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Large-scale hybrid simulations of the magnetotail during reconnection

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Abstract. Large-scale, 2-D hybrid simulations are used to investigate the ion kinetic physics associated with quasi steady-state reconnection in the magnetotail. The simulations encompass a significant portion (20×120 R_E) of the tail. After formation of transient plasmoids, the results show the features of fast Petschek-type reconnection. There are two pairs of thin transition layers attached to the x-point which divert and accelerate the flow within a few ion inertial lengths. These transition layers do not quite conform to the properties of the expected slow shocks. The reason for this appears to be the fact that the ion dissipation scale is comparable to the thickness of the developing plasma sheet. As a result, we find signatures of only partially thermalized, counterstreaming ions in what resembles the plasma sheet boundary layer. A fast ion beam forms immediately upstream of the boundary layer. The results are consistent with the notion that slow shocks or similar transition layers are responsible for the heating and formation of the central plasma sheet and for the ion beams observed in the plasma sheet boundary layer.

1. Introduction

More than 30 years ago *Petschek* [1964] suggested that steady-state reconnection in the Earth's magnetotail could be achieved in a configuration in which the majority of the flow acceleration, field reversal, and plasma heating take place outside the magnetic diffusion region, via two pairs of attached slow shocks. Since then, slow shocks have indeed been observed in the far tail with the ISEE 3 satellite [e.g., *Smith et al.,* 1984, *Feldman et al.,* 1985, *Schwartz et al.,* 1987] and recently by GEOTAIL [*Machida et al.,* 1994]. In a recently described ISEE 3 tail crossing, the observed region showed a pair of slow shocks, field reversal, jetting plasma and additional characteristics expected from steady-state reconnection [*Ho et al.,* 1994].

In *Petschek's* model, the slow shocks associated with steady-state reconnection provide the transition between the lobe and the central plasma sheet (CPS), thereby accounting for the changes of the observed plasma properties between the lobe and the CPS. Recent GEOTAIL observations of cold ions [*Hirahara et al.,* 1994] have confirmed that the plasma sheet boundary layer (PSBL) is magnetically open and that the lobe plasma contributes directly to the plasma sheet population. A slow shock separating the lobe from the CPS could also provide an explanation for the ion beams observed in the PSBL [e.g., *DeCoster and Frank,* 1979], because both observed [*Feldman et al.,* 1987] and simulated [e.g., *Omidi and Winske,* 1992] slow shocks show ions streaming back from the shock. However, not all observed transitions between the lobe and the CPS conform to the characteristics of slow shocks [*Feldman et al.,* 1985]. Moreover, in a collisionless plasma there has to be sufficient wave-particle interaction to achieve the required shock dissipation. Because of the complexity of such processes, it is by no means clear if or when steady-state reconnection should be associated with slow shocks. For example, the ion distributions observed in both the PSBL and CPS are often far from being thermalized [*Saito et al.,* 1994, *Frank et al.,* 1994]. This could confirm that the transition is not always a slow shock, or it could indicate that the dissipation scale associated with slow shocks is comparable to the thickness of the plasma sheet.

Large-scale steady-state reconnection has so far only been addressed within the framework of MHD [e.g., *Sato,* 1979, *Scholer,* 1989]. To answer questions concerning the actual configuration of steady-state reconnection in a collisionless plasma, it is necessary to account for the kinetic response of the ions. Obviously, a kinetic approach is also necessary to explain the observed ion distributions in the PSBL and CPS. In the past, kinetic studies of reconnection have concentrated on the physics of the diffusion region [see, e.g., *Burkhart et al.,* 1991, *Hesse and Winske,* 1994]. In contrast, here we have performed hybrid simulations that encompass a significant fraction of the magnetotail and are thus large enough to address the questions surrounding the global reconnection configuration. The goal is a realistic description of both the macrophysics and the ion kinetics involved in the formation of the PSBL, the CPS, and the emerging plasmoids [e.g., *Moldwin and Hughes,* 1992]. Here, we show initial results of such simulations, which for the first time demonstrate the self-consistent formation of a Petschek-type reconnection configuration in a kinetic plasma. The simulations imply that much of the heating of the CPS as well as the ion distributions in the PSBL may be understood as a consequence of the shock-like transition zones attached to the reconnection region.

