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REPLY

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Special Section:
Major Results From the MAVEN Mission to Mars

Key Points:
- Electron whistler instability saturates to its marginal instability threshold in PIC simulations
- Mirror instability isotropizes the electrons to values below the electron whistler instability threshold
- Mirror instability and electron whistler instability can coexist throughout the magnetosheath

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Reply to comment by Remya et al. on "Effects of electron temperature anisotropy on proton mirror instability evolution"

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Abstract In the comment to our paper, Remya et al. (2017) state that we conclude that their theory is incorrect; however, no such conclusion is in our paper. In fact, as stated in their paper, we agree with their theory that shows the impact of heavy ions and electron temperature anisotropy on the competition of the ion anisotropy instabilities. While their linear theory is correct, our paper focused on the nonlinear evolution, where one needs to be careful in assuming a given electron anisotropy, because electrons themselves can be unstable to the electron whistler instability, which quickly lowers the anisotropy to levels where, in the absence of heavy ions, it is not sufficient to significantly change the balance between proton cyclotron and mirror mode. We agree that the electron whistler instability will not lead to complete isotropization of the electrons but only lower it to the instability threshold. In the parameter regime addressed, this limited isotropization will still eliminate the dominance of mirror mode and restore the usual dominance of the proton cyclotron mode, so our point still stands. Our simulations showed an isotropization of the electrons beyond the electron whistler threshold. In this reply, we will show that there are two contributing reasons: The nonlinear evolution of the mirror instability affects the electron anisotropy, as does unphysical numerical heating due to the limited resolution of a particle-in-cell simulation. We further discuss the coexistence of electron whistler instability and mirror instability, and we agree that both instabilities can be present in the magnetosheath.

1. Heavy Ion Effects

Remya et al. [2017] argue that a small electron temperature anisotropy of $T_{e\perp}/T_{e||} = 1.2$ will cause the proton mirror instability to be stronger than the proton cyclotron instability. They use linear dispersion theory to study the effects of electron temperature anisotropy on the proton mirror instability, whereby they include a heavy component of density $n_\alpha = 0.1n_p$. Based on this mode analysis, they conclude that $T_{e\perp}/T_{e||} = 1.2$ is a sufficient electron temperature anisotropy value for the mirror instability to have higher linear growth rate than the proton cyclotron instability.

However, the addition of heavy ions, which were not present in our simulations, profoundly alters the properties of the plasma. *Price et al.* [1986] have shown that the presence of heavy ions can significantly suppress the proton cyclotron instability while leaving the mirror instability unaffected. Thus, the stabilization of the proton cyclotron mode by heavy ions is likely the dominant reason that the mirror mode dominates in their analysis. Thus, our conclusion that in an electron-proton plasma without the presence of heavy ions, $T_{e\perp}/T_{e||} = 1.2$ is not enough to make the mirror instability stronger than the proton cyclotron instability still stands.

Remya et al. [2013] further argue that as they decrease the heavy ion density, a higher electron temperature anisotropy is needed for the mirror instability to be dominant over proton cyclotron instability. For example, when they decrease n_α to $0.01n_p$, the minimum electron temperature anisotropy is $T_{e\perp}/T_{e||} = 1.8$. This is in line with our linear analysis, which shows that the minimum required electron temperature anisotropy in an electron-proton plasma is $T_{e\perp}/T_{e||} = 1.5$ according to Figure 3 in *Ahmadi et al.* [2016]. At this electron temperature anisotropy, both proton mirror instability and proton cyclotron instability have roughly equal growth rates.

We also note that when performing a linear analysis, one should be careful to choose plasma parameters that fall into the stable regime for electron whistler waves, in order to avoid the electron whistler instability effects.

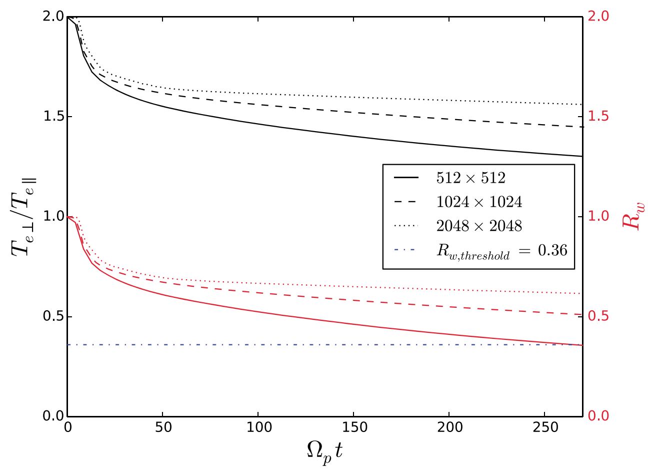

Figure 1. Electron temperature anisotropy and electron whistler instability threshold evolution in PIC simulations with different resolutions. Black lines show the electron temperature anisotropy, and red lines show electron whistler instability threshold. The solid lines are the simulation with $n_y = n_z = 512$, the dashed lines are $n_y = n_z = 1024$, and the dotted lines are $n_y = n_z = 2048$. The blue dash-dotted line shows the threshold of electron whistler instability ($R_{w,\text{threshold}} = 0.36$).

