

Response to “Comment on ‘Parallel electric fields in the upward current region of the aurora: Numerical solutions’” [Phys. Plasmas 10, 1175 (2003)]

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The Comment on our article contains a general statement and three more specific points to which we reply. We hold that the general statement of the Comment, “a fully dynamic, multidimensional analysis is needed for even the lowest order solution (of an oblique double layer)” is not true in the example that we presented. The general statement is based on an argument that the first adiabatic moment of H⁺ is violated as the ion traverses the double layer. We demonstrate here that this argument is erroneous and that, in fact, the first adiabatic moment of H⁺ is largely conserved. Our article identifies several areas where a dynamic simulation is needed to fully understand the observations of the auroral double layer and the ion (mainly O⁺) dynamics. © 2003 American Institute of Physics. [DOI: 10.1063/1.1559477]

The Comment¹ on our article² contains a general statement and three more specific points. Part of Point (2) of the Comment¹ is valid. There is an inaccuracy in the table in Fig. 6 of the original article² which we correct here (Table I). We called out the temperature of the ionospheric electrons as ~3 eV in that table. Here, we remove that number, recognizing that it was inaccurate and misleading. The derived and observed electron distributions are highly non-Maxwellian and the ~3 eV temperature reflects a small, cold core which does not dominate the ionospheric electron behavior.

We correct two other errors in our article² not relevant to the Comment.¹ The ionospheric ion temperature is 3.2 eV, not 32 eV as stated in the same table. The correct temperature is in several places in the article² and the Comment¹ did recognize and use the correct value. We also correct an error in Eq. (10) of the original article. The equation should read

$$\frac{n_p v_p}{n_u v_u} = \sqrt{\left(1 - \frac{e}{M \omega_{ci}^2} \frac{dE_x}{dx}\right)^2 + \left(\frac{e}{M \omega_{ci}^2} \frac{dE_x}{dz}\right)^2} \times \left(\frac{K_0 - e\Phi}{K_0 - e\Phi - \frac{1}{2} M \left(\frac{E_x}{B}\right)^2}\right)^{1/2}. \quad (1)$$

The numerical solutions in the original article use the correct form of the equation.

The introductory section of the Comment¹ contains several minor factual errors that we would like to address. We do not neglect E_x as the Comment¹ indicates. The solutions are not “quasi-neutral,” rather, they contain two charge lay-

ers as plotted in Fig. 6(d) in our article.² Ambient electron measurements are available down to 5 eV, but such electrons may contain satellite-generated photoelectrons so we did not use this population of electrons for direct comparison. The low-energy (<1600 eV) electrons that emerge from the ionospheric side are not entirely a “free parameter.” These electrons are calculated from the planar double layer model and compared to the observations which are valid in the 100 eV to >1600 eV energy range. In our opinion, the entire problem is quite well constrained.

The Comment¹ contends that the ion gyroradius plays an important role in the perpendicular scale of the double layer. Interestingly, to make this point, the Comment¹ calls for analytic solutions³ to take precedence over fully dynamic numerical simulations of oblique double layers⁴ (which conclude that the ion gyroradius does not play a major role), decidedly the opposite argument used in his abstract (fully dynamic simulations are needed for the lowest order solution). We disagree that Swift⁵ supports the arguments in the Comment.¹ Swift⁵ concludes that “the ion gyroradius must in some sense be small in comparison to the width of the shock.” We are in full agreement with this conclusion. While there may be cases in which the ion gyroradius must be considered, the plasma conditions in the observed double layer that we analyzed have small H⁺ gyroradii ($\rho_i \cong 20$ m) compared to the scale size of the double layer ($z_0 = 4$ km; $x_0 = 2$ km) so it is unlikely that the H⁺ gyroradii play a major role in the scale of the double layer (O⁺ gyroradii, however, may play a role). The Comment¹ also contends that test particle simulations⁶ have shown that magnetic moments of ions are not conserved as they pass through double layers. We interpret the results of the referenced ar-

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TABLE I. Corrected table for Fig. 6 of Ref. 2.

