Peer Review File

Manuscript Title: Earth’s ambipolar electrostatic field and its role in ion escape to space

Redactions – unpublished data

Parts of this Peer Review File have been redacted as indicated to maintain the confidentiality of unpublished data.

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

t of Earth’s Electric Potential

By G. A. Collinson et al.

Summary:

The authors report on a novel, in situ measurement of the Earth’s ambipolar electric field as produced by the Endurance rocket, and specifically made by two complementary instruments, the Endurance Photoelectron Spectrometer (PES) and the Swept Langmuir Probe (SLP).

The ambipolar electric field has been inferred from profiles of the electron number density and temperature for many years (Wahlund et al., 1992; Wu et al., 1992) and more recently (Godbole et al., 2022), giving values that are quite consistent with the present observation. However, this is the first time – to this reviewer’s knowledge – that this electric field value has been measured in situ, which is very exciting and worthy of publication in Nature. Simply plugging into the electron pressure gradient formula assumes that formula is correct. The PES method on Endurance is the first measurement I know of using a technique that does not assume that pressure gradient formula.

Major comments:

The details of the PES instrument are terse in this Nature article, but they have already been described in much greater detail in citation [8] in space science reviews. The article is oversimplifying the physics somewhat by saying that the line they are observing is coming from N2+ (A 2Pi_u). They are really seeing a superposition of lines, and N2+ (A 2Pi_u) and O+(2D) end up almost exactly on top of each other. This is correctly explained in Figure 4 b of citation [8], however. Hwoever it doesn’t really matter where the line comes from for this analysis.

I’m surprised that there are not more pronounced lines from O+(4S) and O+(2P), since those lines are very prominent in the AE-E data. Is it because Endurance was launched into an N2-rich atmosphere?

The biggest possible issue with the data analysis is whether the corrections for spacecraft potentials were accounted for correctly. I must this was done correctly, given how consistent the agreement with the EISCAT radar data is in the end, but it would be worth explaining this a bit more.

Minor comments:
L91: “U” shouldn’t be capitalized

L94: I think this is meant to be “latter”

References:

Godbole Niharika H., Lessard Marc R., Kenward David R., Fritz Bruce A., Varney Roger. H., Michell Robert G., Hampton Don (2022). Observations of ion upflow and 630.0 nm emission during pulsating aurora. Frontiers in Physics, 10, doi:10.3389/fphy.2022.997229

Wahlund, J.-E., Opgenoorth, H. J., Häggström, I., Winser, K. J., and Jones, G. O. L. (1992), EISCAT observations of topside ionospheric ion outflows during auroral activity: Revisited, J. Geophys. Res., 97(A3), 3019–3037, doi:10.1029/91JA02438.

Wu, Jian & Blanc, Michel & Alcayde, Denis & Barakat, A. & Fontanari, Jean & Blelly, P.-L & Kofman, Wlodek. (1992). Observations of the structure and vertical transport of the polar upper ionosphere with the EISCAT VHF radar. II - First investigations of the topside O(+) and H(+) vertical ion flows. Annales Geophysicae. 10.

Referee #2 (Remarks to the Author):

This manuscript reports on the results from the Endurance sounding rocket experiment, which launched from Svalbard, Norway on 11 May 2022. Using measurements from a photoelectron spectrometer (PES), Langmuir probe (SLP), and electromagnetic fields instruments (FIELDS). The authors conclude that they have observational evidence showing that Earth's topside ionosphere exhibits a constant, large-scale, ambipolar parallel electric field (E-field), which can explain much about the nature of ion outflow from the polar ionosphere.

The evidence and results are compelling and certainly intriguing, and I would be supportive of publication of these results if the authors can address my concerns below. In particular, I am concerned that there may be some fundamental flaws in the ambipolar field model that the authors apply to explain their results. I am also concerned with the observations themselves, particularly of the electric potential field. These concerns are detailed below.

The authors' model to explain the constant, large-scale, ambipolar parallel E-field in Earth's topside ionosphere involves an electron thermal pressure gradient and the ability of electrons to more easily loft in Earth's gravity field compared to (much heavier) positive ions. However, this model results in a steady-state, large-scale (100s of km in Earth's ionosphere) charge separation and corresponding parallel E-field system. My primary concern (and that of several colleagues whom I posed this scenario to) is that such a system fundamentally invalidates the core assumptions of magnetohydrodynamics, particularly quasi-neutrality and the free motion of electrons along magnetic fields to nullify any large-scale parallel E-fields. Insufficient detail was provided to show how this model is truly steady state. I understand that the photoionization by sunlight is essentially the "free-source" of energy into the system, which may maintain the pressure gradients. Also, it is feasible that the system might reach some steady-state where the pressure gradient is indeed sustained by some constant potential drop. However, the details in the manuscript (including the additional materials outside of the main article) are not comprehensive to support such a model. Furthermore, there are concerns with the E-field measurements themselves, as those are notoriously difficult to make in space plasmas. These concerns are detailed further below.