2. Simulation Model

The simulations are carried out with a 2-D predictor-corrector hybrid code [*Harned,* 1982], in which the electrons form an isothermal, massless fluid and the ions are treated as macro particles. An overview of the

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simulation configuration is given in Figure 1. We use conventional tail coordinates, where the plasma is injected at the z-boundaries $\pm z_{max}$. The injection speed $v_{zo}(x, z = \pm z_{max})$ is a *sine* function of x with a maximum of 0.1 v_A in the center of x, where v_A is the upstream (lobe) Alfvén speed. Initially, the plasma flow velocity $v_z(x, z, t = 0)$ has the same x-profile as the injection velocity $v_{zo}(x, z = \pm z_{max})$ described above. To ensure a smooth start, $v_z(x, z, t = 0)$ varies as $\sin(-\pi z/2 z_{max})$ in the z direction, making a transition from zero at $z = 0$ to the injection speed at the inflow boundaries $\pm z_{max}$. The magnetic field is antiparallel $\mathbf{B}_o = \pm B_o \hat{\mathbf{x}}$ in the two halves ($z > 0$, $z < 0$) of the simulation domain, where $\hat{\mathbf{x}}$ is the unit vector in the x-direction. The density and temperature are initially uniform, with electron and proton betas $\beta_e = \beta_p = 0.05$. Note that the simulations are dynamic in nature and aimed at the situation where current-layer thinning has taken place, and reconnection onset is triggered by the emergence of significant resistivity. We have varied the initial thickness of the current layer from 1 to 10 cells and have found no qualitative differences. The outflow boundaries are open, maintaining a zero derivative of the first two plasma moments as discussed by *Forbes and Priest* [1987]. The cell size is one proton inertial length c/ω_p, and the time step is $0.05\ \Omega_p{}^{-1}$ (inverse proton cyclotron frequency). The largest simulations are 120×600 cells with initially 20 particles per cell, and are run for a time of $800\ \Omega_p{}^{-1}$. Assuming a lobe density of 0.05 particles/cm^3 and a value $\Omega_p{}^{-1} = 1.5$ s, there are approximately 6 c/ω_p per R_E, and the total run time of $800\ \Omega_p{}^{-1}$corresponds to 20 min real time. Here we are interested in the large-scale and ion kinetic consequences of reconnection and bypass any questions regarding the microinstabilities leading to onset of reconnection. Given that the hybrid code does not describe the physics on electron scales, we set the resistivity that accomplishes reconnection explicitly. It is largest in the center of the simulation box with a maximum resistive scale length $\ell_\eta = 2c/\omega_p$, falls off away from the center with the same scale, and corresponds to an electron diffusion of approximately 1/2 the Bohm diffusion rate. By varying ℓ_η (and the cell size) we have found an extremely weak dependence of the overall solution and outflow speed on ℓ_η, as expected from Petschek-type reconnection.

3. Results and Discussion

We present results of a simulation that applies to the far tail, with no normal (B_z) component of the magnetic field initially. Figure 2 shows the magnetic field lines in the simulation plane at three different times. The field lines are equivalent to contour lines of the vector potential component A_y, which is also displayed using a linear grey scale. At reconnection onset several islands form that convect away from the center and, by the time they reach the left or right boundary, coalesce into 1–2 plasmoids on each side. After this transient process, a quasi steady-state, single x-line configuration develops. Figure 3 shows the flow velocity vectors in the simulation plane and a linear grey-scale plot of the parallel ion temperature $T_\|$ at $t = 17.5$ min, when the plasmoids have just left the box. The plasma is diverted and heated at a well-defined boundary, and is accelerated and jetting out at a maximum speed of just above the lobe Alfvén speed. The average ion temperature of the far downstream plasma, which we identify as the CPS, is 15 times the lobe value. The flare (half-) angle of the outflow jet is ~ 4°, similar to but smaller than what has been obtained in comparable MHD simulations [*Sato,* 1979, *Scholer,* 1989].

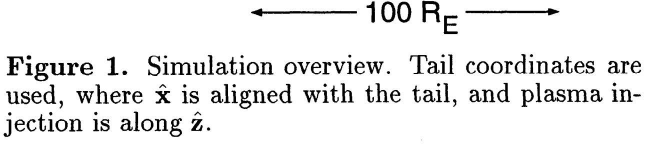

Figure 1. Simulation overview. Tail coordinates are used, where $\hat{\mathbf{x}}$ is aligned with the tail, and plasma injection is along $\hat{\mathbf{z}}$.

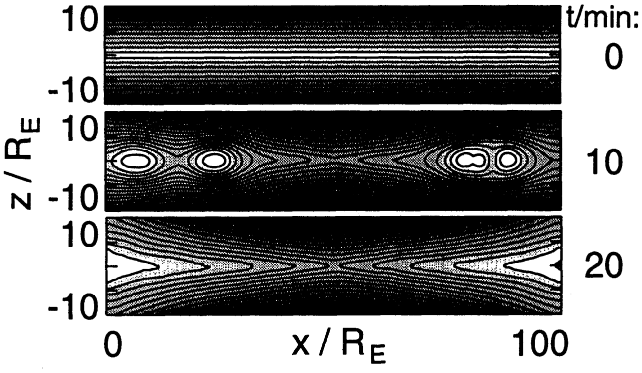

Figure 2. Magnetic field lines at start, middle, and end of simulation. Displayed are both contours and a grey scale of the associated vector potential A_y. Note development of transient plasmoids as well as x-line formation.

