Report on the manuscript angeo-2019-108
"Using the Galilean Relativity Principle to Understand the Physical Basis for Magnetosphere- Ionosphere Coupling Processes"
by Mannucci et al.

This reader agreed to review this manuscript because the title sounded very interesting, but the manuscript really had limited new information in it. This review is not of the opinion that this manuscript should not be published (it does in fact make the reader think), but the manuscript could be improved with more focus on attaining information relevant to its title, and more focus on being accurate in its discussion of the behavior of high-latitude ionospheric electrodynamics.

This manuscript fails to fulfill the promise of its title: the manuscript says what is not correct (which has been said before), but does not say what physical processes form the basis for magnetosphere-ionosphere coupling. I.e. it is never explained how the magnetosphere drives ionospheric motion and currents (which co-exist).

We appreciate these comments from the reviewer. In the following we attempt to clarify our explanations.

The closest it comes to an explanation is saying that momentum is transferred from the magnetosphere to the ionosphere (Lines 429-436).

We here elaborate on this explanation. The process by which momentum is transferred from the magnetosphere to the ionosphere is the same process by which momentum is carried in a particular direction by the solar wind. The solar wind consists of a non-collisional, magnetized, fully ionized plasma. The momentum is largely carried by the ions due to their larger mass compared to the electrons. Due to its non-collisional nature, the only interactions between the ions and electrons are electrodynamic. These electrodynamic forces lead to a collective motion of the plasma away from the sun towards the Earth. Without such forces, the random motion of the plasma would disperse the plasma and it would not travel collectively, carrying momentum in a well-defined direction. When this directed plasma encounters the magnetosphere, momentum is imparted via electrodynamic forces to magnetospheric ions, and eventually down towards the ionosphere until at lower altitudes collisional forces begin to play a role.

What has been said before is (a) that the perpendicular current is caused by the relative motion of plasma and neutrals across the magnetic field, (b) that Joule heating is associated with the work done to move charged particles through the neutrals (cf. the Drude model), and (c) explanations for ionospheric electrodynamics exist that do not focus on electric fields.

We agree that (a) has been stated previously. We would appreciate references to the Drude model so that we can reference it in the context of this paper. We would appreciate references for (c). Although explanations may exist that do not rely on electric fields, there are explanations that do rely on electric fields. We are addressing those explanations that do rely on electric fields.

This reviewer is aware that clear pictures of cause and effect in plasma electrodynamics are difficult because Maxwell's equations describe consistency, not cause and effect.

We appreciate this comment. We believe cause and effect can be inferred to some extent from Maxwell's equations (ME) because ME determine how electric and magnetic fields originate from their sources (charges and currents). Electric and magnetic fields determine the forces on charges and currents, thus leading to various effects.

One should look at the mechanisms that extract energy (and momentum), that convert energy and momentum, and that transport energy and momentum. It seems unwise to use PGR, which only sometimes works, to organize a discussion describing the driving of currents, the transfer of momentum, and the transfer of energy. As Section 2.3 notes, Poynting's theorem does not hold in PGR. Perhaps this is why the title of the article is not fulfilled. The concepts of PGR seem more like handcuffs than tools.

We appreciate this comment, but do not completely agree with all of it. The PGR "always works" in the sense that the principle of special relativity (PSR) is absolute: the laws of physics are invariant to reference frame. The approximate form of special relativity as embodied in the PGR is not always consistent with ME. In this paper, we use those aspects of the PGR that are useful, despite its imperfection. We believe the paper may be clearer if we refer to the PSR, and not always to the PGR. We can do so in a revision. We propose a revised title to address this comment: "A discussion of physical processes in magnetosphere-ionosphere coupling, including the problematic use of Galilean relativity."

Transfer of energy and momentum is relevant to the PSR because the PSR suggests that the electric field is not always a suitable explanation for such transfer. This is described in the paragraph lines 411-421.

We agree that the discussion of momentum transfer (lines 429-436) is not well motivated in the current version. We address this below (under your comment for lines 459-480).

Several times in the manuscript it is stated that "something" is inconsistent with PGR (e.g. lines 164, 166, 304): it is hard to tell if this is a criticism of the "something" or a criticism of PGR.