The pressure calculation on line 79 should use the full pressure tensor, or the assumption of electron pressure isotropy should be justified here; this is again an issue concerning parallel electric fields and electrons: electrons are essentially free to move parallel to field lines in the presence of any parallel E-field and thus are also responsible for the currents that equilibrate and effectively eliminate any excess E-parallel on larger scales (as the authors are arguing here at a global Earth scale).

From many, many spacecraft observations, it is well understood that parallel electric field structures tend to be extremely localized and limited to electron kinetic scales [e.g., Malaspina+ 2014: 10.1002/2014GL061109; Vasko+ 2017 : 10.1002/2016JA023337; Mozer+ 2021: 10.3847/1538-4357/abed52]. What is responsible for maintaining that presumably global-scale, ambipolar field? Why wouldn't the electrons simply move along the field to effectively cancel the potential difference? The authors suggest that this field is always present, meaning that something must be actively sustaining the very large-scale charge separation. There seems to be an issue here with self-consistency in the conceptual model presented by the authors.

What about the motion of the rocket relative to the background plasma; was the relative motional E-field of the plasma accounted for at all in the measurements and analyses?

The authors discuss a "global electrostatic energy field" but what exactly is this field relative to? What is true ground? How was true ground maintained on a rocket moving through a charged plasma? Little detail is given concerning the sensitivity of the instruments. Error estimates are provided, but most of the error bars overlap on Figure 1. Also, how were the error bars quantified throughout the study (are they all +/- 1-sigma of presumably binned measurements?)? Are there any known calibration errors or offsets in the measurements?

What about spatiotemporal differences along the trajectory? Single point rocket observations seem insufficient to warrant claim of discovery of such an electrostatic field. Simultaneous multipoint observations of voltage differences larger than the intercalibration error between the different sensors might be necessary.

Error ranges on the data fitting constants (including the derive E-parallel values listed in Fig 1) should also be included.

Figure 1 : Do the upleg and downleg plots have the same X-axis, most importantly, the same absolute X = 0.0 V point? This is critical to any kind of confidence here in the results

No evidence is provided showing quiet geomagnetic conditions during this event

Lines 33-34: This statement is too suggestive that the cold ions are the cause of strong storms; that is not true at all. An abundance of cold ions in the magnetosphere and enhanced ionospheric outflow are correlated with more intense geomagnetic activity, yet correlation is not causation. This statement needs to be edited for clarification.

Author Rebuttals to Initial Comments:

Response to Referees' comments:

Referee #1 (Remarks to the Author):

The authors report on a novel, in situ measurement of the Earth's ambipolar electric field as produced by the Endurance rocket, and specifically made by two complementary instruments, the Endurance Photoelectron Spectrometer (PES) and the Swept Langmuir Probe (SLP).

The ambipolar electric field has been inferred from profiles of the electron number density and temperature for many years (Wahlund et al., 1992; Wu et al., 1992) and more recently (Godbole et al., 2022), giving values that are quite consistent with the present observation.

References:

- *Godbole Niharika H., Lessard Marc R., Kenward David R., Fritz Bruce A., Varney Roger. H., Michell Robert G., Hampton Don (2022). Observations of ion upflow and 630.0 nm emission during pulsating aurora. Frontiers in Physics, 10, doi:10.3389/fphy.2022.997229*
- *Wahlund, J.-E., Opgenoorth, H. J., Häggström, I., Winser, K. J., and Jones, G. O. L. (1992), EISCAT observations of topside ionospheric ion outflows during auroral activity: Revisited, J. Geophys. Res., 97(A3), 3019–3037, doi:10.1029/91JA02438.*
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> Thank you for these references, we have added them to the main body of the paper to back up the assumption that "To the first order, $E_{\parallel} \approx -\nabla P_e / q n_e$"

However, this is the first time – to this reviewer's knowledge – that this electric field value has been measured in situ, which is very exciting and worthy of publication in Nature. Simply plugging into the electron pressure gradient formula assumes that formula is correct. The PES method on Endurance is the first measurement I know of using a technique that does not assume that pressure gradient formula.

Major comments:

The details of the PES instrument are terse in this Nature article, but they have already been described in much greater detail in citation [8] in space science reviews.

