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Dependence of anomalous resistivity on bulk drift velocity of electrons in the reconnecting current sheets in solar flares *

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Abstract Anomalous resistivity is critical for triggering fast magnetic reconnection in the nearly collisionless coronal plasma. Its nonlinear dependence on bulk drift velocity is usually assumed in MHD simulations. However, the mechanism for the production of anomalous resistivity and its evolution is still an open question. We numerically solved the one dimension Vlasov equation with the typical solar coronal parameters and realistic mass ratios to infer the relationship between anomalous resistivity and bulk drift velocity of electrons in the reconnecting current sheets as well as its nonlinear characteristics. Our principal findings are summarized as follows: 1) the relationship between the anomalous resistivity and bulk drift velocity of electrons relative to ions may be described as $\eta_{\rm max} = 0.03724 \left(\frac{v_{\rm d}}{v_{\rm e}}\right)^{5.702}$ $\Omega\,$m for $v_{\rm d}/v_{\rm e}$ in the range of 1.4–2.0 and $\eta_{\rm max} = 0.8746 \left(\frac{v_{\rm d}}{v_{\rm e}}\right)^{1.284}$ $\Omega\,$m for $v_{\rm d}/v_{\rm e}$ in the range of 2.5–4.5; 2) if drift velocity is just slightly larger than the threshold of ion-acoustic instability, the anomalous resistivity due to the wave-particle interactions is enhanced by about five orders as compared with classic resistivity due to Coulomb collisions. With the increase of drift velocity from $1.4v_{\rm e}$ to $4.5v_{\rm e}$, the anomalous resistivity continues to increase 100 times; 3) in the rise phase of unstable waves, the anomalous resistivity has the same order as the one estimated from quasi-linear theory; after saturation of unstable waves, the anomalous resistivity decreases at least about one order as compared with its peak value; 4) considering that the final velocity of electrons ejected out of the reconnecting current sheet (RCS) decreases with the distance from the neutral point in the neutral plane, the anomalous resistivity decreases with the distance from the neutral point, which is favorable for the Petschek-like reconnection to take place.

Key words: instabilities — waves — Sun: flares — acceleration of particles

1 INTRODUCTION

It is widely accepted that an eruption of a solar flare is attributed to the release of free magnetic energy through reconnection on a timescale of $10^2 \sim 10^3$ s. A lot of multi-wavelength observational signatures related to the magnetic reconnection have been revealed. For example: 1) the *Yohkoh*/X-ray telescope and *SOHO*/EIT observations showed that this process indeed occurs above the soft

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X-ray flaring loops, and the plasmoid ejects out of the reconnection region (Tsuneta et al. 1992; Tsuneta 1996; Masuda et al. 1994; Yokoyama et al. 2001; Zhao et al. 2008; Zhou & Ji 2009); 2) RHESSI observations presented for the formation of a large scale current sheet in the solar flare on 2002 April 15 (Sui & Holman 2003); 3) Huang et al. (2008) calculated the magnitude of the transverse magnetic field and found its short-term impulsive increase during the rising phase of the flare according to the radio data on 2002 November 1 from the Nobeyama Radio Observatory, which may be considered as a signature of the magnetic reconnecting process.

In order to trigger such fast magnetic reconnection to take place in the high electric conductivity of the coronal plasma, anomalous resistivity caused by kinetic-scale wave-particle interactions is usually assumed. A number of numerical resistive MHD simulations demonstrated that not only the magnitude of anomalous resistivity but also its distribution decide the reconnection rate (Ugai & Tsuda 1977; Yokoyama & Shibata 1994; Ugai et al. 2003; Ugai & Zhang 2005; Uzdensky 2003 and references therein). The main conclusions are that: 1) a spatially uniform resistivity triggers the Sweet-Parker reconnection to take place on a timescale of several hours (Kulsrud 1998); 2) a locally enhanced resistivity inside the diffusive region near the center of an X-type neutral point leads to a Petschek-like reconnection to occur on a timescale of $10^2 - 10^3$ s, and the fast reconnection drastically evolves through a positive feedback between the global reconnection flow and the anomalous resistivity (Ugai 1984, 1999; Ugai et al. 2003; Uzdensky 2003 and references therein).

