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Flushing effect in reconnection: Effects of minority species of oxygen ions

H. Karimabadi [a,b,*], V. Roytershteyn [c], C.G. Mouikis [d], L.M. Kistler [d], W. Daughton [c]

[a] SciberQuest, Inc., Del Mar, CA 92014, USA
[b] University of California at San Diego, Department of Electrical and Computer Engineering, 9500 Gilman Drive, La Jolla, CA 92093, USA
[c] Los Alamos National Lab., Los Alamos, NM 87544, USA
[d] University of New Hampshire, Durham, NH 03824, USA

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ABSTRACT

Effects of O^+ ions on magnetic reconnection in the magnetotail are examined in a Harris equilibrium using a combination of linear Vlasov theory and large-scale driven and non-driven two-dimensional fully kinetic particle simulations. Linear theory of multiple species plasma indicates that the growth rate is rather insensitive to the composition of the background (lobe) or its temperature but more sensitive to the properties of the current carriers. Thus O^+ can affect significant changes to the linear growth rate of tearing mode only as a current carrier. However, it is demonstrated that in the nonlinear stage reconnection can effectively move trace material from the lobes into the current sheet proper. If the supply of lobe markers (like O^+) is sufficiently permanent in the lobe, an initially proton-dominated current sheet can be virtually replaced by the marker ions through this "flushing effect". The dominance of marker ions introduces finite Larmor radius signatures with marker gyroradii scales rather than that of the protons. In this way, the presence of heavier marker species in the lobe can lead to (i) reduced efficiency of energy conversion, (ii) reduction in the number and repetition frequency of secondary islands, (iii) broadening of the quadrupole magnetic structure, (iv) slowing down of the coalescence process and (v) modification of the composition of the ion current carriers. Using Cluster observations, we show the evidence for the "flushing effect" in the data. Detailed comparison with observations is planned for future work.

1. Introduction

In many applications where magnetic reconnection is operative, the plasma consists of a mixture of ion species. An example is in the Earth's magnetosphere where O^+ can dominate both the density and the pressure at times (e.g., during storm times) and there is clear observational evidence for the presence of O^+ in some reconnection events (e.g., Kistler et al., 2005; Wygant et al., 2005). Given the prevalence of O^+ in these reconnection events, there has been surprisingly little work on kinetic studies of effects of O^+ or other minority species on reconnection. Aside from a general theoretical interest, there are a number of key issues in magnetospheric physics that require a better understanding of the effects of O^+ on the reconnection process. For example there is a considerable controversy on whether the presence of O^+ affects the loading and unloading in the magnetotail or whether it has an influence on the location where substorms are initiated.

For a given thermal energy, an O^+ ion will have a gyroradius 4 times that of H^+. Since current sheet instabilities such as tearing mode have typically larger linear growth rates for thinner sheets, Baker et al. (1982, 1985) proposed that a relatively localized region of oxygen-dominated plasma might be the most likely region where the substorm would develop. The observational evidence for this is mixed. The observed statistical analysis shows significant dawn–dusk asymmetries in O^+ in the plasma sheet (e.g., Sharp et al., 1981). Assuming that locations of most probable neutral line formation are those with the highest tearing growth rates, then one would expect the location of substorm onset to also show a similar dawn–dusk asymmetry and this is indeed what is observed (Frey et al., 2004; Østgaard et al., 2006). However, Nosé et al. (2009), in a long-term study using Geotail/STICS data, found no correlation between the O^+ in the plasma sheet and the number of substorms. The model of Baker et al. (1982) was based on the linear ion tearing mode theory of Schindler (1974). They indicated the importance of extending the linear theory analysis to three species. As it turns out, while linear theory provides some guidance, the main effects of O^+ on reconnection occur through nonlinear processes, as we demonstrate. Hesse and Birn (2004) using three-species full particle simulations with periodic boundary conditions concluded that

* Corresponding author at: University of California at San Diego, Department of Electrical and Computer Engineering, 9500 Gilman Drive, La Jolla, CA 92093, USA. Tel.: +1 858 7937063.
E-mail address: homakar@gmail.com (H. Karimabadi).

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oxygen background has very little effect on the reconnection process but cautioned about the generality of their result due to their use of a small simulation box. Shay and Swisdak (2004), on the other hand, used a three-fluid reconnection simulation with periodic boundary conditions and concluded that in addition to the usual two scales associated with collisionless two-fluid reconnection (the light whistler and the light Alfven) there are two more, larger, scales, the ''heavy whistler'' and the ''heavy Alfven'' scales. The length scale that is associated with the ''heavy whistler'' produces a larger scale quadrupolar out-of-plane magnetic field structure whereas the one associated with the heavy Alfven wave can slow the reconnection rate.

Here we present a kinetic study of collisionless reconnection in three-species plasma using a combination of linear Vlasov theory, and non-driven and driven full particle simulations. We will examine the effects of the minority species on the linear growth rate, onset, the peak reconnection rate and the overall structure of the reconnection layer. As we demonstrate, one critical piece of physics missing from previous considerations is what we refer to as the ''flushing effect'': as reconnection proceeds, plasma is sucked in from the lobe while the initial population of current carriers gets ejected from the system. Thus, in time, it is the lobe plasma that becomes the dominant species in the system and carries most of the ion current. To best capture this process and its effect in time as reconnection proceeds requires the use of simulations with open boundary conditions. We present the first fully kinetic 2D PIC simulations with open boundaries of three-species plasma to quantify the effects of a third heavy species on reconnection. We find that the presence of a third species in the lobe can significantly change the evolution and the resulting structure of the reconnection region. Observational support for the ''flushing effect'' will be shown using Cluster data. Detailed comparison of the simulation results with data is planned for future work.

