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

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1 Replies to comments by Referee 3

Cited referee comments are in red, replies in magenta.

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

1) The paper discusses the motivation for using the term "entanglement" in analogy with its use in quantum mechanics. To my knowledge this term is used exclusively for a quantum mechanical effect that does not apply here. The term "coupled" is used in circuit applications which are direct analogs of the simple system considered here, and I suggest is the more appropriate (and clearer) term.

Reply:

"Coupled" in "coupled dynamos" would not be a good adjective. An essential point is that the dynamos only exist because of the mismatched or not mapping neutral winds at conjugate points in a dipole-like magnetic field configuration. "Uncoupled" there are no dynamos. This is different from a ionosphere and a magnetosphere which may exist independently (examples are Venus and Mars having only ionospheres and Mercury having only a magnetosphere), but can be coupled for planets like the Earth. Therefore I don't want a title having "coupled dynamos". A title like "Interhemisphere coupling of the ionosphere-thermosphere and Joule heating" seems too general, unspecific.

There are cases in classical physics where "entangled" is being used, for example Islam and Archer (2001), "Nonlinear rheology of highly entangled polymer solutions in start-up and steady shear flow.".

The original word used by Schrödinger is the German "verschränkt", which can alternatively be translated to English as "crossed."

An alternative translation is "crossed", like in "crossed arms". "Crossed" would also be an approriate word describing here "crossed dynamos". There are similarities with entangled states known from quantum mechanics:

has been added in section 5.1

It is true that essential features of quantum mechanical entanglement do not apply here: There is no quantization and no probability interpretation. For example, by considering another spatial direction John Bell arrived at his

famous inequality predicting the statistical outcome of a large number of measurements. Here one will have to consider not only zonal, but also meridional winds to establish a more realistic model. This is mentioned in the manuscript. But the outcome of taking into account the other spatial direction will certainly not resemble Bell's inequality in any way, as probabilities aren't involved. However, as mentioned in the manuscript, the "entangled dynamos" do have an element of action at a distance which, in the quantum mechanical case, Einstein had called "spooky" (="gespenstisch").

2) In the discussion about open field lines (p14) the author states "it is doubtful that the neutral gas can act as a dynamo for the collisionless plasma in space over larger areas." As the author notes elsewhere in the paper, changes in electric field perpendic- ular B propagate along B as an Alfven wave. This change in electric field will change plasma drift velocity along B, will have associated with it electric currents and magnetic perturbations, and the energy content of the flux tube will change accordingly.

Consider a scenario with steady southward IMF leading to a large polar cap with open field lines. Furthermore let the solar wind speed be small so that solar-wind-driven Poynting flux into the polar cap is negligible. Next let the neutral wind in the ionosphere increase starting from zero. The result will be an Alfven wave launched upward along B, which will increase the energy density of the flux tube relative to the initial, undis- turbed state. The rate of energy transfer will be associated with an upward Poynting vector, and the correct interpretation is that the neutral wind is acting as a dynamo to drive plasma motions in the collisionless region above the ionosphere. In this case the collisionless flux tube acts as a load with characteristic impedance $\mu_0 * V_A$ (as opposed to $1/Sigma_P$ in the case of a conjugate ionosphere).

I agree that it may be challenging to determine the appropriate frame in which to carry out this analysis, however I believe it is incorrect to say that the neutral wind cannot act as a dynamo on open field lines, regardless of the size of the region. I suggest that the claim quoted at the beginning of this point be removed, that the related text be removed or corrected, and that clarification of this point be left to a future communication.

Reply: The statement that the the neutral wind cannot act as a dynamo on open field lines refers to a steady state. The manuscript generally describes only the steady state as mentioned in the introduction. The statement has been changed to

...doubtful that the neutral gas can act as dynamo for the collisionless plasma in space ~~on average~~in a steady state over larger areas. Temporal variations of a neutral wind would in principle excite Alfvén waves adjusting the mechanical stress balance between ionosphere-thermosphere and space plasma which, however, does not lead to any dynamo driven dissipation in space.

