How Is the Ionosphere Driven by the Magnetosphere?

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Abstract

In the ionospheric community, the electric field is often considered the driver of the ionospheric motion. We demonstrates from theoretical points of view that the electric field cannot be the driver of the motion. Instead, the electric field is a result, not the cause, of the motion. The causal relationship can be clearly understood in particular in dynamic processes and in heating processes. We call for a review and correction of the misused concept of electric field being a driver of motion and in particular the incorrect concept of penetration electric field.

1. Introduction

The ionosphere is known to be driven by the magnetosphere in short time scales related to magnetospheric convection. Conventionally, the process is understood as being driven by the electric field [e.g. Kelley, 2009]. For example, the polar region antisunward convection during southward IMF has been interpreted as being driven by the electric field mapped from the solar wind through the magnetospheric field, and the correlation between the upward motion of the equatorial ionosphere and the southward turning of the IMF has been interpreted as the penetration of the solar wind electric field into the low-latitude ionosphere [Huang et al., 2005], see Figure 1. It is interesting to point out that although most of the direct observations involved are actually velocity measurements, upper panels of Figure 1, they are converted to the electric fields for correlation. According to the conventional models, lower panels of Figure 1, the solar wind electric field, which varies with the IMF orientation and the solar wind velocity, is mapped to the polar cap open-field region. The global distribution of the electric field can be derived by solving (steady state) Faraday's law. The electric field in the closed field line region, referred to as the penetration electric field, in turn drives the ionosphere in the closed field line regions by the **E**x**B** drift, as described in Figure 2.

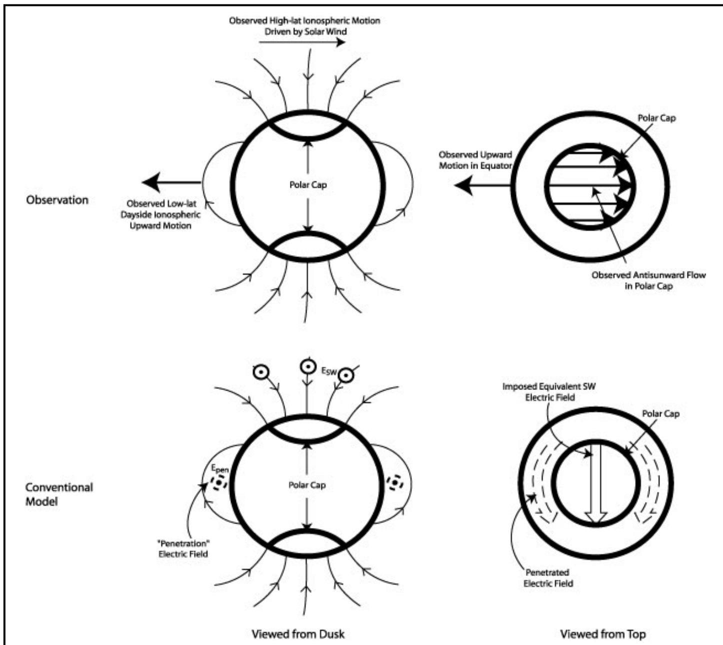

Fig. 1. The ionosphere and near Earth magnetosphere viewed from dusk, left panels, and from north, right panels. Magnetic field lines are indicated by thin solid lines with an arrowhead, streamlines thick lines with an arrowhead, and electric field lines open arrowheads. The derived electric field is indicated by dashed arrowheads.

2. The ionosphere cannot be driven by an imposed electric field from the magnetosphere

The conventional way of thinking has been questioned by Vasyliūnas [2001], (and in a laboratory context by Buneman [1992]), who showed analytically that the electric field is unable to drive flow, and, instead, it is the flow that produces the electric field. Later, Tu et al. [2008] conducted a full particle simulation and confirmed the same concept. This conclusion can be understood by the following. Figure 3 shows a setting with a uniform magnetic field pointing out of the page. When introducing to the system an electric field that points down, according to the single particle description, an electron will conduct **E**x**B** drift to the left and so does an ion. However, if the electron and ion coexist