Some of the plasma parameters used in their analysis fall into an electron whistler unstable plasma regime based on the theoretical threshold for electron whistler instability [*Gary and Wang*, 1996] and may thus alter the properties of the proton cyclotron and mirror modes.

This is particularly important when one considers the nonlinear evolution. In our paper [*Ahmadi et al.*, 2016], we showed that the electron whistler instability quickly grows and saturates, thereby consuming most of the electron free energy as the proton mirror instability is just starting to grow. Thus, in the nonlinear regime of the proton mirror instability, the electron whistler instability has already saturated and can no longer change the electron temperature anisotropy. Any further change of the electron temperature anisotropy can only be the result of nonlinear ion instabilities; in the case of numerical simulations using the particle-in-cell method, however, unphysical numerical heating can also lead to a change in the electron temperature anisotropy, which we address below.

2. Marginal Instability Threshold of Electron Whistler Instability

Remya et al. [2017] further argue that the electron whistler instability should saturate when the threshold for marginal instability is reached. We do concede that in our paper, we overstated the effect of the electron whistler instability: it does not completely eliminate the electron free energy to complete isotropization, but it quickly reduces the anisotropy enough that there is no more significant effect on the proton cyclotron/mirror instability growth rates (in the absence of heavy ions).

If only the electron whistler instability is present in the system, we agree that electrons will achieve the electron whistler instability threshold given by equation (1) in *Ahmadi et al.* [2016]. In the particle-in-cell (PIC) simulation [*Germaschewski et al.*, 2016] presented in our paper, the electrons, in fact, isotropize to temperature anisotropy values below the electron whistler instability threshold. This can be due to the proton mirror instability further isotropizing the electrons or due to numerical heating. However, our main point is actually independent of this effect: Just reducing the electron temperature anisotropy to the electron whistler threshold is enough to lose the increased proton mirror growth rate that would explain the nonlinear dominance of the mirror mode.

In order to address the numerical heating issue, we performed three simulations with different resolutions to investigate the numerical effects on electron whistler instability saturation. The simulation parameters are $T_{p\perp}/T_{p\|} = 1$, $T_{e\perp}/T_{e\|} = 2$, $\beta_{p||} = \beta_{e||} = 1$, $B_0 = v_A/c = 0.1$, and $L_y = L_z = 16d_p$. We chose isotropic protons to isolate the effects of resolution on the electron whistler instability saturation. The resolutions are $n_y = n_z = 512$, $n_y = n_z = 1024$, and $n_y = n_z = 2048$. The simulation with $n_y = n_z = 512$ had identical numerical parameters to the simulation in Figure 18 in *Ahmadi et al.* [2016]. Because of numerical cost, we only ran these simulations to $t = 270\,\Omega_p^{-1}$.

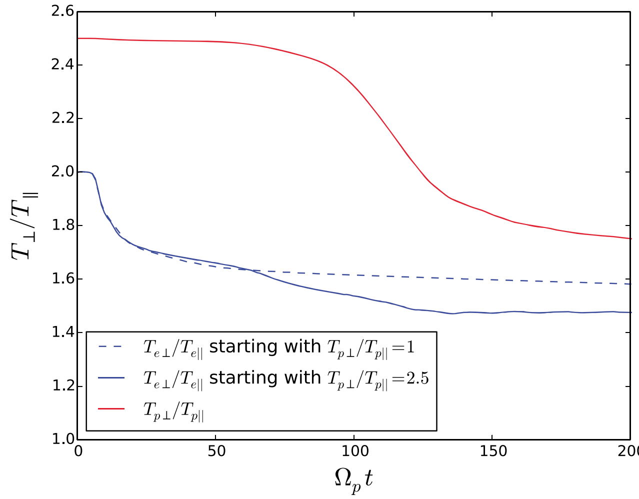

Figure 2. Electron temperature anisotropy and proton temperature anisotropy in PIC simulations. Solid lines show the results of the simulation starting with anisotropic protons. Red solid line shows the proton temperature anisotropy, and blue solid line shows the electron temperature anisotropy. The blue dashed line shows the electron temperature anisotropy in the simulation starting with isotropic protons.

