Kinetic models of solar wind current sheets

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Current sheets in the collisionless solar wind usually have kinetic spatial scales. In-situ measurements show that these current sheets are often approximately force-free, i.e. the directions of their current density and magnetic field are aligned, despite the fact that the plasma beta is found to be of the order of one. The measurements also often show systematic asymmetric spatial variations of the plasma density and temperature across the current sheets, whilst the plasma pressure is approximately uniform. Neukirch et al. (2020) [1] found exact equilibrium models of force-free collisionless current sheets which allowed for asymmetric plasma density and temperature gradients. These models assumed that the form of the distribution function for electrons and ions is the same. In this contribution we generalise this approach to current sheets with static ions. As a consequence the force-free condition is only satisfied approximately and quasi-neutrality requires the presence of a nonvanishing electric potential.

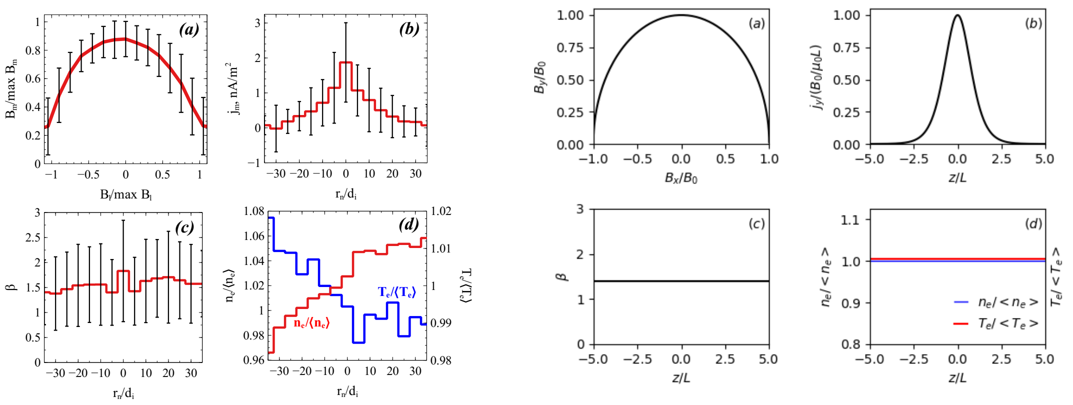

Figure 1: *Left panel: Average profiles of magnetic field, current density, and plasma characteristics for a data set of ~200 discontinuities observed by the ARTEMIS spacecraft in the near-Earth solar wind; Right panel: Theoretical profiles based on known analytical collisionless force-free current sheet equilibria [3, 4]. These do not have the required density and temperature asymmetries.*

ARTEMIS measurements of average profiles of magnetic field, current density and plasma characteristics of discontinuities ("current sheets") in the near-Earth solar wind [1, 2] are shown in Fig. 1, in the four panels on the left. On the right of Fig. 1, we show theoretical profiles of the same quantities based on exact collisionless force-free current sheet equilibria as first presented in [3] and discussed in more detail by [4]. While it is easily possible to get a good match of the general magnetic field, the current density and the plasma β profile, these equilibria generically result in spatially constant particle density and temperature profiles. We remark that equilibria with density and temperature variations that are symmetric with respect to the centre of the current sheet have also been found [5] (for a general overview of the field see [6]).

The basic model used in [3] and [4] is a one-dimensional force-free magnetic current sheet with the B_x component being identical to the standard Harris sheet [7], $B_x = B_0 \tanh(z/L)$ (we assume all quantities to vary only in z with a typical length scale L). The corresponding B_y component is defined by $B_y = B_0/\cosh(z/L)$ and hence $B_x^2 + B_y^2 = B_0^2 =$ constant. The current density components are given by $\mu_0 j_x = (B_0/L)\sinh(z/L)/\cosh^2(z/L)$ and $\mu_0 j_y = (B_0/L)1/\cosh^2(z/L)$. The relevant component of the pressure tensor for maintaining the force balance, P_{zz}, does not vary with z. It can be shown that self-consistent particle distribution functions (DFs) for this magnetic field are given by

