Electron and ion heating due to magnetic reconnection at the heliopause

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Abstract. Magnetic reconnection is a well-known source of electron and ion bulk heating, as well as energetic particles, in the solar system. Several authors have suggested that reconnection occurs at the heliopause. The paper’s primary focus is to predict the amount of electron and ion bulk heating for heliopause reconnection, using the empirical relations of T. Phan and colleagues between the changes in electron and ion temperature and an Alfvén speed $V_{A,\text{asym},r}$. This Alfvén speed depends on the strengths of the reconnecting magnetic fields and includes asymmetries in the magnetic fields and densities on the two inflowing sides of the reconnection region. For the undisturbed interstellar flow the predicted $V_{A,\text{asym},r} \approx 25$ km/s and the predicted changes in electron and ion temperature are $\Delta T_e \approx 1000$ K and $\Delta T_i \approx 6000$ K. These changes are relatively small and likely not important for dynamics at the heliopause. However, a plasma depletion layer (PDL) is predicted beyond the heliopause, analogous to the PDLs observed sunwards of the magnetopauses of Earth, Mercury, Jupiter, and Saturn. In the PDL, the interstellar (ISM) magnetic field lines drape over the heliopause. Plasma ions and electrons with relatively large parallel temperatures escape along the field, increasing the field strength, decreasing the plasma density, and increasing the Alfvén speed. In the region of the PDL where these effects are strong, the expected field and density changes are a factor of 4 and 1/4, respectively, increasing $V_{A,\text{asym},r}$ by a factor close to 3 and the temperature changes by almost a factor of 10. Thus, heliopause reconnection in a strong PDL is predicted to increase the electron and ion temperatures by up to $10^4$ K and $8 \times 10^4$ K, respectively, corresponding to changes by factors of order 1.5 and 11 compared to the predicted ISM temperature of $\approx 7500$ K. Thus, the effects of bulk heating in heliopause reconnection regions will be most important for plasma inside or magnetically connected to the strong region of the heliopause PDL. As an aside, Coulomb collisions appear too slow to relax the ion temperature anisotropies in the PDL beyond the heliopause, different than for the electrons.

1. Introduction
Driven by data from the Voyager, IBEX, and Cassini spacecraft and by theoretical work and simulations, our understanding of the solar wind’s interactions with the local interstellar medium continues to evolve (Figure 1. For instance, Voyager-1 and -2 observations demonstrate the existence of the solar wind’s termination shock [1, 2], while Voyager-1 data show the existence of a heliopause that separates the shocked solar wind plasma and magnetic fields (in the inner heliosheath) from interstellar plasma and fields [3, 4]. However, IBEX observations provide very strong arguments against an outer bow shock for the solar system, since the inferred fast
mode Mach number is very close to 1.0 [5]. The plasma and fields just beyond the heliopause, in the outer heliosheath [6], are not those of the pristine interstellar medium. Instead these are modified by charge-exchange between interstellar plasma and so-called solar wind neutrals (themselves formed by charge-exchange between interstellar neutrals and protons in the solar wind and inner heliosheath) [7], MHD effects associated with the interstellar flow being slowed and diverted around the heliopause, and the heliopause’s “plasma depletion layer” or PDL [8–10]. PDLs are observed upstream of Earth’s magnetopause [11–13] and at all other planetary magnetopauses where they have been searched for [14, 15]. By analogy with the models for these PDLs, the heliopause’s PDL is where interstellar plasma and field are slowed and amplified, respectively, until they can be deflected away from the PDL’s center plane and slip around the heliopause obstacle. Maximum slowing and field draping should occur in the plane defined by the pristine interstellar flow velocity $V_{ISM}$, the pristine interstellar magnetic field $B_{∞}$, and the Sun.

