

## ***Interactive comment on “Entangled Dynamos and Joule Heating in the Earth’s Ionosphere” by Stephan C. Buchert***

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NB this review is based on a version of the manuscript download in October 2019.

This paper presents and solves a simple model of magnetically conjugate neutral wind dynamos at mid latitudes. It clarifies and corrects previous descriptions and will serve as a valuable reference in the field, and I recommend that it be published. I have three substantive concerns to be addressed, and numerous suggestions for improving grammar and readability.

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

C1

circuit applications which are direct analogs of the simple system considered here, and I suggest is the more appropriate (and clearer) term.

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 perpendicular to  $B$  propagate along  $B$  as an Alfvén 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 Alfvén wave launched upward along  $B$ , which will increase the energy density of the flux tube relative to the initial, undisturbed 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  $u_0 V_A$  (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.

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.

Grammar and language usage:

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

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 cartesian -> 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. . .

Figure 1 caption: allows to -> allows one to

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

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

P5: L3: wind twice -> wind is twice

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

P7: L1: The current loop between N and S closes exactly (add s to "close")

P8: A similar analysis was later performed with the Oersted. . . (add "the") Arguing with -> Arguing on the basis of already Fukushima (1979) -> Fukushima (1979) already. . .

P9: L7: suggest: . . .would be the result if the condition  $E + u \times B = 0$  determined E

C3

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.

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?)

L16: Suggest: These also cause differences near equinoxes. . .

L33: may only little resemble -> may only slightly resemble

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". . .)

L14: Ampere -> Amperes L16: "to quite consistently between" -> "quite consistently to between"

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. . .

P13: L4: tiny delay -> small delay L11: shallow -> narrow

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.

C4

P15: L8-9: In addition the  $S_q$  variations also reflect of course the dynamics of. . . L28: implicitly -> implicitly L32: such that explicit potential drops. . .

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?)

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