# Reply to comment by J.-P. St.-Maurice on "Nonlinear electron heating by resonant shear Alfvén waves in the ionosphere"

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Received 6 April 2005; accepted 2 June 2005; published 6 July 2005.

**Citation:** Lu, J. Y., R. Rankin, R. Marchand, and V. T. Tikhonchuk (2005), Reply to comment by J.-P. St.-Maurice on ''Nonlinear electron heating by resonant shear Alfvén waves in the ionosphere,'' *Geophys. Res. Lett.*, *32*, L13103, doi:10.1029/2005GL023149.

[1] *St.-Maurice* [2005] questions the validity of the resonant shear Alfvén wave electron heating mechanism proposed by *Lu et al.* [2005]. In particular, the following arguments have been raised: (i) the electron cooling time given by *Lu et al.* [2005] is underestimated because inelastic electron collisions are neglected; (ii) the ionization rate is incorrect; (iii) the electron and ion conductivities are wrong; (iv) the position of the energy deposition layer is incorrect; (v) the energy of precipitating electrons is not well defined, and (vi) the mechanism is simply not applicable. We acknowledge that inelastic collisions with neutrals are important for the electron cooling and ionization processes discussed by *Lu et al.* [2005]. However, we reject all other allegations. We demonstrate that inelastic cooling leads only to a revision of the threshold current in the nonlinear regime of our theory. However, this does not undermine the overall idea proposed by *Lu et al.* [2005]. Our improved model makes our results even more consistent with observations.

[2] To account for inelastic cooling processes, one has only to modify the electron energy balance equation [*Lu et al.*, 2005, equation (1)]:

$$\frac{3}{2}n_e k\frac{\partial T_e}{\partial t} = W_{Te} - n_e(T_e - T_n)\sum\left(L_e + \frac{3m_e\nu_{en}k}{m_n}\right) \quad (1)$$

where $k = 1.38 \times 10^{-16}$ erg/K and $\sum L_e$ is the sum of the inelastic cooling rates.

[3] At low altitudes, elastic collisions, along with rotational and vibrational excitation of $N_2$ and $O_2$, represent the dominant cooling processes, although the excitation of the fine structure levels of atomic oxygen may also be important. The associated cooling rates in $s^{-1}$ are given below, where temperatures are in K, and densities in $cm^{-3}$:

Rotational excitation [*Schunk and Nagy*, 2000; *Pavlov*, 1998]:

$$L_e(N_2) = 4.6 \times 10^{-26} n(N_2) T_e^{-1/2} \quad (2)$$

$$L_e(O_2) = 8.3 \times 10^{-27} n(O_2) T_e^{-1/2}. \quad (3)$$


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Vibrational excitation [*Schunk and Nagy*, 2000]:

$$L_e(N_2) = 4.78 \times 10^{-24} n(N_2)\exp\left(f_N \frac{T_e - 2000}{T_e}\right) \cdot \left[1 - \exp\left(-g\frac{T_e - T_n}{T_e T_n}\right)\right] / (T_e - T_n) \quad (4)$$

where $f_N = 5.3 + 3.76 \tanh[1.1 \tanh(T_e/1000 - 1.8)]$, and $g = 3300 + 1.233(T_e - 1000) - 2.056 \times 10^{-4}(T_e - 1000)(T_e - 4000)$.

$$L_e(O_2) = 8.32 \times 10^{-25} n(O_2)\exp\left(f_O \frac{T_e - 700}{T_e}\right) \cdot \left[1 - \exp\left(-2770\frac{T_e - T_n}{T_e T_n}\right)\right] / (T_e - T_n). \quad (5)$$

where $f_O = 4.71 - 1.20 \sin[1.91(10^{-4} T_e - 0.27)]$.