Species	Type of fit	Dens (cm ⁻³)	Temp (eV)	Drift (ν_d/ν_{th})
Ionospheric ions	Drifting Maxwellian	4.00	3.2	2.0
Ionospheric electrons (>1600 eV)	Flat top Eq. (7)	0.30	~1500 (500)*	...
Ionospheric electrons (≤1600 eV)	Derived	3.40
Auroral cavity ions	Maxwellian	0.15	5000	...
Auroral cavity electrons	Flat top Eq. (7)	0.30	~1800 (500)*	...

ticle (Ref. 6) far differently; Borovsky⁶ demonstrates that H⁺ adiabatic moments are generally conserved (see Fig. 15 in Ref. 6). In that article (Ref. 6), the change in magnetic moment in the test particle simulations was demonstrated under substantially different plasma conditions ($\rho_i \sim x_0$) so they do not apply directly to our analysis. We demonstrate the H⁺ first adiabatic moment is largely conserved in the double layer that was analyzed in our article.²

The first part of Point (2) of the Comment discusses the density of the positive charge layer. The density of the reflected ionospheric electrons (derived) in Fig. 6 of our article (Ref. 2) does not behave as a Maxwellian of 3 eV. We realize that ~3 eV was entered in the table on Fig. 6 of our article² and correct that inaccuracy here.

In the second part of Point (2) the author of the Comment¹ makes the argument that the ambient perpendicular electric force ($e\Delta E_x$) exceeds the magnetic force ($e\nu_{\perp}B$) which should break the proton's first invariant. We argue that the condition $e\Delta E_x > e\nu_{\perp}B$ is not relevant to breaking or preserving the first adiabatic invariant, rather, it is a condition for cyclodial motion. We hold that the condition used in our article² and by Swift⁵ is more applicable:

$$\epsilon = \frac{e}{M\omega_{ci}^2} \frac{dE_x}{dx} < 1. \quad (2)$$

The double layer that was analyzed had $\epsilon \sim 0.05$ for H⁺.

To demonstrate this point, we performed a test particle simulation. The path of a 3.2 eV proton is plotted in Fig. 1(a). It has an initial drift velocity of 50 km/s and an initial perpendicular velocity of 25 km/s and traverses a 63° double layer [Eq. (6) of Ref. 2] in a constant magnetic field ($B_z = 14\,000$ nT). These are the conditions used in the Comment¹ in which they argue for breaking of the first adiabatic invariant. In this test particle simulation, the perpendicular electric field is in the $-x$ direction. One can see the strong $\mathbf{E} \times \mathbf{B}$ drift in the y direction and a smaller polarization drift in the $-x$ direction. In the rest frame, the particle undergoes cyclodial motion but its gyroradius (magnetic moment) does not significantly change from beginning to end. Figure 2(b) shows the results of a test particle simulation for 1000 H⁺ ions with random initial gyrophase and initial perpendicular and parallel velocities representative of a drifting Maxwellian ($T_{\perp} = 3.2$ eV, $\nu_d/\nu_{th} = 2$). There is less than 0.01 eV (0.3%) change (between beginning and end) in the