The modern picture of the PDL involves of draping of magnetic fields across the obstacle (e.g., the heliopause), escape of particles with relatively large $v_{∥}$ along $±B$ away from the draping region (thus decreasing the plasma density), increase of $v_{⊥}$ due to conservation of magnetic moment and $B$ increasing in the draping region, increase of a temperature anisotropy $T_{⊥}/T_{∥}$ via these effects, wave growth driven by the temperature anisotropy, limitation of the wave growth and temperature anisotropy by moving perpendicular particle energy into the waves and parallel particle energy, and evolution of the system to a state of marginal stability in which particle loss along $±B$, the temperature anisotropy, and wave growth are balanced [8–10, 12, 13, 16]. Thus the PDL in the outer heliosheath should have large-scale, anti-correlated gradients in $n$ and $B$.

Figure 1. (a) Schematic of the solar system’s termination shock, heliopause, and PDL, together with interstellar magnetic field lines that are draped over the heliopause. (b) Schematic of the density as a function of radial distance $r$ from the Sun in a direction close to anti-parallel to the undisturbed interstellar flow direction. This shows the $r^{-2}$ fall-off in the solar wind, the increase at the termination shock, and the increase in density at the heliopause and then in the PDL.
with small \( n \) and large \( B \) close to the heliopause. These effects are observed [10], providing strong evidence for a PDL beyond the heliopause. The characteristic spatial scale of the PDL is observed to be of order \( \approx 2.6 \) AU [10], somewhat smaller than the estimated 6–12 AU estimated from a scaling relation based on PDLs observed elsewhere in the solar system [14]; this difference may be due to the heliopause moving outwards due to the effects of solar transients and solar cycle variations [10].

Recently J.R. Jokipii and J. Giacomone [17, 18] and Mostafavi and Zank [19] have argued that the plasma particles should have small mean free paths for Coulomb collisions that are less than 1 AU. This suggests that Coulomb collisions might isotropize the plasma particles and remove the temperature anisotropy required for the foregoing model of the PDL at the heliopause. These aspects are addressed in the Discussion Section below.

When two plasmas with anti-parallel components of \( B \) impinge on one another magnetic reconnection sometimes occurs. This magnetic involves the magnetic field lines reconnecting from one side to the other to change the magnetic topology, the bulk plasma escaping from the reconnection site at speeds close to a suitably defined Alfvén speed (see below) perpendicular to the relative velocity vector of the impinging plasmas, and conversion of some magnetic energy (from the anti-parallel field components) into heating of the bulk plasma and the acceleration of energetic particles.

Magnetic reconnection at the heliopause is expected, by analogy for example with Earth’s magnetopause, with reconnection between draped interstellar (solar wind) magnetic fields and the inner heliosheath (magnetospheric) fields. This paper does not address reconnection in the distant solar wind or in the inner heliosheath well away from the heliopause or changes in the large-scale topology and the shape of the heliopause [20, 21]. Similarly, it does not address the conditions under which reconnection should occur at the heliopause [9, 22] or whether reconnection was occurring when Voyager 1 crossed the heliopause [9, 22–24]. It also does not address whether energetic particles are accelerated in reconnection regions at the heliopause.

Here we predict the amount of electron and ion bulk heating expected at the heliopause, both inside and outside the strong region of the PDL. The approach taken is strongly empirical: we apply the empirical relations of Phan and colleagues (Section 2) and applying them to magnetic reconnection at the heliopause, both within and outside the strong region of the PDL (Section 3). The basic result is that reconnection will not produce major heating at the heliopause, with at most factors of 2 and 10 increase for the electrons and ions, respectively, although heating in the strong field region of the PDL will be approximately a factor of 10 larger than in weak regions of the PDL. Given the low plasma temperatures \( \approx 7000 \) K expected in the local ISM. These results are discussed in Section 4, including comparisons with the heating expected from pickup of charge-exchange protons and lower hybrid drive (LHD) beyond the heliopause [6], which are at least 2 orders of magnitude larger, and a quick sketch of other solar system and astrophysical applications for this empirical prediction technique. The conclusions are in Section 5.