In response to this comment, we have included a new Methods section giving a brief description of the 3 instruments used in this study, including a brand-new figure which shows their final deployed configuration.

The article is oversimplifying the physics somewhat by saying that the line they are observing is coming from N2+ (A 2Pi_u). They are really seeing a superposition of lines, and N2+ (A 2Pi_u) and O+(2D) end up almost exactly on top of each other. This is correctly explained in Figure 4 b of citation [8], however. However it doesn't really matter where the line comes from for this analysis.

The reviewer is quite correct, while our understanding is that this photopeak is dominated by N2+ (A 2Pi_u) emission (as per Coates et al., 2011), it is indeed a superposition of other emission lines. We have updated the language in the main paper (for a more general audience) to be agnostic as to the exact emission line.

"Fig 2A,B shows Earth's ionospheric electric potential drop measured by the shift in a bright He-II photopeak [...]"

We have updated the methodology section below figure 4 to read that it is dominated by this emission line, rather than implying a single emission

"The brightest He-II photopeak observed during the flight was from a photopeak generated by a superposition of emission lines, but dominated by emission by the N_2 A^2 Π_u atomic transition, which generates electrons at precisely $24.09\ eV$ [4, 5]"

We then refer to it as just "the photopeak" for the rest of the section. We have updated our language after figure 5 to read

"resolved the peak dominated by N_2 A_2 Π_u photoemission"

As a final note, we wish to stress that our measurement of Earth's potential is based on the relative shift of any photopeaks between the photoproduction region and apogee and is agnostic to the exact emission line measured. But we are in firm agreement with the reviewer's point that we need to accurately describe the photoelectron peaks captured by PES.

I'm surprised that there are not more pronounced lines from O+(4S) and O+(2P), since those lines are very prominent in the AE-E data. Is it because Endurance was launched into an N2-rich atmosphere?

For several reasons we were forced to make the energy window for the PES high-resolution scan very narrow (20.30 eV to 25.85 eV). This means that with the slightly negative spacecraft potential the $O^{+}(4S)$ will be just out of range. There are teasing hints that we caught the very tail of it near apogee, but we think we just missed it.

The plot opposite is from our internal analysis when we were trying to identify the photopeaks captured. This shows three scans of PES with the GLOW superthermal electron model (green) superimposed, using the FISM solar irradiance model (guided by SDO measurements of solar emission spectra during the flight), and the MSIS model for the thermosphere (which densities from our Bayer Alpert Ionization Gauges were consistent with). There is a very good agreement between the high-resolution measurements made by PES.

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GLOW predicts that the $O^{2}P$ line is there, but its subtle. The other emission line visible in the data is the N_2X^2 $Sigma_g$. This can be pretty clearly seen in Fig 5 of the paper as a hump to the right of the main photopeak. We haven't drawn attention to this in this paper simply for brevity.

As a final note on other photopeak physics, we are committed to make all PES data (including these high-resolution scans) public (via CDAWEB) simultaneous with publication so anyone interested in photopeaks *per se* can get their hands on them.

The biggest possible issue with the data analysis is whether the corrections for spacecraft potentials were accounted for correctly. I must this was done correctly, given how consistent the agreement with the EISCAT radar data is in the end, but it would be worth explaining this a bit more.

A new section has been added to our methodology describing how measurements were corrected for spacecraft potential. This feeds from the description of SLP (above) which describes the basic I-V curve fitting process.

We have also included a full plot of EISCAT data (supplemental data Fig S3) which shows the EISCAT vs. SLP electron density and temperature measurements, showing the good agreement noted by this reviewer.

Minor comments:
L91: “U” shouldn’t be capitalized

> Would the reviewer please give a little more context? We cannot find this errant capital “U”

L94: I think this is meant to be “latter”

> Corrected, thank you

Referee #2 (Remarks to the Author):

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The authors' model to explain the constant, large-scale, ambipolar parallel E-field in Earth's topside ionosphere involves an electron thermal pressure gradient and the ability of electrons to more easily loft in Earth's gravity field compared to (much heavier) positive ions. However, this model results in a steady-state, large-scale (100s of km in Earth's ionosphere) charge separation and corresponding parallel E-field system.

> We see how a reasonable reading of our previous draft could easily have given the erroneous impression that a charge separation occurs. The reality is exactly the opposite, such fields arise due to the need to maintain quasi-neutrality and avoid a bulk steady-state charge separation. We have clarified this paragraph as below.
>
> > “At a minimum, Earth’s electrostatic field is thought to be underpinned by a “polarization” or “ambipolar” electric field [6] [7]. Such fields are generated as ionospheric electrons attempt to escape to space under their own thermal

pressure. As the electrons attempt to pull away from the heavier ions, the ambipolar field arises to maintain charge neutrality."

