Nonlocal electron heating at the Earth’s bow shock and the role of the magnetically tangent point

J. J. Mitchell and S. J. Schwartz

1. Introduction

Shocks occur in numerous situations in space plasmas, including the solar wind upstream of planetary magnetospheres. These bow shocks slow the solar wind flow to submagnetosonic speeds, creating a region of heated plasma in the magnetosheath, which lies between the shock and the magnetopause. Electron and ion heating at the shock is thought to depend to some extent upon the local conditions upstream of the shock, including the Alfvén and magnetosonic Mach numbers, $M_A$ and $M_{ms}$, the ion and electron plasma betas, $\beta_i$ and $\beta_e$, and the angle $\theta_{fu}$ between the upstream solar wind magnetic field $\mathbf{B}_u$ and the shock normal $n$.

Typical features of the magnetosheath plasma include a larger temperature for the ions than for the electrons, with the temperature increase for each species typically satisfying $\Delta T_e/\Delta T_i \sim 0.1–0.2$ [Schwartz et al., 1988], highly anisotropic ion velocity distributions with $T_{i\bot} > T_{i||}$, with subscripts $\| \text{ and } \perp$ denoting temperatures relative to the magnetic field [Thomsen et al., 1985], and very isotropic electron distributions (although often becoming less isotropic moving deeper into the magnetosheath toward the magnetopause) [Masood and Schwartz, 2008]. The electron distributions display non-Maxwellian features and are characterized by a flat-top shape [Feldman et al., 1983].

Some idea of the properties of the shocked solar wind may be gained using the Rankine-Hugoniot jump conditions [e.g., Burgess, 1995], which are obtained by treating the plasma as a fluid, assuming a planar shock, and enforcing fluid and electromagnetic conservation laws across the shock. This approach suffers from a number of drawbacks, including that it often does not distinguish between electron and ion heating, instead making use of the total plasma temperature; it ignores kinetic effects; and it requires an assumption about the equation of state of the plasma, often prescribed as a polytropic law relating the thermal pressure $P$ to the mass density $\rho$, of the form $P \propto \rho^{\gamma}$, for some index $\gamma$.

Much work has been done on the mechanisms involved in shock heating of electrons and ions. Many processes may influence electron heating, including interactions with waves and instabilities [Galeev, 1976; Wu et al., 1984] and electron scattering [Balikhin et al., 1993]. Detailed...
reviews of these include Savoini and Lembège [1994], Gedalin and Griv [1999], Hull et al. [2001], and Lembège et al. [2003]. Early work on the theory of shock heating made use of a critical Mach number, below which resistive processes in the shock would be sufficient to account for shock heating, while for supercritical shocks some other mechanisms are required. See Treumann [2009] for a review.

[6] In studying electron heating at shocks, it is often useful to work in the de Hoffmann-Teller frame of reference, in which the shock is at rest and in which the bulk velocity \( \mathbf{U} \) and the magnetic field \( \mathbf{B} \) are (anti-)parallel, resulting in the motional electric field \( \mathbf{E} = -\mathbf{U} \times \mathbf{B} \) being zero. In this frame, the electrons’ energy gain is controlled by the cross-shock potential. The normal incidence frame of reference, defined as the frame in which the upstream bulk velocity is antiparallel to the shock normal, is also important. However, in this frame, the energy gain depends upon the trajectory each electron takes in crossing the shock and, in particular, upon distance the electron drifts along the shock front in the direction perpendicular to the upstream (and downstream) \( \mathbf{B} \) and \( \mathbf{U} \). Transforming from the normal incidence frame into the de Hoffmann-Teller frame requires a boost velocity of magnitude \( |U_n \tan \theta_{bn}| \), where the subscript “\( n \)” denotes the component along the shock normal. Close to the tangent \( \theta_{bn} = 90^\circ \) point on the shock where this exceeds the speed of light, it becomes impossible to define a de Hoffmann-Teller frame. Electron behavior at such perpendicular shocks depends on both the transverse particle drifts and internal shock structure [e.g., See et al., 2013].