For the generation of anomalous resistivity $\eta_{\rm eff}$, it was often assumed that the current driven electrostatic ion-acoustic instability was excited after a shrinkage of the current sheet in the resistive MHD simulations. If the current density is larger than the threshold of ion-acoustic instability, the resistivity suddenly increases several orders above the classic Spitz resistivity. Using its relation to the effective collision frequency $\nu_{\rm eff}$ in the presence of current driven ion-acoustic waves, i.e., $\eta_{\rm eff} = \nu_{\rm eff}/(\varepsilon_0\omega_{\rm pe}^2)$ (Labelle & Treumann 1988), we have

$$\eta_{\rm eff} = \frac{1}{\varepsilon_0\omega_{\rm pe}}\frac{\varepsilon_0\delta E^2}{2n\kappa T_{\rm e}}, \tag{1}$$

where $\omega_{\rm pe}$ is the electron plasma frequency, n is the electron number density, $T_{\rm e}$ is the electron temperature, and $\varepsilon_0\delta E^2/2$ is the observed wave power of the fluctuations, and κ is the Boltzmann constant. If the current density continues to increase, the anomalous resistivity may alternatively be expressed as (Sagdeev 1967)

$$\eta_{\rm eff} = \frac{0.01}{\varepsilon_0\omega_{\rm pe}}\frac{v_{\rm de}}{v_{\rm e}}\frac{T_{\rm e}}{T_{\rm i}} \tag{2}$$

in the $\frac{T_{\rm e}}{T_{\rm i}} \gg 1$ limit, where $v_{\rm de}$ is the bulk drift velocity of electrons relative to ions, $v_{\rm e} = \sqrt{\frac{kT_{\rm e}}{m_{\rm e}}}$ is the electron thermal velocity, k is the Boltzmann constant, $m_{\rm e}$ is the electron mass, and $T_{\rm i}$ is the ion temperature.

Recently, one dimensional (1D) Vlasov simulations with parameters appropriate for the magnetopause and low-latitude boundary layer highlight the importance of the anomalous resistivity produced by the ion acoustic instability. Using a reduced mass ratio of $m_{\rm i}/m_{\rm e} = 25$, Watt et al. (2002) found that resistivity from Vlasov simulations is about three orders higher than the one calculated from Equation (1), where $m_{\rm i}$ is the ion mass. However, Hellinger et al. (2004) found that resistivity from Vlasov simulations is less than one order above the one calculated from Equation (1) with a real mass ratio of $m_{\rm i}/m_{\rm e} = 1836$, while the other parameters are the same as Watt's. Petkaki & Freeman (2008) inferred a non-linear dependence of anomalous resistivity on the bulk drift velocity of electrons with the expression

$$\eta_{\max} = 10^{1.85}\left(\frac{v_{\rm de}}{\theta_{\rm e}^m}\right)^{7.474} \tag{3}$$

for $v_{\rm de}$ in the range of $1.3 \sim 1.6\theta_{\rm e}^m$ and $T_{\rm e} = T_{\rm i}$, where $\theta_{\rm e}^m = \sqrt{2}v_{\rm e}$.

More recently, we performed 1D Vlasov simulations, including the external inductive field with a realistic mass ratio and parameters appropriate for the solar corona for the first time, and found that the excited electrostatic waves have the characteristics of the Buneman instability, i.e., propagating in opposite directions as the growth rate on the order of the ion plasma frequency, and decreasing the wave vector at the maximum growth rate with an increase of the bulk drift velocity of electrons (Buneman 1959; Wu & Huang 2009). Those electrons trapped by the waves stopped accelerating, and the inferred anomalous resistance of the current sheet may have been enough to explain the energy conversion rate in solar flares.

Since anomalous resistivity is sensitive to the plasma parameters and initial white noise (Hellinger et al. 2004; Petkaki et al. 2006; Petkaki & Freeman 2008), it is necessary to investigate the nonlinear dependence of anomalous resistivity on bulk drift velocity by means of Vlasov simulations with parameters appropriate to the reconnecting current sheet (RCS) in solar flares, where the electrons are accelerated to several times their thermal velocity (Litvinenko 2000; Wu et al. 2005). The paper is organized as follows. The basic equation and simulation method are presented in Section 2. The nonlinear dependence of the anomalous resistivity on bulk drift velocity is presented in Section 3. The discussions and conclusions are respectively given in Sections 4 and 5.