We have also made substantial additions and changes to the manuscript to better explain the physics of how such planetary fields have been predicted to form, as will be described shortly.

My primary concern (and that of several colleagues whom I posed this scenario to) is that such a system fundamentally invalidates the core assumptions of magnetohydrodynamics, particularly quasi-neutrality and the free motion of electrons along magnetic fields to nullify any large-scale parallel E-fields.

The reviewer and their colleagues are completely correct, such large-scale parallel electric fields cannot exist in ideal MHD. This is because MHD takes generalized Ohm's law (below)

$$\boldsymbol{E} = -(\boldsymbol{u} \times \boldsymbol{B})/c + (\boldsymbol{J} \times \boldsymbol{B})/(en_e c) - \boldsymbol{\nabla} P_e/(en_e) + \eta \boldsymbol{J}$$

(see e.g. Dorelli, J. C., et al., (2015), The role of the Hall effect in the global structure and dynamics of planetary magnetospheres: Ganymede as a case study, J. Geophys. Res. Space Physics, 120, 5377–5392)

And truncates it to just the first term which can only produce a perpendicular E field.

$$\boldsymbol{E} = -(\boldsymbol{u} \times \boldsymbol{B})/c$$

MHD is a reasonably good approximation for most astrophysical plasmas. However, in certain instances, additional physics are required. The small-scale structures noted later by the reviewer (ion holes, double layers, etc) are all good examples of where MHD breaks down when non-fluid or kinetic effects become important.

Planetary ambipolar fields arise from a very different instance where MHD has limited applicability, specifically that in an ionosphere the $\boldsymbol{\nabla} P_e/(en_e)$ term in Ohm's law cannot be neglected. We will discuss this in more detail shortly.

Insufficient detail was provided to show how this model is truly steady state. I understand that the photoionization by sunlight is essentially the "free-source" of energy into the system, which may maintain the pressure gradients. Also, it is feasible that the system might reach some steady-state where the pressure gradient is indeed sustained by some constant potential drop. However, the details in the manuscript (including the additional materials outside of the main article) are not comprehensive to support such a model.

We agree that the previous draft did not lay a sufficient foundation as to the fundamental physics behind planetary ambipolar fields. To rectify this, the paper now includes a derivation from first scientific principles of how such steady-state parallel electric fields are predicted to arise from the pressure gradient on the topside of the F-layer (see methodology section). Versions of this derivation are discussed in the following papers.

- R. H. Varney, S. C. Solomon and M. J. Nicolls, "Heating of the sunlit polar cap ionosphere by reflected photoelectrons," Journal of Geophysical Research: Space Physics, vol. 119, pp. 8660-8684, 2014.

- T. I. Gombosi and A. Nagy, "Time-dependent modeling of field aligned current generated ion transients in the polar wind," Journal of Geophysical Research, vol. 94, pp. 359-369, 1989.

- M. W. Liemohn, G. V. Khazanov, T. E. Moore and S. M. Guiter, "Self-consistent superthermal electron effects on plasmapheric refilling," Journal of Geophysical Research, vol. 102, pp. 7523-7536, 1997.

In a nutshell, while these references above take slightly different derivations, all involve solving the electron momentum equation for $E_{||}$, and then applying the specific plasma conditions in the ionosphere (which substantially simplifies the problem). All come to the same fundamental conclusion, i.e. the prediction of a 100s km scale steady-state global electric field from the $-\boldsymbol{\nabla} P_e/(en_e)$ term in Ohm's law. As noted by the first reviewer, it has been standard practice in ionospheric science to approximate the ambipolar field by taking this pressure gradient. However, this has never been tested experimentally until now, and it was entirely possible that other processes contributed to Earth's electrostatic field (as at Mars and Venus).

We hope that the derivation now included in the methodology section will more clearly communicate how the pressure gradient on the topside is predicted to generate Earth's ambipolar field. It ties in closely with our main figure (now fig 2) where we directly test the theory that $E_{||} = -\boldsymbol{\nabla} P_e/(en_e)$ against our measurements, finding a close agreement. We have revised our discussion of this agreement and summarized this in the main body.