O fine structure [*Dalgarno*, 1969]:

$$L_e(O) = 5.4 \times 10^{-24} n(O)\left(1 - 7 \times 10^{-5} T_e\right)/T_n. \quad (6)$$

[4] The relative importance of the various electron cooling rates depends on the ionospheric and atmospheric conditions. Here we choose $n(N_2) = 3.47 \times 10^{11}$ cm$^{-3}$, $n(O_2) = 5.46 \times 10^{10}$ cm$^{-3}$, and $n(O) = 3.8 \times 10^{10}$ cm$^{-3}$ from MSIS model [*Hedin*, 1987]. For $T_n$ = 500K, inelastic cooling rates are roughly 20 and 40 times larger than elastic cooling rates for $T_e$ = 1500 and 2500K, respectively. This results in a few hundred K electron temperature increase, which is consistent with observations [*Schlegel and St.-Maurice*, 1981].

[5] *St.-Maurice* [2005] has confused the ion/electron parallel electric conductivity $\sigma$ with the corresponding Pedersen conductivity $\sigma_p$. For example, for ions, $\sigma_i = n_i e_i^2/m_i\nu_i$, does not depend on $B$, while $\sigma_{pi} = \sigma_i \frac{\nu_i^2}{\Omega_i^2 + \nu_i^2}$ does depend on the magnetic field. Equation (2) of *Lu et al.* [2005] corresponds to the limit $\nu_{i,e} \ll \Omega_{i,e}$ where the Pedersen conductivity is inversely proportional to $B^2$. Without such an approximation, equation (2) of *Lu et al.* [2005] reads

$$j_{\perp e} = j_\perp \frac{\nu_e/\Omega_e}{\nu_i/\Omega_i}\left(1 + \frac{\nu_i^2}{\Omega_i^2}\right). \quad (7)$$

[6] We should mention that equation (7) and all analysis and calculations of *Lu et al.* [2005] are based on the above equation, without using the approximation $\nu_i \ll \Omega_i$. Taking

into account inelastic cooling, equation (7) of *Lu et al.* [2005] becomes

$$\frac{j_\perp^2}{\sigma_{P0}}\frac{\nu_e/\Omega_e}{\nu_i/\Omega_i}\left(1+\frac{\nu_i^2}{\Omega_i^2}\right)=\frac{n_e^2}{n_{e0}}(T_e-T_n)\sum\left(\frac{3m_e\nu_{en}k}{m_n}+L_e\right). \quad (8)$$

Therefore, the critical Pedersen current becomes

$$j_c=\sqrt{\frac{\nu_i/\Omega_i}{\nu_e/\Omega_e}\frac{\sigma_{P0}n_{e0}T*}{1+\nu_i^2/\Omega_i^2}\sum\left(\frac{3m_e\nu_{en}k}{m_n}+L_e\right)} \quad (9)$$

The first term in parenthesis is identical to equation (7) of *Lu et al.* [2005]. Inelastic cooling results in a larger current that is needed to enter the nonlinear regime, but it does not forbid this possibility, as St.-Maurice claims.

[7] The ionization rate is not overestimated. In the local ionization equilibrium, the electron number density follows from the Saha formula and behaves as $n_e \sim \exp(-\epsilon_i/2kT_e)$, where $\epsilon_i$ is the ionization potential [*Smirnov*, 2000]. The effective potential given by *Lu et al.* [2005] is $\varphi = \epsilon_i/2 =$ 8 eV. This corresponds to the ionization potential $\epsilon_i = 16$ eV, which is even higher than the value claimed by *St.-Maurice* [2005]. We acknowledge, however, that our model for ionization is only approximate.

[8] The criticism of St.-Maurice regarding the thickness and position of the ionospheric layer is not justified either, and is irrelevant to the proposed heating mechanism. The nonlinear regime of the heating mechanism does not depend on the thickness of the current layer, but only on the total parallel current $\int j_\parallel dx \sim j_\parallel a$. This is important as the thickness of the E-layer has been observed to vary from 10 to 30 km, while its height varies from 90 to 150 km.