2 BASIC EQUATION AND SIMULATION METHOD

Two assumptions are adopted in this paper: 1) the reconnecting and perpendicular components of the magnetic field approach zero, i.e., $B_x \approx B_y \approx 0$, which are appropriate in the center-plane of a current sheet near the X-type point, where the electrons are most effectively accelerated (Coroniti & Eviatar 1977; Pritchett 2006; Øieroset et al. 2002); 2) the Lorentz force ($\boldsymbol{J}\times\boldsymbol{B}$) is smaller than the electric force, when the induced electric field is assumed to be along the z-component of the magnetic field (Watt et al. 2002; Omura et al. 2003; Petkaki & Freeman 2008; Wu & Huang 2009). Therefore, for the study of electrostatic waves, since the only force acting on the plasma is that of an electric field, a 1D approach may be enough to investigate the evolution of the anomalous resistivity due to the current-driven Buneman instability in RCS (Boris et al. 1970; Watt et al. 2002; Petkaki & Freeman 2008; Wu & Huang 2009; Wu et al. 2010).

The 1D electrostatic Vlasov equation is written as (Petkaki & Freeman 2008; Wu & Huang 2009)

$$\frac{\partial f_\alpha}{\partial t} + v_z\frac{\partial f_\alpha}{\partial z} + \frac{q_\alpha}{m_\alpha}E_z\frac{\partial f_\alpha}{\partial v_z} = 0, \tag{4}$$

where f_α is the particle distribution function $(\alpha \in \{i, e\})$, m_α and q_α are respectively the mass and charge of particles, and E_z is the turbulent electric field strength, which may be integrated forward in time, using Ampere's law given by (Horne & Freeman 2001)

$$(\nabla \times \boldsymbol{B})_z = \mu_0(J + \varepsilon_0\frac{\partial E_z}{\partial t}). \tag{5}$$

The electric current density is expressed by

$$J(z,t) = \sum q_\alpha \int v_z f_\alpha(z, v_z, t)dv_z, \tag{6}$$

which may be divided into two parts consisting of a spatially-averaged component and a fluctuating component, with the former being assumed to be balanced by the gradient of an external magnetic field $\boldsymbol{B}$ at all times, i.e., $(\nabla \times \boldsymbol{B})_z = \mu_0\langle J\rangle$ (Omura et al. 1996; Watt et al. 2002), and the latter being related to the turbulent electric field, which is given by $\widehat{J} = J - \langle J\rangle$.

Table 1 Summary of Simulation Parameters

Parameters	Symbol	Value
Ion to electron mass ratio	$m_\mathrm{p}/m_\mathrm{e}$	1836
Plasma density	$n = n_\mathrm{i} = n_\mathrm{e}$	$10^{14}\mathrm{m}^{-3}$
Temperature	$T = T_\mathrm{e} = T_\mathrm{i}$	10^6 K
Number of space grid points	N_z	2000
Number of velocity grid points	$N_{v_\mathrm{e}}, N_{v_\mathrm{i}}$	2500, 400
Resolution of spacial grid	Δz	$0.5\,\lambda_\mathrm{De}$
Resolution of velocity grid	$\Delta v_\mathrm{e}, \Delta v_\mathrm{i}$	$0.01 v_\mathrm{e0}, 0.05 v_\mathrm{i}$
Resolution of time	Δt	$0.003\, w_\mathrm{pe}^{-1}$

The anomalous resistivity may be calculated at each time step using the following expression (Petkaki et al. 2003):

$$\eta_\mathrm{eff} = -\frac{m_\mathrm{e}}{n_\mathrm{e} e^2}\left(\frac{1}{\langle J\rangle}\frac{d\langle J\rangle}{dt}\right). \tag{7}$$

In the initial situation, the large current density, i.e., the large electron drift velocity v_d, is assumed. When v_d is large enough for the the current-driven micro instabilities to be excited, the bulk drift energy is transferred into random energy due to the wave-particle scattering. With the decrease of space-averaged current density, Equation (7) can be employed to estimate the anomalous resistivity.