> "Using SLP measurements of electron density (n_e) and temperature (T_e) we can calculate electron pressure ($P_e = n_e k_b T_e$). By taking the vertical gradient of electron pressure (∇P_e), we may compare the parallel electric field ($E_{\parallel}$) measured by *Endurance* against what would be expected from theory. The derivation of the ambipolar field has been presented in numerous previous publications and is found by solving for $E_{\parallel}$ in the steady state electron momentum equation [8] [9] [10]. To the first order, $E_{\parallel} \approx -\nabla P_e/qn_e$. We find a close agreement between this prediction (orange, Fig. 2AB) and *Endurance* observations (diamonds, Fig. 2AB). Thus, we conclude the only source of electrical potential at Earth observed by *Endurance* was a classical electron pressure-driven ambipolar field."

Furthermore, there are concerns with the E-field measurements themselves, as those are notoriously difficult to make in space plasmas. These concerns are detailed further below.

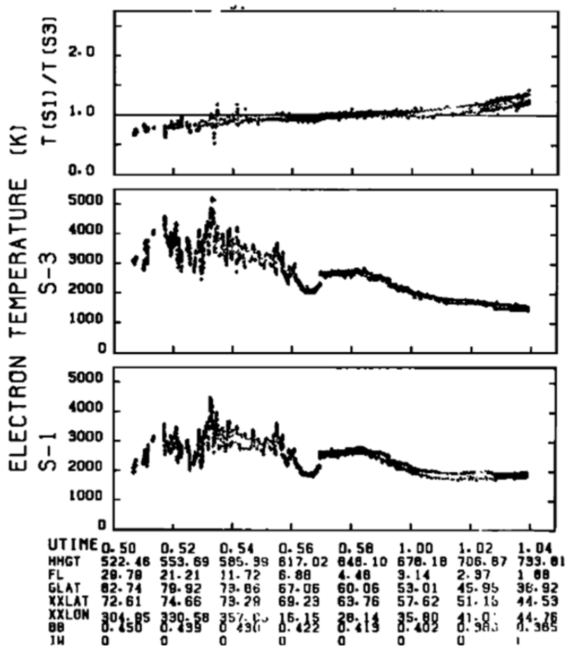
The pressure calculation on line 79 should use the full pressure tensor, or the assumption of electron pressure isotropy should be justified here;

This is a sound concern. The presence of an anisotropy in electron pressures would enhance $E_{||}$, and thus we agree the assumption of isotropy must be justified. We have taken 2 steps to address this. Firstly, as suggested by the reviewer, we have added a justification for the assumption of electron pressure isotropy (in the derivation of the ambipolar field).

> Finally, as per most ionospheric models, we will assume that the bulk population of ionospheric electrons are isotropic $\left(P_{||} = P_{\perp} = P_E\right)$. In reality, satellite measurements at the altitudes and latitudes explored by *Endurance* have revealed a small degree of anisotropy in ionospheric electrons, however this is on the order of only $\approx 10\% \rightarrow 20\%$ [11], and thus to the first order the assumption of isotropy is quite reasonable.

For convenience, below we have appended plots from two relevant papers below. The one on the left is from Oyama and Abe (1987) which is the reference in the passage above.
https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/GL014i012p01195

For good measure we also include a plot (right) from Ganguli et al., 1987 *("Behavior of ionized plasma in the high latitude topside ionosphere: The polar wind")*, which is consistent. Note that this plot begins where electrons are highly isotropic up through ~1,500km, compared to *Endurance's* apogee of 768km.



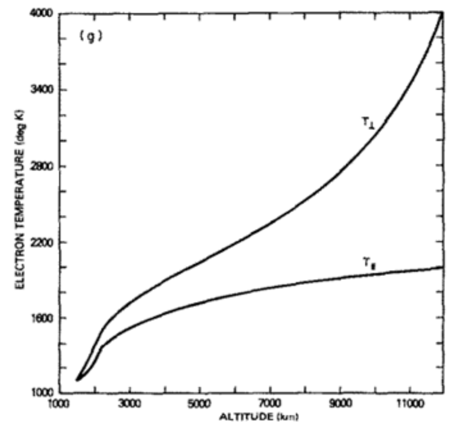


FIG. 1. POLAR WIND PROFILES VS ALTITUDE. The boundary conditions at 1500 km are $n_o = 5000\,\mathrm{cm}^{-3}$, $n_p = 80\,\mathrm{cm}^{-3}$, $V_p = 16\,\mathrm{km\,s}^{-1}$, $T_{p\|} = T_{p\perp} = 3500\,\mathrm{K}$, $T_{e\|} = T_{e\perp} = 1000\,\mathrm{K}$, $T_o = 1200\,\mathrm{K}$. (a) Oxygen ion number density, (b) H^+ ion number density, (c) electron number density, (d) H^+ ion velocity, (e) electron velocity, (f) H^+ ion temperatures parallel and perpendicular to the geomagnetic field and (g) electron temperatures parallel and perpendicular to the geomagnetic field.