[7] Ions are heated via a different mechanism. In the de Hoffmann-Teller frame, an ion interacting with the shock encounters an increasing magnetic field, as well as a cross-shock potential which acts to decelerate the ion. While most of the ions are able to cross the shock, up to around 20% of ions are reflected by the magnetic field gradient and cross-shock potential. At quasi-perpendicular shocks (\( \theta_{bn} > 45^\circ \)), the guiding center of reflected ions still moves downstream, however, resulting in ion distributions in the magnetosheath which tend to be highly anisotropic, with \( T_{\perp} > T_{\parallel} \) [Paschmann et al., 1980]. The ion and electron heating are linked by the total shock energy budget. Additionally, the de Hoffmann-Teller frame cross-shock potential is supported by the electron thermal pressure gradient, again linking the electron heating to the ion dynamics [Goodrich and Scudder, 1984; Scudder et al., 1986a].

[8] Observations of electron heating at shocks show that the single most important parameter in determining the change in electron temperature is the upstream, unshocked (subscript “\( u \)” or “\( \text{up} \)” bulk kinetic energy \( E_{\text{ram}} = m_p U_n^2 \text{up}/2 \), where \( m_p \) is the proton mass. Schwartz et al. [1988] showed that the electron heating, when normalized to this bulk kinetic energy, approximately varies as \( M_{\text{d}}^{-1} \), although this holds less well for subcritical shocks. Similar dependencies have been found at high Mach number shocks at Saturn [Masters et al., 2011] and even supernova remnant shocks [Ghavamian et al., 2013].

[9] Feldman et al. [1983] pointed out that solar wind electrons crossing the bow shock would traverse the magnetosheath and exit back into the solar wind at some other location on the bow shock surface. More recently, Mitchell et al. [2012] used observations from two spacecraft to demonstrate that such electrons traverse the magnetosheath without appreciable scattering, since the shape of the relevant portions of the electron phase space distribution, \( f_e(\mathbf{v}) \), was consistent with the predictions of Liouville’s theorem. The fact that portions of \( f_e(\mathbf{v}) \) are imposed by distant shock processes means that the heating at a point on the shock surface may not be determined purely by the local upstream conditions. Instead, shock electron heating (and therefore shock ion heating) may be a global problem that requires consideration of electrons arriving from different points on the bow shock. For brevity, we refer to this concept as “electron cross talk.”

[10] J. J. Mitchell and S. J. Schwartz (Isothermal magnetosheath electrons due to nonlocal electron cross talk, submitted to Journal of Geophysical Research, 2013) investigated this global electron heating problem by a combination of Liouville-mapping procedures, following both solar wind electrons which enter the magnetosheath and shocked electrons as they traverse the magnetosheath, and shock conservation laws. In this way, they reconstructed the electron distributions, \( f_e(\mathbf{v}) \), as a function of location just downstream of the bow shock. Their method is summarized briefly in section 2. The result of this calculation is that the electron temperature along a magnetic field line, as it convects deeper into the magnetosheath and hence crosses the bow shock at different locations, remains remarkably constant despite the fact that purely local Rankine-Hugoniot considerations require a much larger variation in the total (ion plus electron) shock heating. Mitchell and Schwartz (submitted manuscript, 2013) interpreted this result as a consequence of the high electron mobility which essentially communicates the electron heating at one shock location to another. The one location that cannot receive shocked electrons is the point of magnetic tangency, i.e., the point where the magnetic field line first touches the bow shock surface and where the shock geometry is exactly perpendicular. In Mitchell and Schwartz (submitted manuscript, 2013), the shock heating at this point is a free parameter which then sets the scale of the electron temperature everywhere else. As the field line convects deeper into the magnetosheath, the temperature on a particular field line decreases [Feldman et al., 1983] but only slightly. We stress here that this process (see section 2) relies on the convolution of \( f_e(\mathbf{v}) \) values from different locations, transported unchanged by scatter-free electron trajectories with help from Liouville’s theorem, to construct \( f_e(\mathbf{v}) \) downstream of the bow shock. This nonlocal perspective is very different from a local prescription of electron heating based, e.g., on an equation of state or collision-like thermal conduction law.

