of ionization in magnetic reconnection without and with thermal conduction. (A color version of this figure is available in the online journal.)

(a) Petschek Reconnection

(b) Without Thermal Conduction

(c) With Thermal Conduction

Figure 12. Spatial variation of the radiative energy loss rate and electron temperature in the downstream of the slow-mode shock with the assumption that the iron abundance is 100 times higher than that typically observed in the average corona. The figure format is the same as Figure 10.

It is useful to estimate how the radiative cooling can be enhanced due to anomalies in elemental abundance, which are often observed during solar flares (e.g., Feldman & Widing 1990). Figure 12 shows the variation of the radiative energy loss rate and electron temperature with the assumption that the iron abundance is 100 times higher than the typical observed in the average corona. The figure format is the same as Figure 10. The radiative loss rate is enhanced 100 times because of the anomalous iron abundance. The electron temperature can be cooled down to ∼25 MK in the case of non-equilibrium. Even in the extreme case, the radiative cooling does not affect much the dynamics of magnetic reconnection. Therefore, we can conclude that the radiative cooling cannot affect reconnection dynamics even if we take into account time-dependent ionization in most coronal conditions.

In this paper, we used several assumptions. For example, Petschek-type magnetic reconnection, \( T_i = T_e \), and fast thermal conduction. There are some discussions that Petschek reconnection is unstable unless resistivity increases at the reconnection site (Kulsrud 2001; Zweibel & Yamada 2009). Recently, the effect of the \( T_i \neq T_e \) condition on the structure of magnetic reconnection is also discussed (Longcope & Bradshaw 2010). Plasma mixing or trapping in a non-steady reconnection region, which includes magnetic islands or turbulence, might affect the time-dependent ionization process. Therefore, we think testing time-dependent ionization in non-steady magnetic reconnection is important. Comparison between the observations of solar flare and the time-dependent ionization results in a steady or
non-steady magnetic reconnection calculation may reveal which type of reconnection is dominant in the solar corona.

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