Figure 1 shows the electron temperature anisotropy and electron whistler instability threshold evolution in the three simulations with increasingly higher resolutions. Black lines show the electron temperature anisotropy, and the red lines represent the electron whistler instability threshold condition R_w. The blue line shows the marginal instability threshold or $R_{w,\text{threshold}} = 0.36$. While the linear and initial nonlinear saturation resemble each other as resolution increases, the electron temperature anisotropy in the long-term saturation regime is noticeably different. In particular, in the lowest-resolution run, the electron anisotropy decreases below the electron whistler instability threshold, while higher resolutions as expected show an approach to, but not a crossing of the threshold. Therefore, the electron whistler instability does not isotropize the electrons to completely isotropic distributions, as expected. It can be seen that numerical heating has a significant effect exaggerating the isotropization of the electrons in the long-time saturation regime.

To study the effect of the proton mirror instability on the electron temperature anisotropy, we performed another simulation using the finest resolution ($n_y = n_z = 2048$), now starting with the proton temperature anisotropy $T_{p\perp}/T_{p\|} = 2.5$. The other simulation parameters are identical to the previous simulations. Figure 2 compares the evolution of electron temperature anisotropy. Solid lines show the results of the simulation

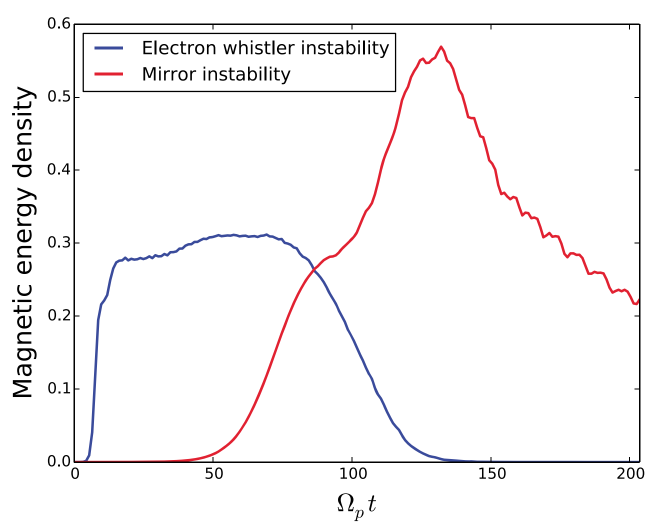

Figure 3. Magnetic energy density evolution. Red line shows the mirror instability energy density, and blue line shows the electron whistler instability energy density.

starting with anisotropic protons. The red solid line shows the evolution of the proton temperature anisotropy. The blue lines show the electron temperature anisotropy in the case of simultaneous nonlinear mirror instability (solid blue) and the previous case of no ion instability (dashed blue). Comparing the electron temperature anisotropy in these simulations, we see that electrons are further isotropized in the simulation starting with anisotropic protons. This shows that mirror instability can isotropize the electrons to values below the electron whistler instability threshold.

Figure 3 shows the magnetic energy density of the instabilities in the anisotropic proton and electron simulation. Red line shows mirror instability magnetic energy density, and blue line represents electron whistler instability magnetic energy density. Figure 3 shows that electron whistler instability is damped while mirror instability is growing.

Based on these results, we do not agree with the conjecture of *Remya et al.* [2017] that the electron whistler instability stays in the simulation box because of the periodic boundary condition and isotropizes the electrons.

3. Observations of Mirror Mode Waves

We agree that mirror modes are observed throughout the magnetosheath [*Tsurutani et al.*, 1982; *Soucek et al.*, 2008; *Génot et al.*, 2009], as also stated in the introduction to our paper. We did not intend to imply that mirror modes are preferentially observed near the magnetopause. As outlined in our conclusions, we think that there is likely a mechanism that continuously drives the electron temperature anisotropy within the magnetosheath to higher values. One example given in *Ahmadi et al.* [2016] is the adiabatic expansion close to the magnetopause, i.e., in the plasma depletion layer, that can drive the electron temperature anisotropy as shown by *Midgeley and Davis Jr.* [1963] and *Zwan and Wolf* [1976].