[11] The global nature of shock electron heating has two important consequences. First, if the model captures the primary physics, then the electron heating everywhere at curved bow shocks can be linked to the conditions at exactly perpendicular shocks. This removes the local shock geometry, i.e., the angle \( \theta_{bn} \) between the shock normal and upstream magnetic field, from the parameter space (Mach number, plasma \( \beta \), etc.) and thus reduces the dimensionality of the problem. Second, the nonlocal nature of the electron heating has potential implications for the ion heating. The ion heating may need to compensate for the lack of variation in electron heating as the total one-fluid Rankine-Hugoniot heating requirements vary around the shock. That compensation may be small due to the dominance of ion
heating [Schwartz et al., 1988], especially at higher Mach numbers. Additionally, the strong influence of the electron physics on the details of the shock transition (current layers, cross-shock potential) may impact on the ion kinetics (e.g., specular versus nonspecular reflection [Scopke et al., 1983, 1990] and thickness of the shock layer [Schwartz et al., 2011]) which in turn modifies the effective ion equation of state.

[12] In this paper we examine a number of shock crossings to study the effects of electron cross talk and to determine whether the tangent point is indeed in control of electron heating at the bow shock. In section 2, we review the model of Mitchell and Schwartz (submitted manuscript, 2013) and their conclusion that the electron temperature is highly influenced by the heating at the point where the field line first encountered the shock. In section 3, we discuss the sources of the data and some analysis techniques used. Section 4 compares electron temperatures measured by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) B and Cluster 2 spacecraft in the magnetosheath at times when they both encounter the same field line. We find that on these occasions the electron temperatures measured by the spacecraft are very similar, in agreement with the predictions based on electron cross talk. Section 5 presents the statistics of observations of electron heating in terms of parameters both locally and inferred for the tangent point. We find that there is a better correlation between heating and plasma parameters at the tangent point than with local parameters, confirming the prediction based on electron cross talk that heating at the tangent point has a major influence on the electron temperature throughout the magnetosheath.

2. Global Modeling of Electron Behavior at the Bow Shock

[13] In this section, we briefly summarize work presented by Mitchell and Schwartz (submitted manuscript, 2013) on the motion of electrons between distant regions on the shock surface and the effects this has on the heating properties of the shock. A sketch summarizing electron motion is displayed in Figure 1. It is convenient to decompose the velocity of electrons in the magnetosheath into different parts, specifically a portion parallel to the magnetic field, a perpendicular component gyrating about the magnetic field, a perpendicular component perpendicular to B, and a drift component perpendicular to B, \( \mathbf{v}_\parallel \approx \mathbf{E} \times \mathbf{B} / B^2 \). (We neglect gradient and curvature drifts.) The large-scale motion of electrons is therefore determined by \( \mathbf{v}_\parallel \) and \( \mathbf{v}_\perp \), which give the velocity of the gyrocenter. The \( \mathbf{E} \times \mathbf{B} \) drift results in the perpendicular motion being the same as the perpendicular component of the plasma bulk velocity, since the electric field is dominated by the motional part, \( \mathbf{E} = -\mathbf{U} \times \mathbf{B} \).

[14] Mitchell and Schwartz (submitted manuscript, 2013) employ an approach that steps with the field line as it convects deeper into the magnetosheath and therefore as its entry/exit points move along the shock surface away from the initial tangent point of contact. Figure 1 depicts the situation at a time when the field line in question threads the bow shock at points A and B and for which the electron distribution function \( f_e(\mathbf{v}) \) has already been determined along the blue portion of the bow shock. Mitchell and Schwartz (submitted manuscript, 2013) consider electron trajectories arriving at A from this blue portion. Assuming the electrons travel without scattering [Mitchell et al., 2012], Liouville’s theorem implies that \( f_e(\mathbf{v}) \) will be the same at a trajectory’s starting position, \( A_i \), and at \( A_f \). Due to their different values of \( \mathbf{v}_\parallel \), the resulting portions of \( f_e(\mathbf{v}) \) at \( A \) are a convolution of values from these different points \( A_i \) with the initial and final positions and velocities connected by individual electron trajectories.