With the periodic boundary conditions and simulation method described in Horne & Freeman (2001), Equation (4) is integrated forward in time, with initial unstable waves which originated in a white noise electric field applied at $t = 0$ (see eqs. (4) and (5) in Petkaki et al. 2003). The simulation parameters are summarized in Table 1, where v_i is the ion thermal velocity ($v_\mathrm{i} = \sqrt{kT/m_\mathrm{i}}$), and λ_De is the plasma Debye length. The initial ion and electron populations are respectively Maxwellian distribution functions, drifting backward to each other, i.e.,

$$f_\mathrm{i} = n/[(2\pi)^{1/2} v_\mathrm{i}]\exp[-v^2/(2v_\mathrm{i}^2)]\,,$$

and

$$f_\mathrm{e} = n/[(2\pi)^{1/2} v_\mathrm{e}]\exp[-(v - v_\mathrm{d})^2/(2v_\mathrm{e}^2)]\,.$$

The space, velocity space, time step, and the numbers of grid points are carefully selected to ensure the numeric stability and accuracy of the integration algorithm (Horne & Freeman 2001; Petkaki et al. 2003).

3 THE NONLINEAR DEPENDENCE OF THE ANOMALOUS RESISTIVITY ON THE DRIFT VELOCITY

As stated in Petkaki et al. (2006, 2008), that the anomalous resistivity during the nonlinear phase of unstable waves is highly variable in time, and sensitive to the initial noise fields, we numerically solved Equations (4)∼(7) for different initial drift velocities (see Table 2), and used an ensemble of 10 Vlasov simulations for each set of initial conditions, which differ from that in Petkaki et al. (2006, 2008) only in the initial electric field noise. The time evolution of the ensemble Vlasov simulations for $v_\mathrm{d}/v_\mathrm{e} = 1.5,\ 1.8,\ 2.0,\ 4.0$ are respectively plotted in Figure 1(a)–(d). The resistivity is represented by the mean of peak value $\overline{\eta}_\mathrm{max}$, the sensitivity to the initial noise field is represented by standard deviation $\sigma(\overline{\eta}_\mathrm{max})$ and relative error $\sigma(\overline{\eta}_\mathrm{max})/\overline{\eta}_\mathrm{max}$, and t_max denotes the peak time of anomalous resistivity (see Table 2 and Fig. 2).

In our simulations, if we take $v_\mathrm{d}/v_\mathrm{e} < 1.4$, there are not any unstable waves that can be excited. It is consistent with previous linear theory that the critical drift velocity for the onset of ion-acoustic instability with $T_\mathrm{e}/T_\mathrm{i} = 1$ is about 1.35v_e. When $v_\mathrm{d}/v_\mathrm{e} = 1.4$, the current driven unstable waves

Table 2 Relationship between the Anomalous Resistivity and the Bulk Drift Velocity

$v_\mathrm{d}/v_\mathrm{e}$	$t_\mathrm{max}(\omega_\mathrm{pe}^{-1})$	$\overline{\eta}_\mathrm{max}$ (Ω m)	$\sigma(\overline{\eta}_\mathrm{max})(\Omega$ m)	$\sigma(\overline{\eta}_\mathrm{max})/\overline{\eta}_\mathrm{max}$
1.4	1542.8	0.1705	0.1905	1.1173
1.5	827.1	0.3015	0.1350	0.4478
1.6	673.0	0.5774	0.1699	0.2943
1.8	411.8	1.1647	0.3879	0.3330
2.0	292.5	1.8981	0.5396	0.2843
2.5	175.6	3.8192	0.6077	0.1591
3.0	91.9	2.9772	0.2939	0.0987
3.5	67.6	3.5808	0.4320	0.1206
4.0	53.4	5.5430	0.4149	0.0749
4.5	48.4	7.0528	1.0437	0.1480