Before we get to the question whether the transition between the lobe and the CPS is a true slow shock, it is important to address the consequences of the transition concerning the ion distributions and heating. Figure 4 shows the magnetic field lines, $T_\|$, and the ion velocity distribution in three regions, as indicated. The phase space density contours are spaced a factor of two apart. Just at the edge of the transition we find an ion beam (5 to 10% of the lobe density) propagating away from the x-point at nearly twice v_A. These ions could correspond to the earthward propagating beams that are routinely observed in the vicinity of the PSBL. There is no equivalent tailward beam within the earthward side of the x-point, because our model so far does not include ion reflection in the Earth's dipole field. Farther inside the transition to the CPS, in what may be identified as the PSBL, the plasma consists of two ion populations that drift at a speed of ~ 1 v_A with respect to each other. In the vicinity of $z \sim 0$ (i.e., in the CPS) the ions appear fairly isotropic. There is a continuous evolution of this two-component plasma, with diminishing relative speed towards the CPS. By tagging the simulation particles we find that the low-velocity component (centered around $v_x \approx 0$ in panel labelled "PSBL" in Fig. 4) consists mostly of lobe particles that have just entered; the accelerated component is made up of ions that have resided in the plasma sheet for a while and consists to 50% of particles from either lobe side. The fast beam at the edge of the PSBL consists to about 60% of particles from the adjacent lobe. The counter-streaming ions cannot easily be separated in terms of

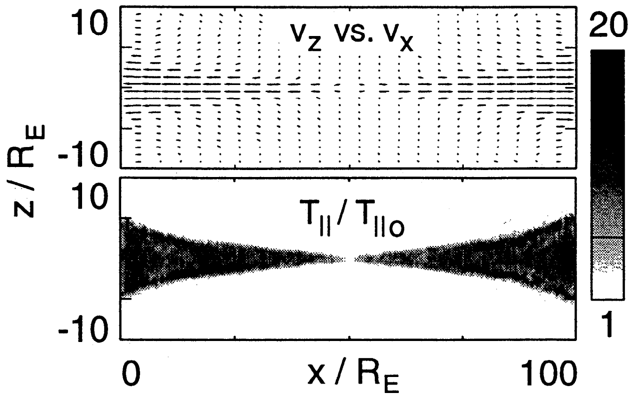

Figure 3. Flow vectors in simulation plane and grey scale of parallel ion temperature $T_{\|}$ toward end of simulation.

their parallel and perpendicular velocity and are not gyrotropic. While more work needs to be done to understand the evolution of the ion distributions, the results clearly indicate the importance of reconnection and the attached transition zones in the formation of the PSBL ion populations and the heating of the CPS.

Our assessment that the reconnection is of a fast Petschek type is based on (1) the existence of a boundary at which the flow is diverted and accelerated, (2) the approximately Alfvénic outflow speed, and (3) a slight acceleration of the plasma in the z direction toward the diffusion region (weak fast-mode expansion). The normal of the boundary where the flow diversion and heating take place makes an angle of $\theta_{Bn} = 87°$ with the upstream magnetic field. We have evaluated the local plasma parameters along the normal of this apparent discontinuity. Taking into account the associated uncertainties, we find that it matches the Rankine-Hugoniot jump conditions of a slow shock that is within 10% of the switch-off limit (with regard to the intermediate Mach number). However, the transition does not quite conform to what one would expect from a slow shock. For example, the perpendicular temperature and magnetic field exhibit a fairly gradual change, attaining the expected downstream value only at the center $z = 0$. Given that the ions do not thermalize fully until the center is reached, our results seem to indicate that in this run, there is insufficient time/space for thermalization and a "complete" slow shock to form in the downstream wedge. It is likely that the small flare angle plays a role in this, either by limiting the space available for thermalization, or by forcing a nearly perpendicular geometry ($\theta_{Bn} = 87°$) for what would be the slow shock. Evidently, these results and conclusions could change with plasma parameters and in situations that we have not yet simulated. We are currently studying in detail under which conditions a true slow shock may form, and when the transition takes on different characteristics.