[9] In their brief report, *Lu et al.* [2005] present only the general features of coupling and feedback processes. Nevertheless, we have used the parameters of the ionospheric layer (boundary at 120 km with a thickness of 20 km) suggested by St.-Maurice, and took into account inelastic collisions. The result shown in Figure 1 demonstrates that although inelastic collisions do reduce the ionization rate compared to elastic collisions, the proposed nonlinear mechanism still works. This new result is consistent with observations pointed out by St.-Maurice, which suggest that small-amplitude perpendicular electric fields (<60 mV/m) do not produce large temperature enhancements. Figure 1 also indicates that ionospheric feedback is very effective at small initial Pedersen conductivities (<1 S).

[10] The comment by *St.-Maurice* [2005] about the energy of precipitating electrons does not undermine anything in our work. On the contrary, the low energy of precipitating electrons is one of the principal arguments which justify our nonlinear heating mechanism. In this regard, *St.-Maurice* [2005] has completely misunderstood our work. As pointed out by *Lu et al.* [2005], precipitating electrons are effective only at high frequencies 0.1–1 Hz, and can only affect the conductivity over one half of an Alfvén wave period. *Lu et al.* [2005] are dealing with wave frequencies of a few mHz and do not include the effect of precipitating electrons on the ionospheric conductivity. Our theory was proposed for field line resonances (FLRs). These long period (tens of minutes) waves extend for many 1000's of km along field lines, but close through small scale (several km) Pedersen currents in the ionosphere. In looking to observations, one should keep this in mind.

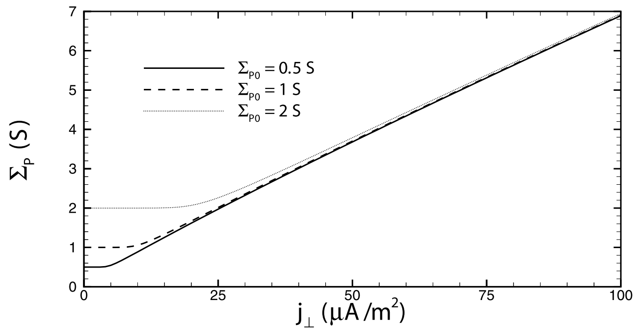


**Figure 1.** Pedersen conductivity as a function of ionospheric current for $\Sigma_{P0}$ = 0.5S (solid), 1 S (dashed), and 2 S (dotted).

[11] We do not agree with the statement that there is no need for new models of magnetospheric-ionospheric coupling. As stated, precipitating electrons cannot explain conductivity enhancements in FLRs. The models mentioned by St.-Maurice are not self-consistent. They use highly simplified and incomplete Alfvén wave models without inclusion of feedback effects. Our model self-consistently incorporates ionospheric electron heating and its feedback into the magnetospheric FLR. As far as we are aware, this is the first work on FLRs which accounts for such an ionospheric process. A communication from St.-Maurice immediately prior to his letter criticizing our model, suggests that the main criticism is our neglect to reference previously published work on ionospheric modification. One resolution would be to merge the ionospheric model of St.-Maurice with the model presented by *Lu et al.* [2005].

[12] In conclusion, we are grateful to *St.-Maurice* [2005] for his comment on the importance of inelastic electron cooling. However, we must reject his other comments and the conclusion that the nonlinear mechanism proposed by *Lu et al.* [2005] "does not apply". Provided parallel currents exceed a critical value defined by our analysis, we show that the electron temperature increase leads to ionization and enhancement of the ionospheric Pedersen conductivity. It is more effective for smaller ambient conductivities (<1S), suggesting, perhaps, that discrete arcs associated with latitudinally narrow FLRs, may have their birth in regions of low background conductivity.

[13] **Acknowledgment.** This work was supported in part by the Canadian Space Agency and the Natural Sciences and Engineering Research Council of Canada.

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