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at the same point, for charge neutrality, when they drift to left, the difference in their gyro motions produces an electric field because of the charge separation. This newly produced electric field is in the opposite direction to the externally introduced electric field. The resulting internal electric field is reduced by a factor of $(V_A/c)^2$, where V_A is the Alfven speed and c is the speed of light. When the plasma is dense enough, with a relatively small Alfven speed, the electric field inside of the plasma is negligibly small, i.e. the externally imposed electric field is unable to "penetrate" into the plasma, which is a fundamental feature of the highly electrically conducting plasma. As a result, the particles will conduct only the gyro motions and not drift motions. What has happened is that an electron (ion) sheath, in which there are net electrons (ions), is formed near the upper (lower) boundary where the electric field is introduced [Tu et al., 2008]. The sheaths, in which the charge neutrality condition is not appliable, shield the electric field from penetrating into the plasma.

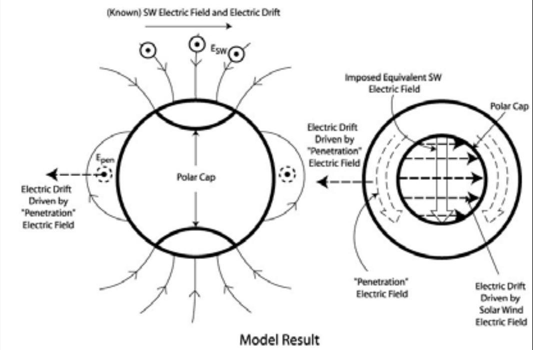

Fig. 2. conventional model with inferred streamlines in dashed lines, in the same format as Fig. 1.

If, instead of imposing an electric field, we give an initial leftward speed to a particle, according to the single particle theory, the particle would start its gyro motion. However, if this process takes place to a pair of colocating electron and ion, the difference in their gyro motions, again, produces an electric field which modifies the particle motions so that they drift to left and do not gyrate at the same point.

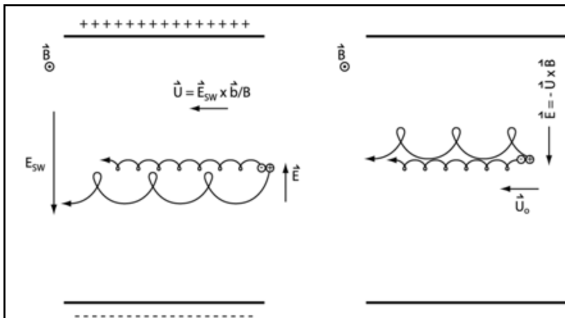

Fig. 3. Electron and ion motion in a uniform magnetic field when an downward electric field, left panel, is imposed and when the particles, right panel, are pushed to the left.

3. The ionosphere is driven by the magnetic tension force

Since the electric field cannot cause the ionosphere to move, a force that produces the motion needs to be identified. Let us consider a simple one-dimensional stratified situation with a vertical magnetic field when there is an initial horizontal motion in the magnetosphere, as shown in Figure 4. Across the magnetosphere-ionosphere boundary, because the magnetospheric plasma starts moving while the ionospheric plasma remains at rest, a kink in the magnetic field is produced if the magnetic field is frozen-in with the plasma as the collisions are negligible in time scales shorter than the ion-neutral collision time [Vasyliūnas, 2005]. The kink corresponds to a current and the **j**x**B** force will accelerate the plasma. The perturbation associated with the kink propagates downward from the magnetosphere into the ionosphere. After the front of the perturbation passes a point in the ionosphere, the plasma at this point moves at the same velocity as that in the magnetosphere. Since the neutrals do not experience the electromagnetic force, they remain at rest. The difference in the motions between the plasma and neutrals results in collisions between the two species. The collisions tend to slow down the plasma motion and the field line becomes kinked between the weakly collisional upper ionosphere and heavily collisional lower ionosphere. The tension force associated with the kink built up in this region tends to balance the frictional force exerted on the plasma associated with the collisions. The collisions also accelerate the neutrals. Eventually, the neutrals reach the same speed as the plasma, the collisions cease and the current diminishes.