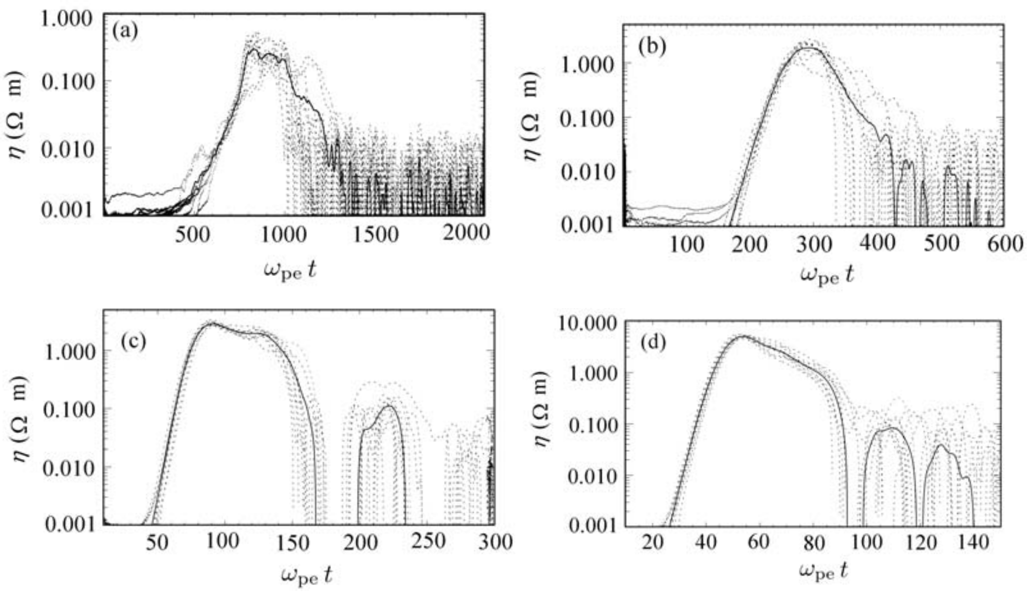

Fig. 1 Anomalous resistivity plotted as a function of time for $v_\mathrm{d}/v_\mathrm{e} = 1.5,\ 2.0,\ 3.0$ and 4.0, respectively in (a)–(d), where dotted lines mark each of the 10 initial noise fields and the solid line denotes mean η .

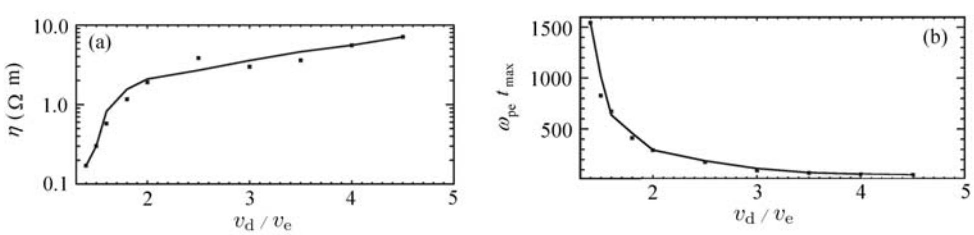

Fig. 2 Anomalous resistivity (a) and its peak time (b) plotted as a function of bulk drift velocity of electrons.

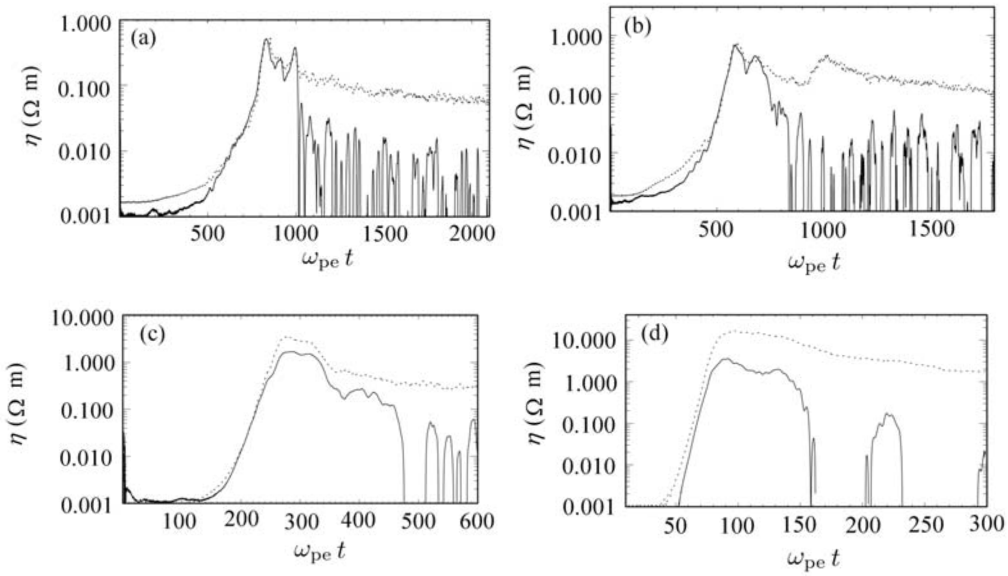

Fig. 3 Comparing the anomalous resistivity calculated respectively from Eqs. (1) and (7), where the solid line marks the one from Eq. (7) and the dotted line denotes the one from Eq. (1), and $v_{\rm d}/v_{\rm e}$ = 1.5, 1.6, 2.0 and 3.0, respectively in (a)–(d).