The situation described by the referee is not a steady state, and is certainly not the explanation for the average upward Poynting flux found in satellite data. The ionosphere-magnetosphere system on open field-lines readjusts very quickly (by transmitting an Alfvén waves) and reaches a new quasi-steady state. Unless there would a continuous sufficiently rapid temporal change of the neutral wind which the large inertia of the neutral gas prevents.

On open field-lines steady state current systems are involved in an exchange of momentum between Earth and the magnetosphere, see also Vasyliūnas (2007). This is a mechanical process based on Newton's second law, the conservation of momentum (not energy). Currents and the $\boldsymbol{j} \times \boldsymbol{B}$ force are independent of the reference frame (in the non-relativistic limit). Undisputably this process takes place in a quasi-steady state. A consistent pattern of the FAC shows up when averaging a large amount of satellite measurements (Iijima and Potemra, 1976).

In some publications it is stated, that this process of mechanical momentum transfer changes the kinetic energy in the ionosphere-thermosphere. This consideration, however, is frame dependent. Any chosen frame would arbitrarily define how much kinetic energy is in the ionosphere-thermosphere, and whether the momentum exchange between ionosphere and magnetosphere increases or decreases it. Therefore, after realising the inherent frame dependence of the $\boldsymbol{u} \times \boldsymbol{B}$ field, I have stayed away in the manuscript from a discussion of the kinetic energy.

Relevant is rather the conversion to thermal energy. This energy is frame independent, and the conversion, in the thermodynamic sense, is irreversible. The space plasma is generally assumed to be collisionless. Still dissipation, i.e. conversion to thermal energy, can take place at special locations. A prominent example is the bow shock. However, it is not plausible that the neutral atmosphere is in any way connected to such processes.

Thus, returning to the scenario of the referee, the thermal energy density of a flux tube with collisionless plasma does not increase because of a neutral wind at the bottom. This is consistent with the electric field and the Poynting flux in the frame of the plasma being zero. If there is a temporal change, as noted by the referee, then Alfvén waves are generated. After the wave has faded away and a new steady state is reached the thermal energy density of the plasma on the flux tube would be unchanged, and there has been no dynamo action by the neutral wind. But an exchange of momentum between ionosphere-thermosphere and space plasma has taken place.

3) P3, L10: it should be stated explicitly here and perhaps elsewhere that u(z) is assumed to be constant within each ionosphere. This is not clear as written.

Reply:

$\boldsymbol{u}$ and $\boldsymbol{B}$ are also assumed constant over the altitude range where there is significant collisional interaction with the plasma. In other words, the ionosphere is assumed to be thin.

has been added.

Grammar and language usage:

P1 L11: evenly matched -> comparable (evenly matched implies they are directly competing with/opposing one another) L15: scholarly in -> in scholarly changed as suggested.

P2: L5: with also further -> also with further (or drop "also") L7: "within two latitude circles" -> "within two constant-latitude rings" L9: in the southern hemisphere a westward (easterly) wind -> with a westward (easterly) wind in the southern hemisphere. L10: and a magnetic field aligned cartesion -> and a magnetic field-aligned cartesian L10: A ionosphere -> An ionosphere L12: interfer -> interfere L13: do play any role -> play any role L27: scholarly treated -> treated in a scholarly manner L29-31 word order: In the frame of the neutral gas in the dynamo region, roughly at altitudes of 90-350 km where collisions are significant, an electric field E* drives Pedersen and

Hall currents. . . . changed as suggested, except for using “circles of latitude” instead of “constant-latitude rings” because it is a fixed expression in geodesy (https://en.wikipedia.org/wiki/Circle_of_latitude)

Figure 1 caption: allows to -> allows one to changed as suggested.

P3: L6: top ionosphere -> topside ionosphere L7: v the ion or electron drift -> and v is the ion or electron drift L9 suggest: “For constant B, E(z) is also constant (where z is the coordinate along B). L12: request -> require L14: analogous -> analogously changed as suggested.

P4: L2: top -> topside L11: In both, -> In both (remove comma) L15: Galilei -> Galilean (search and replace throughout) changed as suggested.

P5: L3: wind twice -> wind is twice changed as suggested.