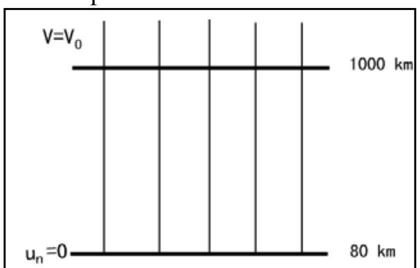

Fig. 4. A one-dimentional stratified ionosphere with vertical magnetic field and being driving by a horizontal velocity $\mathbf{V}_0$ at the top boundary.

Figure 5 shows a numerical calculation of the process [Song et al., 2009]. The calculation was based on a self consistent treatment of the plasma-neutral-electromagnetic field using the parameters at the winter north pole. It solves time dependent plasma and neutral momentum equations and Maxwell equations with generalized Ohm's law [Song et al., 2005]. The Hall and resistive effects are included. The *x*-axis is antisunward and *y*-axis dawnward. The background magnetic field, in the $-z$ direction, is constant in height. A horizontal velocity V_x is imposed at t=0 at the top ionospheric boundary set at 1000 km. It takes 1 sec for the velocity to reach a constant value of 10^{-3} V_A. One can see the acceleration of the ionospheric plasma and formation of a velocity shear in the lower ionosphere in the left panel, the wave front propagation and reflection as well as evolution of the field kink in the middle panel, and the formation and decay of the *F*-layer (Pedersen) current and continuous growth of the *E*-layer current. The detailed results of other components and electric field and neutral wind velocity, as well as their longer time-scale evolutions can be found in Song et al. [2009].

It is important to point out that in this calculation, the system is not driven by an imposed electric field nor by field-aligned currents. The whole ionosphere responds to the magnetosphere rapidly and the ionospheric currents are formed because of the continuously propagation of the field line kinks and not because of field-aligned currents.

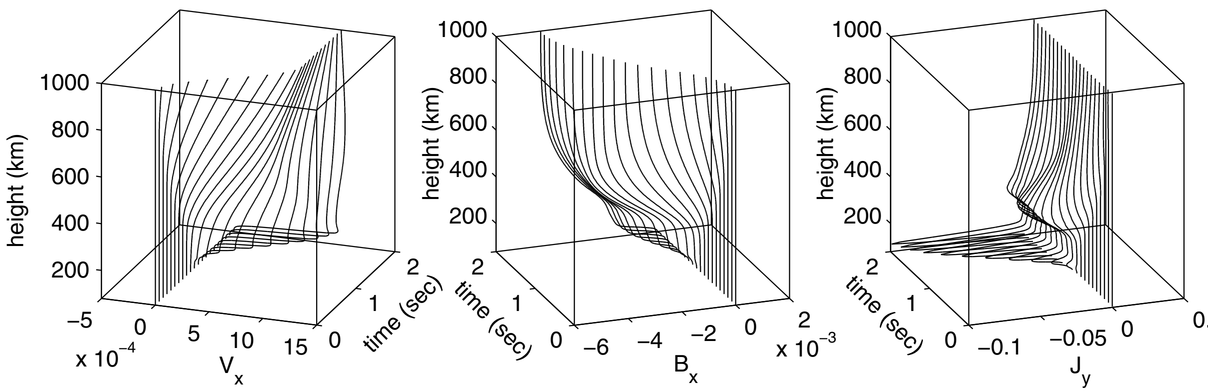

Fig. 5. Numerical solution of a self-consistently coupled plasma-neutral-electromagnetic field system describing the polar ionosphere that is driven by the magnetospheric motion [Song et al., 2009].

4. What drives the closed field line region of the ionosphere

In the last section, we have shown that the open-field line region of the ionosphere can be driven by the magnetic tension force created by the magnetospheric motion, which is described in the polar regions of Figure 6. We now consider the global ionospheric motion, the central issue for global modeling.