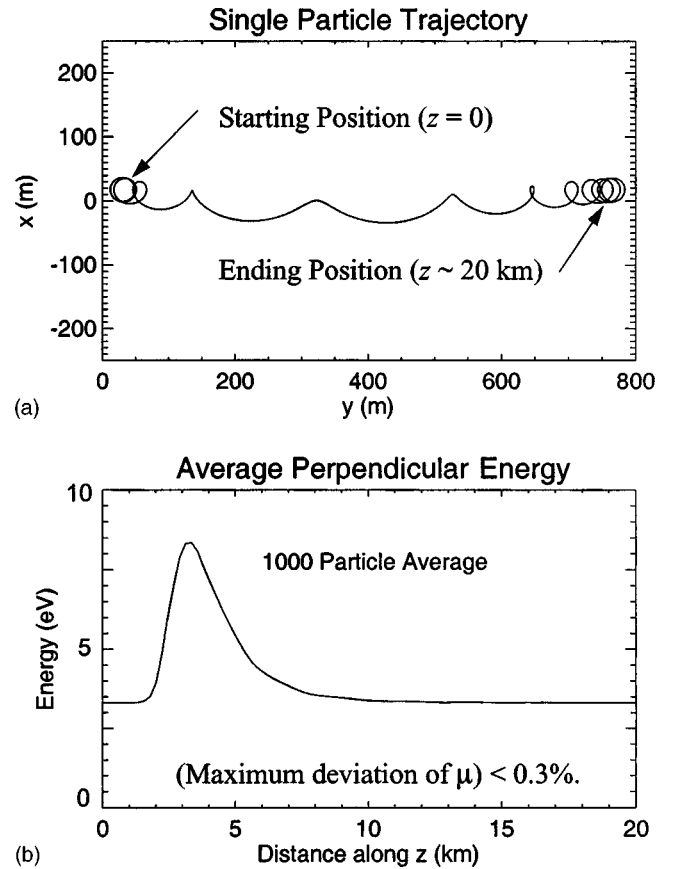


FIG. 1. (a) The path of a test particle in the x - y plane as it traverses an oblique double layer. The particle has an initial perpendicular (x - y) velocity of 25 km/s initial drift velocity (z direction) of 50 km/s and passes through a 63° double layer [Eq. (6) of Ref. 2] in a constant magnetic field ($B_z = 14\,000$ nT). (b) The average perpendicular energy of a 1000 H⁺ ions as they traverse an oblique double layer. The ions start with random gyrophase and perpendicular and parallel velocities representative of a drifting Maxwellian ($T_{\perp} = 3.2$ eV, $\nu_d/\nu_{th} = 2$). The starting perpendicular energy and ending perpendicular energy does not significantly change in any of the 1000 H⁺ ions (the maximum change was <0.3%).

perpendicular energy of any of the H⁺ ions as they undergo a 1600 eV parallel acceleration. Clearly, the violation of the first adiabatic invariant of H⁺ is insignificant.

In Point (3) the Comment¹ contends that the behavior of the ions as described in the Appendix of our article² is incorrect. We point out that our derivation² reduces to that of Swift⁵ and includes both polarization and $\mathbf{E} \times \mathbf{B}$ drifts. In Eq. (1) above, the correction to the density due to the polarization drift depends on dE_x/dx and dE_x/dz . These terms dominate as the particle enters the double layer (E_x is small but dE_x/dx and dE_x/dz are large) and cause a negative density perturbation. Inside of the double layer, E_x is at its maximum (dE_x/dx , $dE_x/dz \approx 0$) so the $\mathbf{E} \times \mathbf{B}$ correction dominates and causes a positive perturbation. These perturbations are seen in Figs. 7 and 8 of our article.² The Comment¹ correctly interprets the effect of the $\mathbf{E} \times \mathbf{B}$ drift but ignores the polarization drift arguing that “Adding a common (lowest-order) polarization drift velocity in the x -direction leaves the inequality $Y' > Y$ intact.” The Comment¹ makes this statement without mathematical proof. The more rigorous mathematical derivation in our article² and by Swift⁵ prove Point (3) untrue.

We emphasized in our paper² that the adiabatic moment of O⁺ may not be preserved and that the O⁺ behavior in Figs. 7 and 8 of our paper² is not exact but an estimate. We agree that a detailed dynamic simulation is needed, but disagree that the low-order solution of H⁺ is invalid under the arguments presented in the Comment.¹ The detailed behavior of O⁺ in the double layer is currently being studied.

¹O. W. Lennartsson, Phys. Plasmas **10**, 1175 (2003).

²R. E. Ergun, L. Andersson, D. S. Main, Y.-J. Su, C. W. Carlson, J. P. McFadden, and F. S. Mozer, Phys. Plasmas **9**, 3695 (2002).

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⁶J. E. Borovsky, J. Geophys. Res., [Space Phys.] **89**, 2251 (1984).