Although the details of the lobe plasma (e.g., its composition, temperature, etc.) have an influence on the linear tearing mode, the main influence of the lobe is when it becomes assimilated into current carriers through the flushing effect. In comparison with the data, special care is required since the system is highly inhomogeneous and one must distinguish between signatures that are generic and those that may be different depending on particular cuts in the simulation and/or data or vary depending on the exact composition of the lobe.

Here we focus on several predicted signatures that can be more directly compared with the Cluster data. In particular, we show evidence for the flushing effect in the data. The complex process of assimilation of marker ions into the current sheet proper can cause the composition of the plasma inside the plasmoids to be very different than in regions in the vicinity of the electron diffusion region. We summarize the results and conclude in Section 5.

2. Linear nonlocal Vlasov theory

We consider a Harris equilibrium with zero guide field using a coordinate system where the initial magnetic field is $B_z = B_0 \tanh(x/L)$, and L the half-width of the layer. The density profile is $n(x) = n_o \,\mathrm{sech}^2(x/L) + n_b$ where n_o is the peak Harris density and n_b the background density. For linear growth rate estimates, we use our linear Vlasov code using the formally exact approach described in Daughton (2003), which has been modified to allow for electron and ion anisotropies (Daughton and Karimabadi, 2005). This method employs a normal mode stability calculation using a full Vlasov description for both ions and electrons. The results are given in Table 1 where the linear tearing growth rate at wavenumber $kL = 0.5$ is listed for three species plasma with different combinations of hydrogen and oxygen as current carrier and background species. The mass ratio of proton to electron is 1836 and the mass of O^+ is 16 times that of proton.

We have listed the growth rate relative to the proton gyrofrequency, ion gyrofrequency of the current carriers and the Alfven transit time τ_A defined as wavelength divided by the Alfven speed based on the mass of the current carriers. The first measure is useful when one is interested in comparing cases with and without O^+ relative to some absolute unit of time. The second and third measures express the growth rate in terms of physically relevant parameters that characterize a system.

From this table it is evident that the effect of oxygen on the linear growth rate is different depending on whether oxygen is the current carrier or the background. In linear tearing, one way the effect of background comes in is through the plasma beta or more explicitly through $n_b T_b$ where T_b is the temperature of the background. The growth rate is generally reduced for larger $n_b T_b$. The dependence is rather weak with growth rate scaling as $\sim 1/(n_b + n_o)$. The addition of O^+ as a background population can reduce the tearing growth rate but only if the density increases significantly. Table 1 also indicates that linear tearing mode is insensitive to the composition of the background or its temperature.

Of far greater influence are the current carriers. At realistic mass ratios, the electron resonant response is the dominant source of growth for linear tearing while the ion resonant current only acts to reduce the rate (e.g., Daughton and Karimabadi, 2005). Thus a main parameter controlling the growth rate is ρ_e/L which sets the number of available resonant electrons. When $T_H^+ = T_O^+$, ρ_i/L would be four times larger if oxygen carries the current (cases 1 and 6 in Table 1). Both cases have the same ρ_e/L

Table1
Growth rate of linear collisionless tearing model for various combinations of hydrogen and oxygen ion species. Mass ratio of electron to proton is 1836. O^+ has a mass 16 times that of proton. Growth rates (γ) normalized to the (i) gyrofrequency of the current carrier species ($\gamma_{c.c.}$), (ii) proton gyrofrequency and (iii) Alfven transit time are listed. The Alfven speed is based on the mass of the current carriers and length is based on $kL = 0.5$.

Case #	Current carrier	Lobe	ρ_i/L	ρ_e/L	T_i/T_b	n_b	β	$\gamma_{c.c.}$	γ_p	$\gamma\tau_A$
1	H^+	H^+	1.5	0.035	1.0	0.3	0.3	0.145	0.145	0.76
2	O^+	H^+	1.5	0.009	1.0	0.3	0.3	0.088	0.0055	0.47
3	H^+	O^+	1.5	0.035	1.0	0.3	0.3	0.149	0.149	0.74
4	H^+	O^+	1.5	0.035	1.0	**0.1**	0.1	0.166	0.166	0.89
5	O^+	O^+	1.5	0.009	1.0	0.3	0.3	0.09	0.0056	0.49
6	O^+	H^+	6	0.035	1.0	0.3	0.3	1.48	0.0925	2.04
7	O^+	O^+	6	0.035	1.0	0.3	0.3	1.49	0.093	2.08
8	H^+	H^+	1.5	0.035	**0.5**	0.3	0.6	0.149	0.149	0.85
9	H^+	H^+	1.5	0.035	**2.0**	0.3	0.15	0.141	0.141	0.6
10	H^+	O^+	1.5	0.035	**0.25**	0.3	1.2	0.154	0.154	0.1875