2. Summary of Phan et al.’s empirical model

Phan et al. [25] have analysed over 79 crossings of Earth’s magnetopause and correlated the variations of the bulk electron heating observed as functions of the plasma and field parameters. As illustrated in Figure 2(a), where the quadratic dependence is clear, their result is

\[ k_B \Delta T_e = 0.017 m_i V_{A,\text{asym},r}^2. \]  

Here \( k_B \) is Boltzmann’s constant, \( m_i \) is the ion (proton) mass, and \( V_{A,\text{asym},r} \) is the so-called “asymmetric reconnecting Alfvén speed” that depends on the possibly different magnetic field
strengths and plasma densities on either side of the reconnection region and only involves the reconnecting portion of the fields (e.g., not including the guide field) [27–29]. In detail,

\[ V_{A,\text{asym},r}^2 = \frac{B_{ih}B_{oh}(B_{ih} + B_{oh})}{\mu_0 n_i(B_{ih} + n_{oh}B_{ih})}. \]  

(2)

Here subscripts \( \text{ih} \) and \( \text{oh} \) refer to the inner heliosheath and outer heliosheath, respectively. In the limit that the two sides are symmetric and there is no guide field then (2) reduces to the standard Alfven speed. Including the guide field in \( B_{ih} \) and \( B_{oh} \) will overestimate \( V_{A,\text{asym},r} \) and so the bulk heating.

Equation (1) explains the very small bulk electron heating observed in reconnection regions in the solar wind at 1 AU [25, 30]. In brief, Eq (1) predicts that 1.7% of the ion kinetic energy in the reconnection exhaust regions is found in bulk electron heating in the outflow. This result is qualitatively consistent with multiple kinetic simulations [31, 32].

Analyses by Drake et al. and Phan et al. [26, 33] show a very similar empirical relation to Eq. 1 for the bulk ion heating (Figure 2):

\[ k_B \Delta T_i = 0.13 \frac{m_i}{V_{A,\text{asym},r}^2}. \]  

(3)

Thus the bulk ion heating is predicted to be approximately 7 times the electron heating, naturally producing strongly non-equilibrium plasma with greater ion temperatures than electron temperatures. At this time we assume the heating is isotropic, rather than anisotropic relative to \( \mathbf{B} \). Again, kinetic simulations provide some qualitative support for this model [31–33].

3. Heating due to reconnection at the heliopause

An initial, order of magnitude, estimate for the bulk heating expected from magnetic reconnection at the heliopause follows by assuming that \( V_{A,\text{asym},r} \approx 20 \text{ km}^{-1} \), a typical value expected in the heliosheath without significant draping effects or a bow shock. Figure 2 immediately predicts that \( k_B \Delta T_e < k_B \Delta T_i < 10 \text{eV} \). More precisely Eqs (1) and (3) predict \( k_B \Delta T_e \approx 800 \text{ K} \) and \( k_B \Delta T_i \approx 7000 \text{ K} \). In comparison the temperature in the local ISM is believed to be \( 7500 \pm 500 \text{ K} \) [5].

\[ \begin{array}{c}
(a) \\
\Delta T_e (\text{eV}) \\
V_{A,\text{asym},r} (\text{km/s}) \\
\end{array} \quad \begin{array}{c}
(b) \\
\Delta T_i (\text{eV}) \\
m_i V_{A,\text{asym},r}^2 (\text{eV}) \\
\end{array} \]

Figure 2. (a) After Phan et al.’s [25] Figure N: observations of \( \Delta T_e \) versus \( V_{A,\text{asym},r} \) in terrestrial magnetopause reconnection regions, an associated quadratic fit, and red vertical bars which show the values of 25 and 100 km s\(^{-1}\) relevant to the heliopause for a nominal (Voyager 1) and strong PDL, respectively. (b) Similar to (a) but for the ion heating \( \Delta T_i \), after Phan et al. [26].
The nominal effect of the PDL is to increase the predicted heating by up to a factor $\approx 4$. The reason that is in the strong region of the PDL $B$ is expected to increase by up to a factor of 4 while $n$ decreases by a factor of 4; these changes cause the squared Alfven speed factor in Eqs (1) and (3) to increase by a factor of 4.