are excited and the averaged maximum anomalous resistivity due to the wave-particle scattering is about 0.1705 Ω m. It is enhanced by about five orders compared with the classic resistivity due to Coulomb collisions, which can be calculated from the formula $\eta \approx 10^{-3}\, T_{\rm e}^{-\frac{3}{2}}$ (eV)=10^{-6} Ω m with $T_{\rm e}$ =100 eV. When $v_{\rm d}/v_{\rm e}$ varies from 1.4 to 4.5, the anomalous resistivity continues to increase by about two orders of magnitude (see Fig. 2(a)).

In previous investigations, Equation (1) is usually used to estimate the anomalous resistivity due to the ion-acoustic turbulence (Smith & Priest 1972; Wu et al. 2005). The ratio of the turbulent energy to thermal energy is often assumed to be 0.01, and the corresponding anomalous resistivity is 2.0 Ω m. Considering the nonlinear development of unstable waves, we may plot the evolution of the anomalous resistivity calculated from Equation (1), and compare it with the one from Equation (7) (see Fig. 3). It is shown that: 1) in the rising phase of unstable waves, the anomalous resistivity obtained in two ways has the same order of magnitude; 2) in the maximum phase of unstable waves, the difference between them increases with an enhancement of $v_{\rm d}/v_{\rm e}$; 3) after saturation of unstable waves, because of stochastic energy exchanges among the waves and particles, the averaged total energy of unstable waves or particles changes little, and the electron distribution in velocity space also hardly changes. Since the wave-particle interaction is very dynamic, Equation (1) is too simple to describe the evolution of anomalous resistivity.

In order to find the relationship between the anomalous resistivity and the bulk drift velocity, we use the function of $\eta_{\rm eff} = a(v_{\rm d}/v_{\rm e})^b$ to fit the data with MATLAB's cftool function. Setting (weights)$_i$= 1.0/$\sigma(\overline{\eta}_{\rm max})_i^2$, which transform the response variances to a constant value, we obtain the fitting parameters of $a = 0.0372 \pm 0.0378\, \Omega$ m, $b = 5.702 \pm 1.557$ for $v_{\rm d}/v_{\rm e}$ in the range of 1.4–2.0 and $a = 0.8746 \pm 1.3934\, \Omega$ m, $b = 1.284 \pm 1.131$ for $v_{\rm d}/v_{\rm e}$ in the range of 2.5–4.5. Therefore, the relationship between them may be described as

$$\begin{cases} \eta_{\max} = 0.03724 \left(\frac{v_{\rm d}}{v_{\rm e}}\right)^{5.702}, & \text{for } 1.4 \le v_{\rm d}/v_{\rm e} \le 2.0, \\ \eta_{\max} = 0.8742 \left(\frac{v_{\rm d}}{v_{\rm e}}\right)^{1.284}, & \text{for } 2.5 \le v_{\rm d}/v_{\rm e} \le 4.5\,. \end{cases} \quad (8)$$

4 DISCUSSION

In principle, the anomalous resistivity and its distribution in RCS may be fully understood only when the 3D self-consistent dynamic reconnection is solved. However, due to the limit of the run time and storage memory of computers, a simplified model and unrealistic plasma parameters are often used to get some insight into its physical nature. In the present paper, we numerically solve the 1D Vlasov equation with parameters appropriate for the solar corona and the real mass ratio of an electron to an ion, and investigate the evolution of anomalous resistivity due to wave-particle scattering and its dependence on bulk drift velocity of electrons relative to ions. These results are appropriate to the center of RCS, where the Lorentz force may be ignored.

Based upon the observations in the impulsive phase of a solar flare, the total HXR flux exhibits a temporal correlation with both the HXR source separation speed and the reconnection rate, i.e., the induced electric field strength. The reconnection electric field has an order of 1–10 V cm $^{-1}$, it is strongly correlated to the hard X-ray flux and anti-correlated to the spectral index, which support the electron acceleration by the electric field generated in the reconnecting current sheet (Lin et al. 2003; Liu et al. 2008; Liu & Wang 2009).