Our second step to address this comment was to explicitly include the idea of anisotropy in our derivation of $E_{\parallel}$. While we believe the assumption of electron isotropy is valid in this region of Earth's ionosphere (the vast majority of ionospheric models make this assumption), this may not be the case for other planets or subsequent higher-altitude measurements at Earth. Thus, we agree with the reviewer that we should acknowledge and discuss anisotropy for the sake of anyone attempting to follow up on Endurance's measurements.

this is again an issue concerning parallel electric fields and electrons: electrons are essentially free to move parallel to field lines in the presence of any parallel E-field and thus are also responsible for the currents that equilibrate and effectively eliminate any excess E-parallel on larger scales (as the authors are arguing here at a global Earth scale).

The reviewer is correct that electrons are free to move along the flux tube, and thus Earth's ambipolar field is in a steady state ($\partial/\partial t = 0$). We have explicitly called this out in our derivation from first principles.

> "… since electrons move very quickly and respond almost instantaneously to changes in the system, we will assume that the bulk population of ionospheric electrons is in a steady state ($\partial/\partial t = 0$). This is consistent with EISCAT Radar observations of the ionosphere throughout the *Endurance* mission, the structure of which was stable and constant during the flight (e.g. consistent with this steady state assumption)."

This free-motion does not however cancel out the vertical gradient of electron pressure along the field lines (see fig S1), from which the ambipolar field derives its energy (we hope the revised manuscript makes this much clearer now).

From many, many spacecraft observations, it is well understood that parallel electric field structures tend to be extremely localized and limited to electron kinetic scales [e.g., Malaspina+ 2014: 10.1002/2014GL061109; Vasko+ 2017 : 10.1002/2016JA023337; Mozer+ 2021: 10.3847/1538-4357/abed52]. What is responsible for maintaining that presumably global-scale, ambipolar field? Why wouldn't the electrons simply move along the field to effectively cancel the potential difference? The authors suggest that this field is always present, meaning that something must be actively sustaining the very large-scale charge separation. There seems to be an issue here with self-consistency in the conceptual model presented by the authors.

We hope our comments above and the new additions to the methodology section have clarified this question, in that the parallel electric field in Earth's ambipolar field arises from the electron pressure gradient term in generalized Ohm's law. Unlike the kinetic-scale structures described in these papers, the ambipolar field does not require a charge separation, and indeed exists to prevent one from forming. The potential difference is not cancelled out because the motion of the plasma is not subject only to electrostatic forces, but also to that of Earth's gravity.

For an even more robust derivation of the parallel electric field in a general plasma, one can consider the combined plasma momentum equation (ions and electrons), as per Varney et al. First, let us imagine as a thought experiment a hypothetical ionosphere consisting of electrons and positrons (opposite charge, equally low mass). For such an imaginary plasma we may basically ignore gravity and the ∇P_e term of General Ohm's law, and thus a global-scale ambipolar field would not form.

In a real ionosphere, where the ions are many orders of magnitude heavier than the electrons, we can no longer ignore gravity. The electrons would still happily escape through their own thermal pressure, but they can't because they are shackled to the ions which feel the downward force of gravity. As the electrons pull away (driven by this counterbalance between gravity and pressure), a very weak ambipolar field forms throughout the plasma to bind it together and maintain quasi neutrality throughout.

Over a large enough distance along the field line (such as those explored by Endurance), the accumulated potential drop from this weak electrostatic field adds up little by little. As Endurance found, by 768km, this accumulated electrostatic force is so strong that no other force is required for the escape of H+ ions, and the scale height of the entire ionosphere is increased.