Consider now the density and field parameters observed at Voyager 1’s crossing of the heliopause [3, 4, 9, 10]: $n_{ih} = 2 \times 10^{-3}$ cm$^{-3}$, $B_{ih} = 0.25$ nT, $n_{oh} = 0.1$ cm$^{-3}$, and $B_{oh} = 0.30$ nT, Then $V_{A,asym,r} = 24$ km s$^{-1}$ and so $\Delta T_e \approx 800$ K and $\Delta T_i \approx 6000$ K $\approx T_i$, assuming that the fields are anti-parallel (otherwise these are upper limits. These estimates are slightly smaller than for the nominal value of $V$ due to the asymmetries across the reconnection region between the inner and outer heliosheaths.

Taking these asymmetries across the PDL for a maximally strong region of the PDL (as expected for Voyager 2 [10]) leads to $V_{A,asym,r} = 72$ km s$^{-1}$. This is a factor of 3 increase, 50% larger than for a symmetric reconnection site, and pointing towards a factor of 9 increase in heating compared with the PDL for Voyager 1. Then Eqs (1) and (3) predict $\Delta T_e \approx 10^4$ K $\approx 1.3 T_e$ and $\Delta T_i \approx 8 \times 10^4$ K $\approx 11 T_i$, respectively.

4. Discussion
The foregoing Section shows that bulk plasma heating at heliopause magnetic reconnection sites should be relatively small (of order a factor of 2 for ions, but $< 20\%$ for electrons) where the PDL is relatively weak, and less than a factor of 10 for ions and a factor of 2 for electrons where the PDL is strong. These estimates are likely overestimates, since they assume that the reconnecting fields are anti-parallel and have no guide field, contrary to realistic expectations [9]. Thus significant bremsstrahlung EUV or X-ray radiation from these regions are not expected.

Future work is necessary to compare these temperature changes in detail with those expected from adiabatic compression in the PDL (less than a factor of 4 [9]) and with the heating expected from pick-up ions and the associated “lower-hybrid drive” (LHD) process [6, 7, 9, 34]. Concerning the latter point, whereas the effective perpendicular temperature of the pick-up ion ring is $\approx m_n v_{sw}^2 / k_B \approx 10^6$ K and the effective parallel electron heating from LHD is $\approx 10^6$ K, the very low pick-up ion fraction $\approx 0.03\%$ suggests that the temperature changes will be less than $10^4$ K and so small compared with the heating in heliopause reconnection regions. Future work should consider the importance of these heating mechanisms as the source of the mildly superthermal electrons, accelerated by shocks, that drive Langmuir waves beyond the heliopause [4].

It is clear that this paper’s approach can be used to estimate the bulk electron and ion heating expected due to magnetic reconnection in multiple other solar system and astrophysical situations, as well as laboratory experiments. For instance, the characteristic electron and ion temperatures in Earth’s plasma sheet, and especially the factor of $\approx 5 – 10$ higher ion temperatures, follow naturally from Eqs (1) and (3) for characteristic Alfven speeds $\approx 500 – 2000$ kms$^{-1}$. Similar comments are appropriate for solar flares and it would be natural to test Eqs (1) and (3) using solar flare data. In addition, note that the upper limit for $V_{A,asym,r}$ is the speed of light, whence the maximum ensuing bulk electron and ion temperatures are $\approx 0.017 m_e c^2 / k_B = 2 \times 10^{11}$ K and $\approx 0.13 m_e c^2 / k_B = 1.4 \times 10^{12}$ K, respectively. The relevance of these estimates to incoherent UV, X-ray, and radio emission from pulsar winds should be determined.

Another possible line of enquiry is whether analogues to Eqs (1) and (3) exist for the fraction of energy released in energetic particles accelerated in reconnection regions. Data from kinetic simulations and either laboratory could be mined for such relations. These relations may depend on the particular acceleration processes active in the simulations, but would be more powerful if not.