$$F_e(H_e, p_{x,e}, p_{y,e}) = \frac{n_0}{(1+b)(\sqrt{2\pi} v_{th,e})^3} \mathrm{e}^{-\beta_e H_e} \left[b - \frac{1}{2} \mathrm{e}^{\beta_e m_e u_0^2/2} \cos(\beta_e u_0 p_{x,e}) + \mathrm{e}^{\beta_e m_e u_0^2/2} \mathrm{e}^{\beta_e u_0 p_{y,e}} \right], \quad (1)$$

$$F_i(H_i, p_{x,i}, p_{y,i}) = \frac{n_{0,i}}{(\sqrt{2\pi} v_{th,i})^3} \mathrm{e}^{-\beta_i H_i}, \quad (2)$$

where $H_s = m_s v^2/2 + q_s \Phi$ is the energy for particle species s, and $p_{x,s} = m_s v_x + q_s A_x$ and $p_{y,s} = m_s v_y + q_s A_y$ are the x- and y-components of the canonical momentum. As usual, m_s is the mass of particle species s, q_s its charge, $\Phi(z)$ is the electric potential, and $A_x(z)$ and $A_y(z)$ are the x- and y-components of the magnetic vector potential, which for the magnetic field above are given by $A_x = B_0 L \arctan[\sinh(z/L)]$ and $A_y = -B_0 L \ln[\cosh(z/L]$ (note that for A_x a different gauge compared to, for example, [3, 4] has been used to have an odd function of z).We have also used the usual notation of $\beta_s = (k_{\mathrm{B}} T_s)^{-1}$ for the inverse temperature and the thermal velocity $v_{th,s} = (m_s \beta_s)^{-1/2}$ of species s . The DFs also depend on the constant parameters n_0 and $n_{0,i}$, which are typical particle densities, the constant velocity parameter u_0 and the dimensionless parameter b, which is linked to the plasma β_p by $\beta_p = b + 1/2$. It can then be shown [1, 3, 4] that self-consistency is achieved by $\Phi = 0$ and the relations $n_{0,i} = n_0(b + 1/2)$, $B_0 L/2 = -(e\beta_e u_0)^{-1}$, $B_0/L = \mu_0 e n_0 u_0$ and $B_0^2/(2\mu_0) = n_0/\beta_e$. As a result the macroscopic length scale L is given in terms of the parameters of the DFs by $L^2 = 2(\mu_0 e^2 \beta_e n_0 u_0^2)^{-1}$. As mentioned above the resulting particle densities are constant and hence do not explain the observed asymmetries.

To get a self-consistent current sheet model which displays asymmetries in particle density and temperature in [1] an additional term was added to the DFs of both ions and electrons. This additional term has the form

$$\Delta F_s = \delta n_s \left(\frac{\kappa_s}{2\pi v_{th,s}^2}\right)^{3/2} \beta_s u_0 p_{x,s} \left(\frac{5}{2} - \kappa_s \beta_s H_s\right) \mathrm{e}^{\kappa_s \beta_s H_s}, \tag{3}$$

with δn_s a constant with the dimension of a particle density and κ_s a dimensionless parameter which is basically the ratio of the temperature of the original DFs defined in Eqs. (1) and (2) to the temperature of the additional DF term (3).

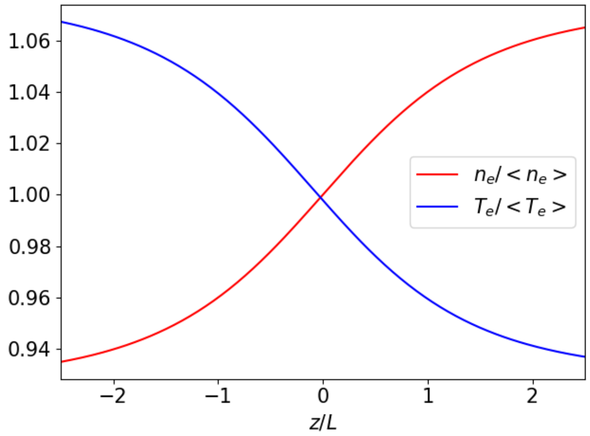

Figure 2: *Particle density and temperature asymmetries introduced by adding a term of the form (3). The parameter values used [1] are* $L/d_i = 10$ *(*d_i *is the ion inertial length),* $\beta_p = 1.4$*,* $T_e/T_i = 1.0$*,* $m_i/m_e = 1836$*,* $\kappa_e = \kappa_i = 1.1$ *and* $\varepsilon = 0.05$*. This results in* $u_0 \approx -3.9 \cdot 10^{-3} v_{th,e}$*.*