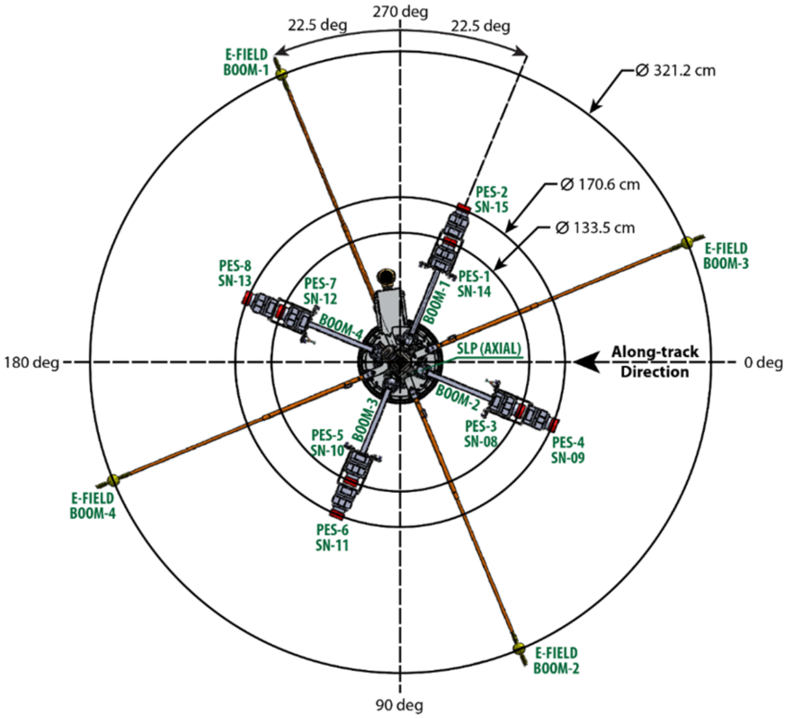
As above, we acknowledge that the previous draft had substantial shortcomings in laying out this conceptual picture. We hope that the inclusion of the theory behind polarization fields (from the electron momentum equation) in the methodology section better communicates the fundamental physics behind ambipolar fields, which is somewhat unusual for an astrophysical plasma.

What about the motion of the rocket relative to the background plasma; was the relative motional E-field of the plasma accounted for at all in the measurements and analyses?

Given the low velocity of the spacecraft (whose trajectory was nearly parallel to the magnetic field), this effect was expected to be very small. However, in response to this concern we have investigated this more thoroughly through a combination of additional data analysis and modeling. The executive summary of our findings is that fortunately these two effects are non-existent or so small that they could be ignored. However, for good measure we have folded them into our error budget. A similar summary is now included in the methods section.

A complete report on our analysis is appended below for full transparency.

To discuss this further in detail requires a little knowledge of the structure of the exposed experiment module of *Endurance*. The eight PES sensors were boom-mounted in opposing pairs with up to 1.7m between apertures. It was very important to the spacecraft design that all these sensors shared a common electrical ground, so all sensors would be at the same reference spacecraft "ground". To achieve this, all instruments were wired to a common spacecraft chassis ground, and the electrical conductivity of all surfaces of Endurance (Especially the booms and sensors), was verified during assembly and prior to launch using a multimeter.



Thus we assumed that everything should be at a common spacecraft ground and all the PES sensors were measuring energies with respect to a common zero point. However, the reviewer's comment made us double check this assumption.

Two motional electric fields were encountered in flight (as alluded to by the Reviewer). We shall deal with them separately as the physical effect on the spacecraft is different.

1.) The motional electric field of the background plasma

$$E_{Plasma} = -\vec{V}_{Ions} \times \vec{B}$$

The first field we considered is the motional electric field of the plasma (as noted by the reviewer), whereby the motion of ions across field lines results in an ambient (perpendicular) electric field. This was directly measured in flight by the *Endurance* FIELDS experiment, and a plot of which is included below so that we may first categorize the conditions encountered by *Endurance*, so that we may then investigate the impact on the spacecraft's differential charging.