We finish this discussion with some remarks on Coulomb collisions and temperature anisotropies in the PDL at the heliopause. Unexpectedly, recent estimates for the Coulomb
collision mean free path beyond the heliopause are mostly less than 1 AU [17–19], suggesting that the temperature anisotropies required for the usual model for the PDL will not develop [17]. In detail the mean free paths for electron-electron, electron-proton, and proton-proton Coulomb collisions in an unmagnetized plasma with temperatures characteristic of the local ISM are \( \approx 0.2 \) – 0.5 AU, while the proton-electron mean free path is \( \approx 20 \) AU [19]. However, standard theory for temperature isotropisation by Coulomb collisions [35] predicts that

\[
\frac{dT_\perp}{dt} = - \frac{dT_\parallel}{dt} = - \nu_T^e(T_\perp - T_\parallel),
\]

where the rate coefficients for each species are

\[
\nu_T^e \approx 8.2 \times 10^{-7} n \lambda T_e^{-3/2}
\]

\[
\nu_T^i \approx 1.9 \times 10^{-8} n \lambda T_i^{-3/2}
\]

in the limit that \( T_\perp \approx T_\parallel \approx T_\alpha \), and \( n \) and \( T \) are measured in cm\(^{-3}\) and eV, respectively. Here \( \lambda \approx 24 \) is the Coulomb logarithm for \( n = 0.05 \text{ cm}^{-3} \) and \( T = 0.6 \text{ eV} \). Then \( \nu_T^e \approx 2 \times 10^{-6} \text{ s}^{-1} \) and \( \nu_T^i \approx 5 \times 10^{-8} \text{ s}^{-1} \), with the corresponding characteristic times \( \tau_\alpha = 1/\nu_T^e \) equal to \( 5 \times 10^8 \text{ s} \) and \( 2 \times 10^7 \text{ s} \) for electrons and protons, respectively. The corresponding convection distances at \( 25 \text{ km s}^{-1} \), the nominal convection speed in the outer heliosheath, are 0.08 AU and 3.3 AU, respectively.

Thus, within the estimated PDL thickness \( \approx 2.6 \text{ AU} \) observed by Voyager 1, Coulomb collisions are not predicted to be fast enough to isotropise the perpendicular and parallel temperatures of the protons and to remove the temperature anisotropies built by the standard PDL physics. Put another way, the standard ion PDL predicted for the outer heliosheath beyond the heliopause should be robust against the effects of Coulomb collisions. In contrast, Coulomb collisions should be fast enough to remove the corresponding electron temperature anisotropy.

5. Conclusions
Observations near 1 AU provide strong evidence for an empirical model in which the amount of bulk electron and ion heating in reconnection regions is 1.7% and 13% of the ion kinetic energy \( 1/2m_i V_{A,asym,r}^2 \) in the reconnection outflows [25, 26, 33]. This asymmetric, reconnecting, Alfvén speed \( V_{A,asym,r} \) is dependent on the strengths of the reconnecting magnetic fields and includes asymmetries in the magnetic fields and densities on the two inflowing sides of the reconnection region [27–29]. Kinetic simulations provide some support for these models [31–33]. Applying this model to reconnection at the nominal heliopause, for instance for the Voyager 1 crossing, yields changes in electron and ion temperatures of only \( \approx 800 \text{ K} \) and \( 7000 \text{ K} \), respectively. The nominal ISM temperature is \( \approx 7500 \text{ K} \) [5]. However, in strong regions of the PDL (e.g., plausibly for the future Voyager 2 crossing), \( V_{A,asym,r}^2 \) is expected to increase by a factor \( \approx 3 \) and the temperature changes by factors \( \approx 11 \): \( \Delta T_e \approx 10^4 \text{ K} \) and \( \Delta T_i \approx 8 \times 10^4 \text{ K} \). Thus reconnection is predicted to produce strong heating at the heliopause in strong regions of the PDL, and so hot electrons and ions in regions magnetically connected to strong regions of the PDL. Multiple future applications of the foregoing approach appear viable for solar system and astrophysical sources, with the maximum electron and ion temperatures estimated to be \( \approx 2 \times 10^{11} \text{ K} \) and \( 1.4 \times 10^{12} \text{ K} \), respectively, when \( V_{A,asym,r} = c \). Finally, Coulomb collisions appear too slow to relax the ion temperature anisotropies in the PDL beyond the heliopause, different than for the electrons.

Acknowledgments
We acknowledge useful discussions at the 2018 AIAA meeting with P. Mostafavi, J. Giacolone, R. Jokipii, M. Shay, T. Terasawa, and G. Zank. Support for this study comes from the IBEX project, part of NASA’s Explorer program.
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