[15] Similarly, Liouville’s theorem can also be applied to electron trajectories traversing the shock from the solar wind at \( A \) into the downstream region. For a given set of upstream conditions (solar wind electron distribution, bulk flow, and plasma parameters) and simple assumptions about the magnetic profile and shock jump conditions, the resulting portions of phase space for such transmitted electrons depend only on the de Hoffmann-Teller cross-shock potential [e.g., Scudder et al., 1986b]. This process leaves holes in phase space corresponding to regions which are inaccessible from both upstream and downstream electron trajectories. Mitchell and Schwartz (submitted manuscript, 2013) fill such holes by setting \( f = F \) = constant, mimicking the observed “flat-top” electron distributions [Feldman et al., 1983]; they also flatten Liouville-mapped values of \( f \) that are higher than this constant value, again taking guidance from many reported observations [Feldman et al., 1983; Scudder et al., 1986b].
This completely specifies the downstream distribution at $A$ as a function of two unknown parameters, namely, the de Hoffmann-Teller cross-shock potential and the value of $F$. These values are adjusted so that the downstream density matches that predicted from the local Rankine-Hugoniot solution for the shock compression and so that the resulting electron distribution carries zero parallel electric current. The second velocity moment of this constructed $f_e$ then provides the downstream electron temperature.

From this brief description, it is perhaps evident that the spread in velocity of the distribution is strongly influenced by the velocities of electrons traversing from the distant points $A_i$ and that the de Hoffmann-Teller potential provides a spread in the opposite direction which must be of a similar scale in order to yield zero parallel current. Thus, the downstream temperature at $A$ is heavily influenced by distant locations along the bow shock rather than purely local considerations.

In order to start this calculation, Mitchell and Schwartz (submitted manuscript, 2013) specify the electron temperature downstream of the tangent point. This is a free parameter in their model, since electrons from other points on the bow shock can never reach it. In practice, a small but finite region in the vicinity of the tangent point is assigned this value of the electron temperature in order to overcome the limitations of superluminal de Hoffmann-Teller transformations for $\theta_{\text{bo}}$ close to 90°. Mitchell and Schwartz (submitted manuscript, 2013) explore the behavior of the model for different values of this tangent point electron temperature.

The main results that emerge from this model are that the electron temperature on a field line remains largely constant as the line convects deeper into the magnetosheath and that this temperature is directly related to the heating that occurs at the tangent point. In this paper we look for observational evidence of these two properties in sections 4 and 5.

### 3. Data and Analysis

In this section, we briefly cover some of the analysis techniques used in this paper and discuss the data obtained from various spacecraft. In particular, we discuss issues involved with simultaneous heating at different locations on the shock during a single shock encounter.

We make use of a coordinate system that we denote by $\mathbf{UB}$, which is defined as follows. (1) The origin lies at the Earth. (2) The $z$ axis is chosen such that it is parallel to the cross product of the unshocked solar wind velocity and magnetic field $\mathbf{U}_{\text{up}} \times \mathbf{B}_{\text{up}}$. (3) The $x$ axis is chosen such that it lies in the GSE $x$-$z$ plane so that the dot product of the GSE and $\mathbf{UB}$ $x$ direction unit vectors is positive, $\mathbf{x}_{\text{GSE}} \cdot \mathbf{x}_{\text{UB}} > 0$. (4) The $y$ axis is chosen such that the system is right handed. In this way, planes of constant $z_{\text{UB}}$ correspond to (upstream) $\mathbf{U}_{\text{up}} \times \mathbf{B}_{\text{up}}$ planes.

