Reply to Octav Marghitu's comment on "Entangled Dynamos and Joule Heating in the Earth's Ionosphere" by

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1 Replies to comments by Referee 1

Cited referee comments are in red, replies in magenta.

I thank the referee, Octav Marghitum, for the interest in the manuscript and the time spent reading it, and for the helpful comments.

1. Using two reference systems has obvious merits, but it is at the same time challenging, in particular by introducing two instances of the Poynting flux. This is detailed in the Discussion section, though I think that the clarity of the message may benefit from sub-sectioning and some re-arrangement:

1a. More specifically, the three paras from p.12, L17 ("We claim that. . .") up to p.13, L21 (". . .and heating effects") could be moved to p.9, L 26, after the para describing the main features of the model. The first part of Section 5, up to this point, together with the three paras, could make the first sub-section of the Discussion, emphasizing the need for two reference systems.

I have moved the discussion on the Poynting flux in different references frames to the location suggested by the referee. Also it is slightly modfied:

We claim that there is Poynting flux from N to S as well as from S to N, each transporting electrodynamic energy from a dynamo to a load. Adding both Poynting fluxes would give zero (in the symmetric case), but this is not a meaningful view. The Poynting flux $\boldsymbol{S} = \boldsymbol{E} \times \Delta\boldsymbol{B}/\mu_0$, where $\boldsymbol{E}$ includes the motional field, is frame dependent, as well as the term $\boldsymbol{J} \cdot \boldsymbol{E}$. There are infinitely many possible reference frames, and in each of these Poynting's theorem is of course valid. But only frames with the physical material at rest, in this case of zero neutral wind are special, are the "laboratory frame" with the $\boldsymbol{J} \cdot \boldsymbol{E}^*$ term and the ionospheric Ohm's law giving the dissipation. We argue that it is in this frame where $\boldsymbol{J} \cdot \boldsymbol{E}$ represents the neutral dynamo's power in Wm^{-2} and the Poynting flux the amount and direction of electromagnetic energy being transported from the dynamo to the load. On each magnetic flux tube the neutral winds at each conjugate end define so two "laboratory" frames connected to physical material. In each of the two frames one end is the location of the load. At the other end is a dynamo where $\boldsymbol{J} \cdot \boldsymbol{E} = \boldsymbol{J} \cdot (\boldsymbol{E}^* - \Delta\boldsymbol{u} \times \boldsymbol{B}) < 0$ matching the dissipation at the load. When switching the reference frames the roles also switch, and the Poynting

flux between both ends flips to the opposite direction. The neutral dynamo power is so determined by the neutral wind difference at the conjugate points.

1b. The rest of the Discussion could be organized in two more sub-sections, one on quantitative estimates of Sq Joule heating (from p.9, L26 up to p.12, L16), and one on applying the model to high latitudes (from p.13, L22 to the end of the Section).

Subjections were added to the long section "Discussion":

1.1 The Model of Entangled Dynamos

1.2 Estimation of the Joule Heating Power

1.3 The Atmosphere, a Dynamo for Space?

2. Speaking about high latitudes, these are associated in the paper with open field lines, both in the last part of the Discussion and in the Conclusions (e.g., p. 16, L8). As a matter of fact, much of the energy dissipation takes place in the auroral region, which is believed to be threaded (mostly) by closed field lines, that connect the two hemispheres via the plasma sheet in the magnetosphere. However, in this case plasma parameters do not preclude any more parallel electric fields (e.g., much lower density compared to plasmasphere). The open field lines are in general associated with the polar cap, where energy dissipation is limited. As of now, the discussion on high latitudes refers mainly to open field lines / polar cap, while the specific case of the auroral region is just touched a bit, implicitly, in the second last para of the Conclusions. Please complete the Discussion and Conclusions by addressing explicitly the auroral region, where the key feature is the parallel electric field on closed field lines.

The manuscript clarifies how the atmosphere dynamo works and what its effects are. It is not intended as new comprehensive theory/model of interaction between ionosphere-thermosphere and space, and of auroral processes. In the latter the atmosphere dynamo is not expected to play an important role. To isolate the atmosphere dynamo from ionosphere-magnetosphere coupling, the plasma, including the one all along closed field-lines between conjugate points, is assumed to be "passive", i. e. it only reacts to neutral dynamics. Observationally the Sq perturbations are clearly visible on quiet days even up to high latitudes, suggesting that the isolated treatment of Sq is in principle testable. On moderate to active days Sq gets buried in larger geomagnetic disturbances even at mid-latitudes. Then the space plasma is not "passive" but has its own dynamics including, at times, the parallel fields mentioned by the referee. The high latitudes are mentioned in the manuscript, because it had been suggested that particularly there, probably on open field-lines, the atmosphere dynamo would transport energy into space, statistically, on average. Also this would be a small effect having probably little relation with aurora and parallel electric fields. The coexistence of Sq driven by entangled atmosphere dynamos with substorms, auroras etc is acknowledged in the 2^{nd} last paragraph which is slightly reformulated:

On closed field-lines the currents and fields of entangled dynamos can coexist with currents and fields induced by plasma motion in the magnetosphere driven by interaction with the solar wind, to use a generic term. This

includes sub-storms, including auroral features sometimes associated with E-fields parallel to $\boldsymbol{B}$, high-latitude plasma convection, its occasional penetration towards lower latitudes etc.

3. The mapping between the two hemispheres could be emphasized by adding the two respective reference systems, (x, y, z), N and S, on the side of Figs 3 and 4, with the x axis pointing northward in N and southward in S. This would also clarify the '+' sign in Equation 5. It would help as well to add J_N and J_S explicitly before Eq. (5), $J_N = \Sigma_N E^*_N$ and $J_S = -\Sigma_S E^*_S$.