P6: L3: suggest: The title of this section, “Symmetric Dynamos”, does not necessarily refer to symmetrically opposing zonal winds in an Earth-fixed frame as drawn in Figure 1 (IS THIS WHAT IS INTENDED?) changed to:

The title of this section “Symmetric Dynamos” does not refer to the zonal winds that are symmetrically opposing in an Earth fixed frame as drawn in Figure 1. The same results are obtained for any wind difference that is equal to this symmetric case. “Symmetric” rather refers to . . .

The point here is the insight that the absolute winds, symmetric in a certain reference frame or not, are irrelevant. Only the wind difference is important.

L12: . . .instead of guessing them. Assumptions include:

Requirements that apply for both the symmetric and asymmetric cases include:

has been added.

P7: L1: The current loop between N and S closes exactly (add s to “close”) changed as suggested.

P8: A similar analysis was later performed with the Oerstedt. . . (add “the”) Arguing with -> Arguing on the basis of already Fukushima (1979) -> Fukushima (1979) already . . . changed as suggested.

P9: L7: suggest: . . .would be the result if the condition E + uxB = 0 determined E exclusively L10+: A wind without any variations along B would not force the plasma to establish an E*, and consequently could not drive currents nor a dynamo due to zero electric field in the neutral frame. changed as suggested.

P10: L9: but here it is an outlook for the future -> but here is left for future work. L12: convenien -> convenient L14+: Sentence beginning with “But probably more. . .”: But more decisive factors are probably the tilt of the geomagnetic field’s dipole axis, its offset from the Earth’s centre, and deviations of the symmetric field with respect to the dipole equator. (Is that what is meant?) changed as suggested (by referee 1).

L16: Suggest: These also cause differences near equinoxes . . . changed as suggested.

L33: may only little resemble -> may only slightly resemble changed as suggested.

P11: L4: The longitudinal dependence is indeed seen in the FAC pattern; please confirm . . . (use a semicolon since it separates independent clauses) L5: make it difficult -> makes it difficult L7, move “particularly” to before “consistent” (“particularly consistent” . . .) changed as suggested.

L14: Ampere -> Amperes L16: “to quite consistently between” -> “quite consistently to between” changed as suggested.

P12: L12: and does particularly not take -> and in particular does not take L15-16: with a more quantitative investigation left to a future investigation. L24: On each magnetic flux tube the neutral winds at each conjugate end provide a physical basis on which to define independent reference frames. L29: adding an in the field -> adding another definition in the field ... changed as suggested.

P13: L4: tiny delay -> small delay changed as suggested.

L11: shallow -> narrow “shallow” means here changing slowly, with a very small derivative/slope, because the distance along the field-line through the plasmasphere over which the change occurs is very large. So I did not change “shallow”.

P14: L1: (= without collisions) -> (meaning without collisions) L6: Desired is really -> The desired expression is rather: L24: “and a neutral wind that is not constant along the magnetic field” -> “and a neutral wind that is constant within the ionosphere but different in each hemisphere. changed as suggested.

P15: L8-9: In addition the Sq variations also reflect of course the dynamics of ... L28: implicitely -> implicitly L32: such that explicit potential drops ... changed as suggested, or text deleted following a comment by referee 2.

P16: L3: groundbased -> ground-based L13: The here presented dual entangled model -> The dual entangled model presented here L15: not restricted to dual -> not restricted to dual systems (is this what’s intended?)

The text is now:

A three-way entanglement of the dynamos in the equatorial F and E regions might turn out to be an applicable concept.

2 References

Iijima, T., and Potemra, T. A. (1976), The amplitude distribution of field-aligned currents at northern high latitudes observed by Triad, J. Geophys. Res., 81(13), 2165– 2174, doi:10.1029/JA081i013p02165.

Islam, M.T. and Archer, L.A. (2001), Nonlinear rheology of highly entangled polymer solutions in start-up and steady shear flow. J. Polym. Sci. B Polym. Phys., 39: 2275-2289. doi:10.1002/polb.1201

Vasyliūnas, V. M.: The mechanical advantage of the magnetosphere: solar-wind-related forces in the magnetosphere-ionosphere-Earth system, Ann. Geophys., 25, 255–269, https://doi.org/10.5194/angeo-25-255-2007, 2007.

3 Other Changes

The manuscript has been changed according to referees 1 and 2 comments and my replies to these comments.