In order to compare heating at different locations on the shock, it is necessary to ensure that comparable portions of the solar wind flow are being examined. This is accomplished by applying time lags to the spacecraft data. That is, given spacecraft at two distant locations, solar wind plasma with the same parameters and fields will generally encounter each spacecraft at different times. This is further complicated by the highly turbulent magnetosheath flow, resulting in varying flow times from one spacecraft to the other. Accordingly, we divide the spacecraft data sets into 5 min subintervals, each of which is given its own lag time. THEMIS is used as the reference time, that is, data from other spacecraft are lagged to match THEMIS data. We lag ACE, Wind, and Cluster 2 data by maximizing the correlation function between each of their magnetic fields and the THEMIS B magnetic field. The lag time associated with...
each data point for the magnetic field data may then be applied to other data sets, such as the temperature. The data used for this comparison are obtained from the following sources. Magnetic field data come from the ACE Magnetic Field Experiment [Smith et al., 1998], the THEMIS Fluxgate Magnetometer [Auster et al., 2008] from the THEMIS B spacecraft, the Cluster 2 Fluxgate Magnetometer [Balogh et al., 1997], and the Wind Magnetic Fields Investigation magnetometer [Lepping et al., 1995]. Shocked electron and ion temperatures are obtained from the THEMIS electrostatic analyzer [McFadden et al., 2008] and Cluster Plasma Electron and Current Experiment [Johnstone et al., 1997]. Upstream ion data are taken from the ACE Solar Wind Electron, Proton, and Alpha Monitor [McComas et al., 1998] while we use the Wind Solar Wind Experiment electron data [Ogilvie et al., 1995].

### 4. Comparison of Simultaneous Heating at the Bow Shock

[23] In this section, we examine electron heating at both the Cluster 2 and THEMIS B spacecraft in the time period between approximately 17:00 and 22:00 on 4 May 2008. During this period, both of these spacecraft are in the magnetosheath approaching the bow shock. Due to the orbits of the spacecraft, they are located at widely separated locations near the bow shock surface, with GSE positions at time 21:30 of [5.8, 17.9, –7.6] RE (Earth radii) and [10.1, –11.9, –0.70] RE for THEMIS and Cluster, respectively. This simultaneous crossing is especially interesting since, for much of the time period in question, the two spacecraft lie in the same, or very similar, Uup × Bup planes. When the spacecraft do inhabit the same plane, the lagging technique described in section 3 may be used to compare conditions when each of the spacecraft encounter an individual magnetic field line. Lagged magnetic fields measured by each spacecraft are displayed in Figure 2. The fact that the fields in the magnetosheath do not closely match is not unexpected, as the increase in each component of B depends upon the local shock geometry, as described by the Rankine-Hugoniot jump conditions.

[24] The electron heating, \( k_B \Delta T_e \equiv k_B(T_e^{up} - T_e^{sw}) \) observed by Cluster 2 and THEMIS B (“C” and “T,” respectively) are displayed in Figure 3, where the upstream temperature \( T_e^{sw} \) is obtained from (lagged) Wind data and \( k_B \) is the Boltzmann constant. This figure also displays \( M_A, \beta_e \) and \( \theta_{Bn} \) in the solar wind, as well as the magnetic fields measured by the spacecraft. The quantities \( \Delta T_e/\Delta E_{kin} \) are calculated both locally and at the tangent point. For the latter, we first find the intersection of a 3-D bow shock model with the individual spacecraft Uup × Bup plane. We then find the point on this intersection where \( \theta_{Bn} = 90^\circ \). Finally, we