The reason that the term (3) was added to the ions as well as the electrons in [1] was that this allows a self-consistent solution with $\Phi = 0$, with the magnetic field remaining unchanged from above, but introduces an additional asymmetric contribution to the particle density of the form

$$\Delta n_s = \varepsilon n_0 \frac{2A_x}{B_0 L}, \tag{4}$$

where we have defined $\delta n_s = \varepsilon n_0$. Because the pressure remains constant, the temperature profile has to be inversely proportional to the particle density asymmetry. The resulting profiles are shown in Fig. 2 for a typical set of parameters. Whereas in the basic model DF (2) the ions were static they are now carrying a part of the current due to the additional term (3). In this contribution we want to explore whether it is possible to have a current sheet model with static ions while still retaining the features found in [1] .

To start we use the ion DF (2) in combination with the full electron DF, i.e. Eq. (1) together with Eq. (3). The quasi-neutrality condition then becomes

$$n_{0,i} \mathrm{e}^{-e\beta_i \Phi} - n_0 \left\{ \mathrm{e}^{e\beta_e \Phi} \left[b - \frac{1}{2}\cos(e\beta_e A_x) + \mathrm{e}^{-e\beta_e u_0 A_y} \right] + \varepsilon\, e\beta_e u_o A_x \left(1 + \kappa_e e \beta_e \Phi\right) \mathrm{e}^{\kappa_e e \beta_e \Phi} \right\} = 0. \tag{5}$$

This equation is not solved by $\Phi = 0$ and the force-free vector potential (A_x, A_y) forms given above, because the final term depends linearly on A_x and hence varies with z even in the case $\Phi = 0$, whereas the first two terms would be constant for $\Phi = 0$.

In principle, one would have to solve Eq. (5) coupled with Ampère's law numerically, but here we make use of the fact that $\varepsilon \ll 1$ to solve Eq. (5) approximately. For simplicity, we will also assume in this contribution that the magnetic field and hence the magnetic vector potential remain unchanged; we intend to probe the validity of this assumption in the future. Expanding the electric potential about $\Phi = 0$ as

$$\Phi = \varepsilon \Phi_1 + \ldots, \tag{6}$$

and using this to expand Eq. (5) up to first order in ε we obtain the identities $n_{0,i} = n_0(b+1/2)$ at order ε^0 and

$$e\beta_e \Phi_1 = -\frac{2}{(b+1/2)(1+\beta_i/\beta_e)} \frac{A_x}{B_0 L}, \tag{7}$$

at order ε^1. Substituting this result for Φ_1 back into the (expanded) expression for the electron density, we obtain

$$n_e = n_0 \left(b + \frac{1}{2}\right)(1 + \varepsilon e \beta_e \Phi_1) + \varepsilon n_0 \frac{2A_x}{B_0 L} = n_0 \left(b + \frac{1}{2}\right) + \varepsilon n_0 \frac{\beta_i/\beta_e}{\beta_i/\beta_e + 1} \frac{2A_x}{B_0 L}. \tag{8}$$

Comparing Eq. (8) and Eq. (4), we see that we have gained a factor $\beta_i/\beta_e/(\beta_i/\beta_e + 1)$ at order ε which is always less than one. For $\beta_i = \beta_e$ we obtain the result that the asymmetric density component at order ε is only half of that obtained in [1].

As a next step we plan to include the magnetic field into the expansion in ε, because the current density components are modified compared to the force-free case if the electric potential Φ does not vanish.

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