A few other features of the reconnection configuration are worth mentioning. Previous local reconnection simulations [e.g., *Hesse and Winske,* 1994] demonstrated a quadrupolar signature of the magnetic field component pointing out of the simulation plane, B_y. Here, this excursion in B_y extends throughout the outflow jets, i.e., there is a significant B_y associated with the transition to the CPS. Upstream of this is a phase-standing Alfvén wavetrain whose spatial extent is limited by its field aligned group velocity, i.e., it is confined by the separatrix that divides reconnected from not-yet-reconnected field lines. With respect to the local plasma parameters, the outflow speed is superfast at a fast magnetosonic Mach number $M_F \sim 1.4$. Superfast outflow is of interest in solar physics in the context of coronal current sheet reconnection, where it may play a role in the formation of 'post'-flare loops [*Forbes and Malherbe,* 1991].

The transient plasmoids that we see in the simulation have a final diameter of ~ 10 to 15 R_E and travel at an average speed of ~ 300 km/s (with maximum speeds of about 1 lobe v_A; here: 660 km/s), which is in very good agreement with average plasmoid properties observed with ISEE 3 [e.g., *Moldwin and Hughes,* 1992] and GEOTAIL [*Lepping et al.,* 1995] in the distant tail. While there is a zero initial B_y, a large and fluctuating Hall-generated B_y develops within the plasmoids, which is of the order of 1/2 the lobe field strength (not shown here). In preliminary runs that differ by having an initial B_{y0} (shear angle between the lobe fields < 180°), we find that the bipolar, Hall-generated field does not add linearly to B_{y0}. Even for a small B_{y0}, the (larger) B_y of the plasmoid may become unipolar and carry the sign of the lobe field, in agreement with the observations. The plasmoids also exhibit an interesting ion kinetic signature: they contain several layers of counterstreaming shells of ions which originate from the x-points surrounding the plasmoid. Such kinetic signatures could be of practical use in two ways. First, they can help to distinguish plasmoids from other types of waves. Second, because of the long ion-thermalization time scales, kinetic signatures should provide useful information with regard to the age of plasmoids. We plan to carry out detailed comparisons of our findings with GEOTAIL observations in the near future.

There are no observations of earthward propagating plasmoids in the near-Earth tail. Close to Earth, it is also no longer appropriate to ignore the presence of a finite normal magnetic field component B_z and its consequences on the plasma evolution. To address these issues, we have performed a run with a normal component $B_z/B_0 = 0.035$, i.e., at a field inclination of 2° with respect to $\hat{\mathbf{x}}$. We find that in this case a plasmoid forms only on the tailward side (see *Pritchett et al.* [1991] for similar results on much smaller scales).

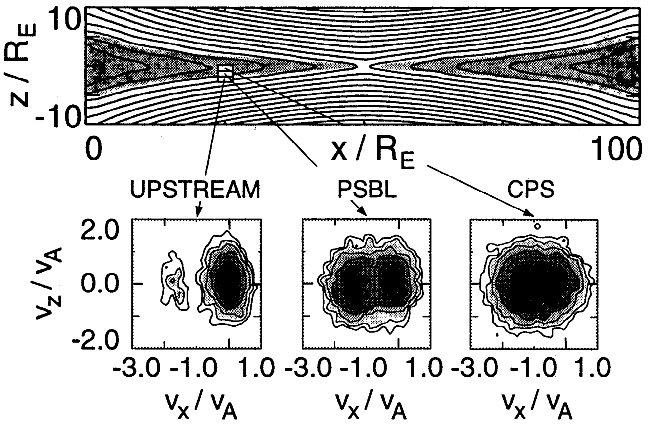

Figure 4. Top: magnetic field profile and $T_{\|}$ at end of simulation; bottom: ion distributions at three locations, as indicated.

4. Summary

Using 2-D hybrid simulations, we have for the first time demonstrated self-consistently that a fast Petschek-type reconnection configuration [*Petschek*, 1964] can form in an ion-kinetic simulation of the magnetotail. The results are similar to recent ISEE 3 observations [*Ho et al.*, 1994]. Discontinuities with slow-shock like properties form and achieve the necessary flow acceleration and plasma heating. We find that the ion dissipation scale is significant and comparable to the thickness of the plasma sheet. As a consequence, there is an incompletely thermalized, two-component plasma in what may be interpreted as the PSBL, consisting of counter-streaming ions. A fast ion beam is found just upstream of the PSBL. The results support the idea that the heating and formation of the CPS as well as the observed ion distributions of the PSBL are caused by slow-shocks or similar transitions surrounding a quasi steady-state reconnection site in the tail. While much work remains to be done, the results demonstrate the great potential of large-scale hybrid simulations to address a variety of ion kinetic problems associated with the PSBL, the CPS, and plasmoids in the magnetotail.

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