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**Figure 3.** Plasma and shock parameters from Cluster 2 and THEMIS B on 4 May 2008. In the first, second, third, and fifth panels, blue and red lines correspond to data from THEMIS and Cluster, respectively. In the second and third panels, light blue and dotted orange curves correspond to local values of parameters, while red and blue lines show values inferred for the tangent point. The first panel shows the electron heating \( k_B \Delta T_e \) measured by the Cluster (red) and THEMIS (blue) spacecraft, where upstream electron temperatures are determined by Wind. The second panel shows the change in electron temperature normalized by the change in ram energy. The third panel displays the Alfvén Mach number; the fourth panel shows the electron and ion \( \beta \) values (green and black lines, respectively). The fifth panel shows the local shock \( \theta_{Bn} \) at each spacecraft, showing that THEMIS B is downstream from a highly perpendicular shock, while Cluster 2 varies between quasi-perpendicular and quasi-parallel. The dashed horizontal lines are at \( \theta_{Bn} = 30^\circ \) and \( 45^\circ \). The sixth and seventh panels show the magnetic field magnitude (black) and GSE components (x, y, and z = red, green, and blue) measured by THEMIS and Cluster, respectively.
find the shock normal and the normal component of the incident velocity there and calculate $\Delta E_{\text{kin}} = (m_e/2)(U_{n,\text{up}}^2 - U_{n,\text{down}}^2)$. Here $U_n$ is the component of the bulk velocity along the shock normal, and $U_{n,\text{down}}$ is its downstream value as deduced with the help of the Rankine-Hugoniot relations. As described in section 2, we assume that $\Delta T_e$ is the same at all locations. Figure 3 already reveals that THEMIS and Cluster are downstreams of different portions of the bow shock (e.g., different upstream $\theta_{Bn}$ values) and that they sometimes, but not always, observe similar electron heating. This figure provides the context for the analysis carried out in the remainder of this section.

[25] Figure 4 shows the difference between the electron temperatures obtained by the two spacecraft, $\Delta T_{SC} = |T_e^C - T_e^T|$. As the quantities displayed in Figure 4 have all been appropriately lagged, in order to determine when spacecraft encounter the same field line, it is necessary only to ensure that each spacecraft occupies the same $U_{\text{up}} \times B_{\text{up}}$ plane. To accomplish this, we display the distance $|\Delta z_{UB}|$ between the $U_{\text{up}} \times B_{\text{up}}$ planes containing Cluster and THEMIS. We predict that when $|\Delta z_{UB}|$ is small, the electron temperature should be the same since the electron temperature is predicted to be almost constant along a field line. It should be pointed out that the converse that large separations should lead to large $|\Delta T_{SC}|$ does not hold.

[26] There are four intervals where $|\Delta z_{UB}|$ is small and therefore where we expect $\Delta T_{SC}$ to be close to zero. These are shaded in Figure 4. In periods 2–4, we see that the expected low values of $|\Delta T_{SC}|$ are indeed observed.

[27] The first interval of low $|\Delta z_{UB}|$ takes place just after 20:25. Here we see that the expected small temperature difference between the spacecraft is not observed. An explanation for the departure from the expected behavior may be found in acknowledging that constancy of electron temperatures along a field line may not hold at very large distances from the tangent point. Influences which may conspire to defeat the expected behavior include the following: (i) The increased distances electrons must travel in such scenarios increase the influence of processes such as interactions with waves and various instabilities that are common in the magnetosheath, influencing both electron mobility (fluxes) and the electron energy (heating) responsible for the cross talk depicted in Figure 1. (ii) The magnetic field increases in the magnetosheath toward the magnetopause such that electrons may be mirrored away from the magnetopause, again limiting electron cross talk. (iii) The increase in $|B|$ near the magnetopause also results in the $VB$ drift becoming...

**Figure 5.** Positions of the bow shock and magnetopause along with THEMIS B, labeled T, Cluster 2, C, and the tangent point, $\perp$, in the $U_{\text{up}} \times B_{\text{up}}$ frame on 4 May 2008 at 20:29:30 and 20:35:00 (corresponding to shaded regions 1 and 2 in Figure 4). (left) The perpendicular point is located far down the flank, so that electrons must travel very large distances to reach Cluster. Their trajectories also penetrate deeper into the magnetosheath and approach quite closely to the magnetopause. (right) The tangent point is much closer to the bow shock nose, leading to trajectories that penetrate less deeply into the magnetosheath.
more influential and thereby dispersing electrons out of the $U_{up} \times B_{up}$ plane.