Labeled arrows for the X and Y axis were added to Figures 5–6. Equation 5 was added as the referee suggests:

...for the current calculation the frames in N and S are not the same:

$$J_N = \Sigma_N E^*_N,\ J_S = -\Sigma_S E^*_S; \tag{5}$$

$$J_N + J_S = \Sigma_N E^*_N + \Sigma_S E^*_S = 0 \tag{6}$$

4. The proxy in Eq. (15) is probably derived by assuming that ion-neutral collision frequency and ion gyro-frequency are roughly equal in the dissipation layer Δz. Please make this clear.

Text is added:

...with $B = 35000$ nT as an average value of the magnetic field strength at mid latitudes and the factor $e/2B$ giving the conductivity where ion gyro and ion-neutral collision frequencies are equal.

p.3, Fig. 1: Please increase the figure (zonal wind arrows are not visible) and font size (in particular for the Legend).

I have revised the Figure. Now it shows the neutral wind relative to the Earths continents, as we tend to imagine it. Later in the manuscript it is argued that the Earth fixed system is actually irrelevant, only wind differences matter.

L4: Perhaps complete the sentence with: "...on the E side, which is the standard form of Lorentz transformation for non-relativistic velocities, u."

The sentence is completed:

Please note that in many publications this equation is written with the $+\boldsymbol{u} \times \boldsymbol{B}$ term on the $\boldsymbol{E}$ side , which is the standard form of the Lorentz transformation for non-relativistic velocities $\boldsymbol{u}$.

Eq. (3): Delete Σ_P in the second term.

The second term should not have a factor Σ_P, it is deleted.

p.4, L13: ...connecting either the latitude lines '1', or the latitude lines '2', or both.

The statement is modfied to:

But this configuration of $\boldsymbol{E}$ implies a potential drop along magnetic field lines connecting either latitude circles "1" or latitude circles "2" or along both these field lines.

L15: are from of Galilei

changed to:

We ~~therefore~~ reject the initial idea that the only electric fields ~~are from of~~are those of Galilei coordinate transformations from neutral to observer frames.

p.5, L9: current => FACs

Changed.

p.6, L3: frame => frame with

"with" is added.

L6: surrendered => relaxed (?) changed.

L11: an opportunity => a stronger motivation (?) changed.

p.7, L1: closeS: closes

p.9, L27: and or or

The statement is deleted after comment by referee 2. Instead text in section "Conclusions and Outlook", 9^{th} paragraph outlines how a computer algorithm could handle relative neutral wind differences in a way that is consistent with the theory described in the manuscript:

L29: and simulations => nor simulations (?)

The statement is deleted after comment by referee 2.

p.10, L9: but => therefore changed.

L15: from a with

The statement is changed to:

...and deviations from a field that is with respect to the dipole equator perfectly symmetric ~~field~~.

L22: given => given as well (?)

The statement is changed to:

Other explanations for the semi-diurnal component in Sq have been given as well (confirm Yamazaki and Maute, 2017).

L32: Delete 'also'. Please explain briefly 'opposite polarity'.

"polarity" is changed to "direction", "also" deleted

p.11, L30: integrated => integrated over "over" added.

p.12, L23: to the load => to the load in the opposite hemisphere

"in the opposite hemisphere" is added.

L30: as a being "a" is deleted.

p.13, Eq. (16): According to Eq. (2), I think this should be written as E^star(z)- u(z)B(z)=const. (if mapping is neglected), i.e., electric field in a given, unique reference system, is constant.

Correct, the sign is changed. I think that this is the mapping condition, at least for the case of only zonal winds.

L19: the describe ... confirm Figure 1

"prescribed" is changed to "described".

L27: It is well accepted => please provide reference.

"It is well accepted" is deleted. Perhaps surprisingly I could not find a reference where this is explicitly stated, and also referee 2 had objections.

p.14, Eq. (17): The '+' sign on the r.h.s. should be '-', similar to Eq. (2).

Eq. (18): Both '+'signs on the r.h.s. should be '-': the first, same as above; the second, satellite velocity with respect to neutral atmosphere is $v_o rb - u$.

All signs are changed, I had myself become confused by the different notation than Kelley's.

L23: Considered => Considered first (?)

Throughout the manuscript only a "passive" plasma is considered, adding "first" would not fit.

2 Other Changes

Changes were made according to comments by referee 2, please confirm the reply for a list.

According to my own comment in section "Preliminaries"

~~, and also the cross-B current~~.

was deleted. Fukushima's contribution is reformulated as:

Fukushima (1979) had suggested that there are electric potential differences between conjugate points of only a few Volts.

References that were added are:

Cosgrove, R. B., Bahcivan, H., Chen, S., Strangeway, R. J., Ortega, J., Alhassan, M., Xu, Y., Welie, M. V., Rehberger, J., Musielak, S., and Cahill, N.: Empirical model of Poynting flux derived from FAST data and a cusp signature, Journal of Geophysical Research: Space Physics, 119, 411–430, https://doi.org/10.1002/2013JA019105, 2014.

Drob, D. P., e. a.: An update to the Horizontal Wind Model (HWM): The quiet time thermosphere, Earth and Space Science, 2, 301–319, https://doi.org/10.1002/2014EA000089, 2015.

Richmond, A. D.: On the ionospheric application of Poynting's theorem, Journal of Geophysical Research: Space Physics, 115, https://doi.org/10.1029/2010JA015768, 2010.