This problem is addressed by de-emphasizing PGR in favor of the PSR. All the physics must be consistent with the PSR. This could be achieved in the revision.

Lines 165-167: The statement "electric fields that arise due to charge accumulation are inconsistent with the usual field transformation equations…" is not true. For example, there is charge density in the ionosphere wherever there is plasma vorticity that is parallel to the magnetic field (i.e. a shear in a perpendicular flow v_{perp}), and that charge density cannot be transformed away. There is an electric field (and a nonzero divergence of the electric field) associated with that charge density (and associated with the shear flow). The motion of the charge density does make a perturbation to B, but its magnitude is $\otimes B = (v_{perp}/c)^2 B$: it is consistent with PGR to ignore this change in B.

The presence of non-zero charge density is inconsistent with the widely-used transformation rule that current density is invariant to reference frame (see the text above Equation (4) in

Thayer and Semeter, 2004). To the best of our understanding, the perturbation to the magnetic field is not second-order. If a charge density ρ exists in the reference frame at rest, then in the moving reference frame the current density originating from this charge density is $-\rho\mathbf{v}_{\boldsymbol{r}}$ (see Equation (7) of this paper). This current density in the moving frame will lead to a magnetic field ($\nabla \times \mathbf{B} = \mu_0\mathbf{J}$), in contradiction to our Equation (4) which is part of the PGR.

Lines 199-207: This reader is uncertain as to the purpose of this paragraph. Landau damping involves an electric field that is parallel to the velocity of interest and that parallel electric field does not change with reference frame as you go to the particle's frame.

We agree this paragraph is somewhat out of context. A previous reviewer had wanted us to include these specific examples of the use of PGR in geospace. We can remove this paragraph in the revision.

Line 225: "For electromagnetic waves," should be "For electromagnetic waves in vacuum,"

Our intention in this sentence was to refer to the hypothetical aether as the "preferred reference frame", that was postulated as the material medium in which electromagnetic waves propagated. The Michelson-Morley experiment is evidence that this aether does not exist. In the context of sound waves, an analogous experiment would show the presence of a material medium for sound waves. We could simply remove this sentence.

Lines 238-241: This reader is completely confused by this paragraph.

We regret that this paragraph is not more clear. It is perhaps sufficient to simply append the following sentence to the end of the previous paragraph and otherwise delete this paragraph.

The second term in the expression for $\mathbf{E}^*$ has been referred to as a dynamo electric field when $\mathbf{V} = \mathbf{V}_{\boldsymbol{n}}$, the velocity of the neutral species (Richmond, 1995), although this term does not refer to a physical electric field.

Lines 304-306: The statement "requires the creation of polarization charge, which is inconsistent with the Galilean invariance of the magnetic field" is not correct. Polarization charge is in fact created at the edges any spatially limited flow (plug in Coulomb's law for a shear flow where the

flow is described by ExB drift). As noted above, advection of such charge density creates a perturbation to be that is of order $(v/c)^2B$ (where v is the advection velocity), which is ignorable in PGR and not "inconsistent" with PGR.

As we have stated above, the presence of a charge density ρ in one reference frame creates a current density in the moving reference frame ($\rho\mathbf{v}_{\boldsymbol{r}}$). The current density in the moving frame should create a magnetic field according to Maxwell's equation. This is not a second-order effect in our view. See Equation (7) of the paper. We can be more explicit in the revision.

Lines 459-480: This is a misleading calculation: no one would believe that the parallel-to-B momentum of the magnetospheric charge carriers has anything to do with the perpendicular-to-B momentum of the ionosphere. This is like calculating the momentum of electrons in a wire to explain momentum provided by an electric fan or the momentum of an electric car. Further, what does this calculation have to do with an electric field? The way to look at the momentum change of the ionosphere is to look at the surface integral of the Maxwell stress tensor, but since Poynting's theorem is not valid in PGR, this might not work in present study.

We agree with your statement that the momentum of electrons in a wire do not explain the momentum of a car. The car experiences a force between the road and tires that changes the car's momentum. If the car were an isolated system, a momentum analysis concerning the electrons in the wire might be relevant. In the current paper version, we do not clearly present an analysis of what external forces are acting on different parts of the system (electrons, ions, neutrals), so the momentum calculation can appear misleading and we will remove it.