For interval 1, starting just after 20:25, as we shall see below, the distance from Cluster 2 to the tangent point is large, with $|x - x| > 40 R_E$. Additionally, the fifth panel of Figure 3 shows that the local $\theta_{bn}$ corresponds to quasi-parallel conditions, usually accompanied by considerable variability in the magnetosheath parameters. This suggests that for such large distances and low values for $\theta_{bn}$, the scatter-free assumption along magnetic field lines from one flank to the other ceases to hold.

To evaluate what is taking place during this interval, we plot the positions of the spacecraft along with the position of the tangent point and model positions for the bow shock and magnetopause. Figure 5 shows these arrangements at times 20:29:30 and 20:35:00, corresponding to periods labeled 1 and 2 in Figure 3. Both of these plots are in the $U_{up} \times B_{up}$ plane, which contains both spacecraft positions along with the tangent point. The curves displayed here are the intersections of this plane with model 3-D shock and magnetopause surfaces. The two plots are very similar, except that the magnetic field direction has rotated slightly between the two plots. As a result, the location of the tangent point is further down the flank in the left plot than in the right and consequently is much farther away from Cluster 2 in the left plot. Furthermore, the view of the tangent point from Cluster 2 is obscured by the magnetopause, meaning that field lines connecting these two points must be heavily draped around the magnetopause nose where $|B|$ is large. We expect therefore that electron transit between the tangent point and Cluster 2 is hampered during the first interval.

Figure 6. Plasma and shock parameters measured by THEMIS B on 2 May 2008. Unbroken and dotted lines show values at the tangent point and local point, where it is necessary to distinguish between the two. The first panel shows the electron heating ($k_B \Delta T_e$) measured by the THEMIS spacecraft, where upstream temperatures are determined by Wind. The second panel shows the change in electron temperature normalized by the change in ram energy. The third panel shows the electron and ion $\beta$ values (green and black traces, respectively). The fourth panel displays the Alfvén Mach number. The fifth panel shows the local $\theta_{bn}$; the dashed horizontal line is at $\theta_{bn} = 45^\circ$. The sixth panel shows the magnetic field measured by THEMIS.

Figure 7. Electron heating at the THEMIS B spacecraft as a function of $M_A$ and $M_{ms}$ calculated at the (a and b) tangent point, and (c and d) locally, for the time period displayed in Figure 6. The lines are log-log linear regression fits to the data, with the values of the slopes as shown in the figure and correlation coefficients $r = 0.69, 0.71$ in Figures 7a and 7b, respectively.
and that agreement between electron temperatures may be poor. In contrast, electrons from the vicinity of the tangent point have a shorter, less obstructed route to Cluster 2 in the second interval, and we see the expected agreement between electron temperatures. We conclude therefore that these observations are consistent with the prediction that electron temperatures are approximately constant along magnetic field lines in the magnetosheath, until the field lines reach points sufficiently deep in the magnetosheath, where processes such as scattering may become important.

5. Variations in Upstream Conditions

[30] In this section, we examine electron heating at the bow shock as a function of upstream conditions by comparing electron heating with local parameters, as well as with upstream conditions at the tangent point. We examine a second shock crossing by THEMIS B on 2 May 2008 between around 15:00 and 19:00, during which the spacecraft is inside the magnetosheath, except for a brief period around 16:30 when it is in the solar wind. Figure 6 provides an overview of the plasma conditions encountered by THEMIS B. During this interval, as on 4 May 2008, THEMIS B is behind a quasi-perpendicular shock (see the fourth panel in Figure 6). Unlike the 4 May 2008 interval, however, the range in $\theta_{\text{bn}}$ is much larger, with the spatial separation between the tangent point and the spacecraft position modest but variable. Thus, we expect reasonably good electron cross talk between the tangent point and THEMIS B, unlike Cluster in the first 4 May 2008 interval. Note that the dotted lines in Figure 6, corresponding to values inferred at the tangent point, show greater departures from the local values than the equivalent pairs of lines in Figure 3.