Since the reconnecting electric field is much larger than the classical Drecier one (on the order of 10^{-5} V cm^{-1}) during the eruptive phase of solar flares, the electrons are freely accelerated near the center of the RCS before the unstable waves are excited; the acceleration time is only limited by the transverse component of the magnetic field (Litvinenko 1996, 2000). In the 3D electromagnetic field of the RCS, the orbits of electrons are extensively studied with test particle methods (Litvinenko 1996, 2000; Wu et al. 2005). It is found that $B_\perp$, the component of the magnetic field perpendicular to the sheet plane, leads the electrons out of the sheet without being further accelerated. Usually, $B_\perp$ is assumed to be proportional to the distance from the center of RCS, and the final velocity and acceleration time after electrons are ejected out of the RCS decrease with the increase of the distance from the center of the RCS (see fig. 1 of Wu et al. 2005). With the induced electric field of 5 V cm^{-1} in the RCS, it will take about 5×10^{-8} s for the electron velocity enhancement of $V_{\rm e}$. Since the acceleration time is larger than 10^{-6} s near the center of the RCS, it takes 2×10^{-7}s for the drift velocity of the electrons to be larger than 4 $v_{\rm e}$, and takes another 10^{-7} s for the unstable waves to reach the peak (see Fig. 2(b)). Hence, the unstable waves have enough time to be excited and scatter the energetic electrons before the electrons are ejected out of the RCS (Wu et al. 2008). While away from the center of the RCS, the acceleration time decreases, and the time for development of unstable waves increases. There may not be enough time for unstable waves to be well developed and scatter the energetic electrons before electrons are ejected out of the RCS. In other words, that anomalous resistivity decreases with the increase of the distance from the center of the RCS. The nonuniform distribution of resistivity is favorable for Petschek-like reconnection to take place (Uzdensky 2003; Ugai et al. 2003; Ugai & Zhang 2005).

On the other hand, it was shown from MHD simulations that once a thin current sheet is formed, extreme current sheet thinning (current concentration) occurs around the X-neutral point (Ugai 1986). The positive feedback between the global reconnection flow and the anomalous resistivity (Ugai et al. 2003) can sustain fast reconnection and electron acceleration. So, this result may be fundamental for discussing the triggering of fast reconnection in the solar corona in the present paper.

5 CONCLUSIONS

The localized anomalous resistivity is solved with 1D Vlasov simulations near the center of the RCS. The main results are summarized as follows:

(1) The anomalous resistivity may be described as the power of the bulk drift velocity of electrons. For $v_\mathrm{d}/v_\mathrm{e}$ in the range of 1.4–2.0, $\eta_\mathrm{max} = 0.03724 \left(\frac{v_\mathrm{d}}{v_\mathrm{e}}\right)^{5.702}$ Ω m , and for $v_\mathrm{d}/v_\mathrm{e}$ in the range of 2.5–4.5, $\eta_\mathrm{max} = 0.8746 \left(\frac{v_\mathrm{d}}{v_\mathrm{e}}\right)^{1.284}$ Ω m.
(2) If $\frac{v_\mathrm{d}}{v_\mathrm{e}}$ is just slightly larger than the threshold of ion-acoustic instability, η_max=0.1705 Ω m, while the classic resistivity due to Coulomb collisions is about 10^{-6} Ω m. Thus it is enhanced by about five orders of magnitude due to the wave-particle interactions. With the increase of drift velocity from 1.4 v_e to 4.5 v_e, the anomalous resistivity continues to increase 100 times.
(3) In the rise phase of unstable waves, the anomalous resistivity is the same order of magnitude as the one estimated from quasi-linear theory. In the maximum phase of unstable waves, the difference between them increases with an enhancement of $v_\mathrm{d}/v_\mathrm{e}$. After the saturation of unstable waves, the anomalous resistivity decreases at least an order of magnitude as compared with its peak value. Since the wave-particle interaction is very dynamic, Equation (1) is too simple to describe the evolution of anomalous resistivity.
(4) Considering that the final velocity and acceleration time of electrons ejected out of RCS decreases with the distance from the neutral point in the neutral plane and the time for unstable waves to be excited increases with the decrease of drift velocity, the anomalous resistivity decreases with the distance from the neutral point, which is favorable for the Petschek-like reconnection to take place.

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