At the foot of a field line, the ionosphere can be approximated as a nearly incompressible flow for global modeling purposes (because the critical time scale for the fast mode traveling in the ionosphere, which is the spatial scale of the ionosphere divided by the fast mode speed, is much smaller than the magnetospheric MHD time scales). In the discussion below, we will include this small effect of compression. But loosely speaking, the ionosphere velocity can be treated as divergence-free, from mass conservation, and a streamline needs to be closed.

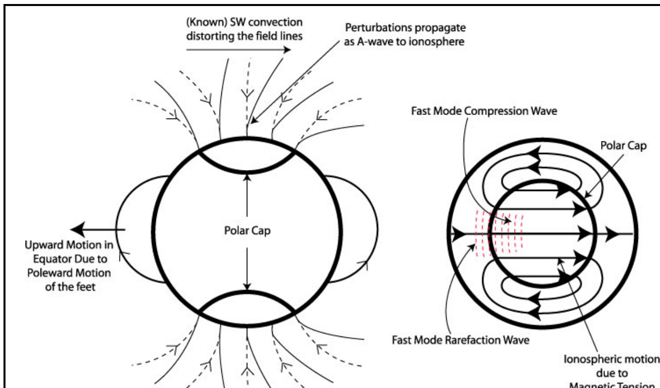

Fig. 6. The magnetic field and plasma motion in and near the ionosphere. Left panel, dashed lines with arrowheads indicate undisturbed Earth's magnetic field in the noon-midnight meridian plane. Solid lines in the two polar regions indicate the field lines perturbations when they, after reconnection, are driven by the solar wind. Right panel, solid lines with arrowheads indicate the convection in the northern ionosphere.

Let us now look at the field lines near the dayside cusp. A closed field line equator side of the cusp in the ionosphere convecting to higher latitudes corresponds globally in the magnetosphere to a field line convects toward the subsolar reconnection site and becomes open after reconnection, according to standard solar wind-magnetosphere interaction models. In other words, on the dayside, the poleward motion of a closed field line can be caused by the antisunward motion of an open field line that is dragged by the solar wind flow, as shown in Figure 6.

In the ionosphere, an enhanced antisunward flow at the footprint of the reconnected field line creates a compressional fast mode wave that quickly propagates throughout the ionosphere. On the dayside closed-field region (lower latitude to the reconnected field lines), the perturbation in the ionosphere is fast mode rarefaction. The convection forms closed convection cells in order to satisfy the mass conservation requirement, as discussed above. The poleward motion of closed field lines produces upward motion in the equatorial region near local noon. This upward ionospheric motion has sometimes been interpreted as a result of a penetration electric field [e.g., Huang et al., 2005] which is, as discussed above, an invalid concept because the electric field cannot penetrate into plasma.

Similarly but reversely, on the nightside, tail reconnection produces an equatorward motion at the feet of the first closed field line as it shortens itself and moving earthward, resulting in downward motion of the equatorial ionosphere if a significant ionospheric *F*-layer exists. This downward motion corresponds to a westward electric field, which has been interpreted as the cause of the downward motion. Again, the nightside downward motion of the equatorial ionosphere is a result of the equatorward motion of the plasma.

5. Conclusion

In summary, the imposed external electric field cannot drive the ionosphere. The ionospheric motion is driven by the magnetic tension force that magnetospheric motion creates. This can be most clearly understood by the fact that the electric field does not appear as a force in the plasma momentum equation for a quasi neutral plasma. The often quoted the fact that the electric field appears in the momentum equations of ions and electrons is a misunderstanding of the physics. The electric field in the electron and ion momentum equations only regulates the relative motion of each species but cannot cause motion as a whole. One may argue that the concept of the electric field driving the ionosphere has been used for a long time [Kelley, 2009], and that the alternative (more correct concept) does not bring much difference in the end. We believe that after people have known more about the correct description, the differences in the results will be recognized. One of such an example has been found concerning the ionosphere/thermosphere heating [Vasyliūnas and Song, 2005; Tu et al., 2011], in which the alternative description provides much simpler derivation of heating and the heating rate is about more than 100% bigger and more consistent with observed heating rate.

6. Acknowledgments

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7. References

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