[31] Figure 7 shows the normalized change in electron temperature against $M_A$ and $M_{\text{ms}}$, using parameters from the tangent point and local values. We find that the normalized temperature change inferred at the tangent point correlates very well with the inverse Mach numbers there. For values at the local point, however, we find a very poor correlation and none of the expected inverse Mach number relationships. This again shows very clearly that since the heating correlates well only with the conditions at the tangent point, it is the tangent point which is responsible for controlling electron heating at the bow shock.

[32] Shock heating of electrons and ions has typically been thought to vary as a function of several upstream parameters including Mach numbers, plasma $\beta$ values, and $\theta_{\text{bn}}$. If electron heating is determined by the tangent point, however, then $\theta_{\text{bn}}$ need not be considered. This reduces the dimensionality of the parameter space. In Figure 8 we show electron heating as a function of Mach number (Alfvén and fast magnetosonic Mach number at the tangent point) and upstream plasma $\beta$ (ion and electron). We recover the tendency for $\Delta T_e/\Delta E_{\text{ram}}$ to decrease with increasing Mach number [Schwartz et al., 1988]. In addition, Figure 8 suggests that $\Delta T_e/\Delta E_{\text{ram}}$ increases with $\beta$. This trend appears more convincing for $\beta_i$ than for $\beta_e$ and probably slightly better for $M_{\text{ms}}$ than for $M_A$. A regression analysis is used to fit the data to a function of the form $\Delta T_e/\Delta E_{\text{ram}} = AM^{m\beta l}$. Fitting to $M_A$ and $\beta_i$, the parameters are $A = 0.45$, $m = -1.03$, and $l = 0.32$. Fitting to $M_{\text{ms}}$ and $\beta_i$, the parameters are $A = 0.35$, $m = -1.06$, and $l = 0.18$.

6. Conclusion

[33] It has long been known that there is a statistical correlation between the electron temperature jump and
the jump in available ram energy [Thomsen et al., 1987]. Examination of such statistical data further revealed an approximate relationship between the change in electron temperature normalized by the change in ram energy over the shock with the inverse Alfvén Mach number [Schwartz et al., 1988]. These gross properties reflect the consequences of changes in the properties of the incident solar wind. In the present study, we have considered the variation of electron heating around the bow shock under relative steady conditions in order to investigate nonlocal influences on the shock heating due to the collisionless nature of the magnetosheath plasma. 

[34] The scatter-free nature and high mobility of electrons along magnetic field lines in the magnetosheath, and the influence of the magnetosheath electrons on the shock itself, imply that the electron temperature on a magnetic field line inside the magnetosheath should remain constant (Mitchell and Schwartz, submitted manuscript, 2013). Furthermore, the point at which the field line first makes contact with the shock, at which the shock is perpendicular, is therefore responsible for establishing that electron temperature.

[35] Examining data from bow shock crossings by Cluster 2 and THEMIS B has allowed us to determine whether these expected behaviors are in fact present. When the two spacecraft are connected by a single field line, we find good agreement between the electron temperatures, although this relationship breaks down when the tangent point is down the flank, impeding the transit of electrons to the other side of the magnetosheath, for example, through mirroring, enhanced drifts, and/or wave-particle scattering.

[36] We also examined the relationship between the electron heating and the conditions both locally and at the tangent point. We find that there is a good correlation between heating and conditions at the tangent point, with the normalized heating decreasing with Mach number and increasing with plasma beta. This correlation is poor using local data. This provides strong evidence that the electron heating at the bow shock is not a local problem, since the tangent point controls electron temperature along a field line. The nonlocal nature of the shock electron heating has potential implications for the energy available for ion heating or, via the impact on the details of the shock fields and structure, the ion dynamics and effective equation of state.

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