We appreciate the comment: "what does this calculation have to do with an electric field?" This leads us to consider how field-aligned currents are related to electric fields in the ionosphere. This relationship is directly relevant to the PGR, because currents and fields have different transformation properties. The relevant literature is that which discusses models that connect the cross-polar cap potential to region 1 currents. The cross-polar cap potential is due to the large-scale convection electric field.

A model that relates region 1 currents directly to the convection electric field is discussed in Siscoe et al. (2002; doi: 10.1029/2001JA000109) where the introduction states "Φ_m (magnetospheric convection potential) is then impressed via equipotential magnetic field lines onto the ionosphere, where it becomes the Φ_{pc} (transpolar ionospheric potential) that generates region 1 currents." This statement suggests a causative relation between electric field and region 1 currents and thus is relevant to our discussion of the PGR. In a revision, we will reference Siscoe et al. (2002) and papers that use this model (Rothwell and Jasperse, 2006 and 2007) and discuss these models in the context of the PGR.

This type of model does not account for the neutrals, which is a key missing element. As we and others argue (e.g. Mannucci et al., 2018; Cowley, 2000) the ionospheric currents are the result of plasma flowing relative to the neutrals. Divergence of these currents can lead to field-aligned currents into the magnetosphere. Processes in the magnetosphere can lead to field-aligned currents also, that enter the ionosphere. Overall, we agree that the momentum discussion does not bring clarity to understanding these processes.

Lines 521-522: "Thus it is problematic to assert that the cause of high velocity plasma flows known as SAID are horizontal currents closing in the ionosphere". You are saying what it is not the cause, but never saying what is the cause!

We are not prepared to state the cause. However, we believe it is useful, using relativistic arguments, to rule out causes that have been proposed.

The manuscript repeatedly criticizes the electric field because it differs from frame to frame, asserting therefore that it cannot be the explanation (cause) of things. One should assume that if a problem is worked correctly in two different reference frames, one should get two answers that agree. (Principle of invariance of proper physical description in relativity.) Maybe PGR is not the right way to think about high-latitude electrodynamics.

We should not be leaving the impression that we are criticizing the electric field. We are merely noting that its transformation properties are important to consider in light of understanding physical processes. We believe that PGR is useful in that it can guide how explanations will differ depending on reference frame. We will add text to clarify this point.

Here is a gedanknenexperiment in support of the ionospheric electric field. Call it the cold-Earth problem. Let's say that the high-latitude ionospheric plasma and neutrals are absolutely cold (no collisions) and that the ions, electrons, and neutrals are all at rest (no wind). The one frame that makes sense to use to look at this is the frame of the observer on the ground, the neutrals, the ions, and the electrons (all the same frame). If from this cold start I want to get the plasma to flow relative to the neutrals, and to get a horizontal current that is associated with the plasma flow through the neutrals, by charged-particle orbit theory I must get a horizontal electric field into the ionosphere to start the ExB drifting of the ions and electrons, which collisions with the neutrals will disrupt and form a Pedersen and/or Hall current. When everything is at rest, there can be no other force on a charged particle than the electric field force. The explanation of how the magnetosphere drives the ionosphere in this cold-Earth gedankenexperiment is explaining how the magnetosphere got that needed electric field into the ionosphere.

This is an interesting experiment. We would describe the processes as follows. To initiate plasma flow relative to neutrals requires imparting momentum to the ions. As we suggest above (response lines 429-436), the momentum transfer occurs via coupling to a moving plasma – the solar wind plasma. The solar wind plasma couples to the magnetospheric plasma, and eventually to the ionospheric plasma, via collisionless processes – the same processes that are responsible for transferring momentum in the solar wind to the outer magnetosphere. Conversely, as Vasyliunas has shown (2001, doi:10.1029/2001GL013014), electric fields imposed on a plasma do not cause that plasma to flow.

This reviewer looks forward to reading an improved draft. (Thinking is good!)

The editor has suggested that the discussion can proceed without the revised draft. This makes sense because we are not yet in full alignment regarding how the paper should proceed forward. We certainly look forward to providing a revised draft once we know how to proceed.