Linear dispersion theory predicts that in an electron-proton plasma, for a typical magnetosheath plasma parameters ($\beta_{p||} < 6$), proton cyclotron instability is stronger than mirror instability [*Ahmadi et al.*, 2016, Figure 2]. But observations show that mirror instability is dominant in the regions where we expect proton cyclotron instability to be stronger. *Remya et al.* [2017] assume in their argument that mirror modes downstream of a quasi-perpendicular bow shock are generated solely by electron temperature anisotropy effects. If that were true, the conclusion from our work would indeed be that mirror modes should not be observed; however, this is not a conclusion that we have drawn. In fact, in our paper we state that there are other possible effects that can lead to the dominance of the mirror mode; e.g., as shown by *Price et al.* [1986], heavy ions can effectively suppress the proton cyclotron instability linear growth rate and thus make the mirror waves the dominant mode. Of course, the presence of an electron temperature anisotropy may be a contributing factor in the dominance of the mirror mode. Our work focused on the isolated effect of electron temperature anisotropy, and it showed that electron temperature anisotropy is quickly reduced by the electron whistler instability to levels where it does not majorly impact the ion instabilities. This is also consistent with measured electron temperature anisotropy values downstream of the bow shock that are usually quite small [*Gary et al.*, 2005; *Masood and Schwartz*, 2008].

In our work, we did not address the presence of multiple mechanisms at the same time, which in combination could make the mirror mode stronger than the proton cyclotron mode. It is certainly possible that there is a regime where the presence of heavy ions is not quite enough to make the mirror mode dominant but where an additional electron temperature anisotropy, even if small because it has been reduced to the electron whistler threshold, can change the balance. Thus, our results do not exclude the possible coexistence of the electron whistler instability and the proton mirror instability. If in the course of the magnetosheath plasma flow the electron temperature anisotropy is again enhanced, the growth of the electron whistlers could proceed, limited by the stability threshold. Therefore, both instabilities can coexist.

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References

Ahmadi, N., K. Germaschewski, and J. Raeder (2016), Effects of electron temperature anisotropy on proton mirror instability evolution, *J. Geophys. Res. Space Physics*, *121*, 5350–5365, doi:10.1002/2016JA022429.

Gary, S. P., and J. Wang (1996), Whistler instability: Electron anisotropy upper bound, *J. Geophys. Res.*, *101*, 10,749–10,754, doi:10.1029/96JA00323.

Gary, S. P., B. Lavraud, M. F. Thomsen, B. Lefebvre, and S. J. Schwartz (2005), Electron anisotropy constraint in the magnetosheath: Cluster observation, *Geophys. Res., Lett.*, *32*, L13109, doi:10.1029/2005GL023234.

Génot, V., E. Budnik, C. Jacquey, I. Dandouras, and E. Lucek (2009), Mirror modes observed with Cluster in the Earth's magnetosheath: Statistical study and IMF/solar wind dependence, in *Advances in Geosciences*, vol. 14: Solar Terrestrial (ST), edited by M. Duldig, p. 263, World Sci., Singapore.
Germaschewski, K., W. Fox, S. Abbott, N. Ahmadi, K. Maynard, L. Wang, H. Ruhl, and A. Bhattacharjee (2016), The plasma simulation code: A modern particle-in-cell code with patch-based load balancing, *J. Comput. Phys.*, *318*, 305–326.
Masood, W., and S. J. Schwartz (2008), Observations of the development of electron temperature anisotropies in Earth's magnetosheath, *J. Geophys. Res.*, *113*, A01216, doi:10.1029/2007JA012715.
Midgeley, J. E., and L. Davis Jr. (1963), Calculation by a moment technique of the perturbation of the geomagnetic field by solar wind, *J. Geophys. Res.*, *68*, 5111–5123.
Price, C. P., D. W. Swift, and L. C. lee (1986), Numerical simulation of nonoscillatory mirror waves at the Earth's magnetosheath, *J. Geophys. Res.*, *91*, 101–112.
Remya, B., R. V. Reddy, B. T. Tsurutani, G. S. Lakhina, and E. Echer (2013), Ion temperature anisotropy instabilities in planetary magnetosheaths, *J. Geophys. Res. Space Physics*, *118*, 785–793, doi:10.1002/jgra.50091.
Remya, B., R. V. Reddy, B. T. Tsurutani, and G. S. Lakhina (2017), Comment on "Effects of electron temperature anisotropy on proton mirror instability evolution", *J. Geophys. Res. Space Physics*, *122*, 745–747, doi:10.1002/2016JA023148.
Soucek, J., E. Lucek, and I. Dandouras (2008), Properties of magnetosheath mirror modes observed by Cluster and their response to changes in plasma parameters, *J. Geophys. Res.*, *113*, A04203, doi:10.1029/2007JA012649.
Tsurutani, B. T., et al. (1982), Lion roars and nonoscillatory drift mirror waves in the magnetosheath, *J. Geophys. Res.*, *87*, 6060–6072.
Zwan, B. J., and R. A. Wolf (1976), Depletion of the solar wind plasma near a planetary boundary, *J. Geophys. Res.*, *81*, 1636–1648.