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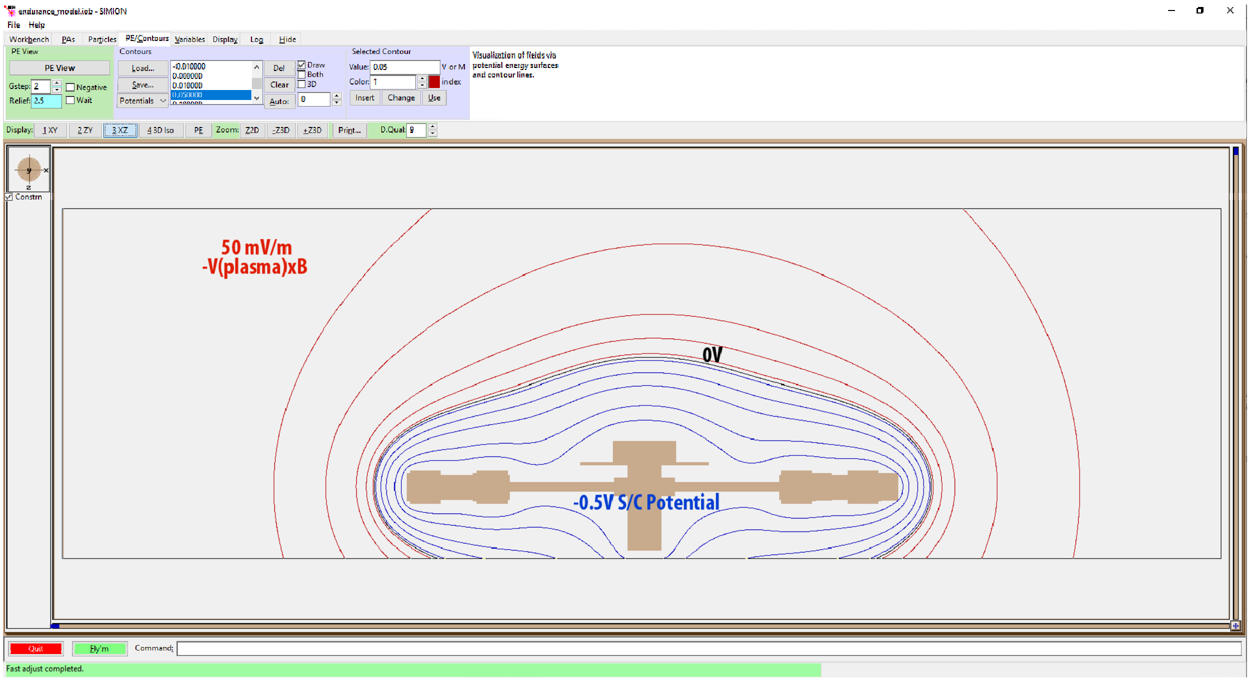
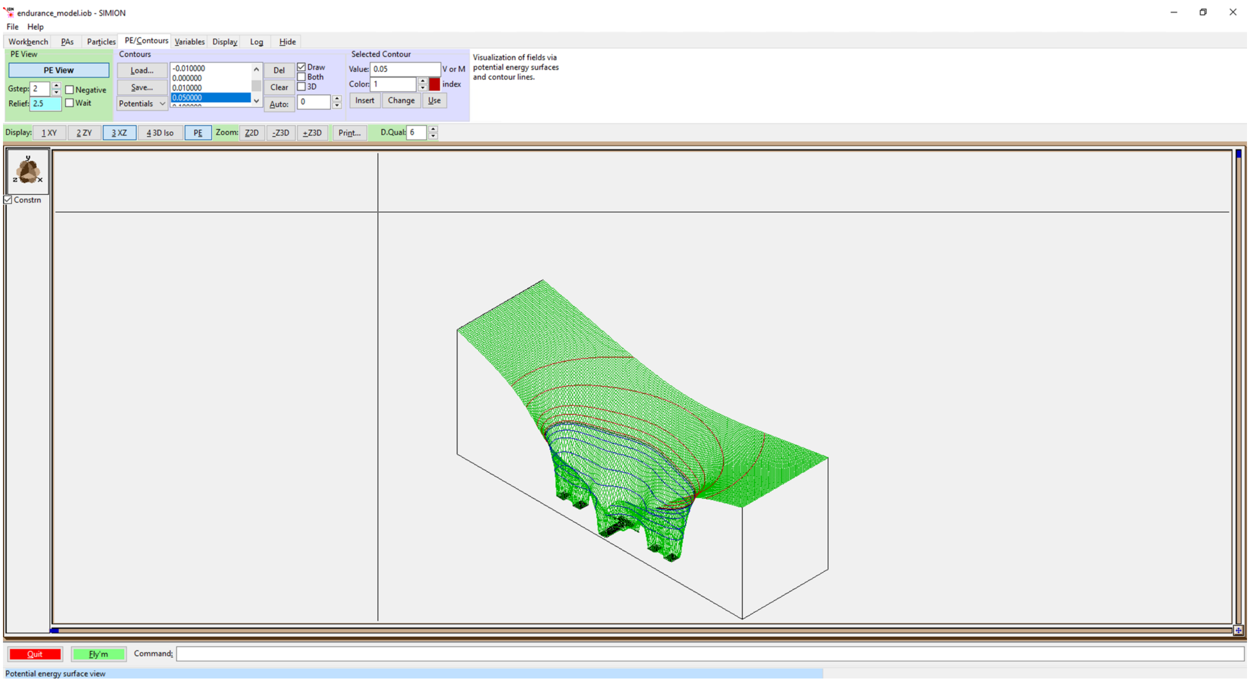
The plot above shows that *Endurance* was effectively bathed in this external electric field of a few tens of mV/m. Let us take ~50 mV/m as a worst case. *Endurance* was a 3-axis stabilized spacecraft, and thus we can basically assume this external field to be constant and not time varying.

To the first order, one would not generally expect such an externally imposed static electric field to result in differential grounding of a spacecraft, as simply bathing a conductor in an external and static electric field should not generate an electrical current within. However, to further test this assumption, we have made a 3D simulation of the upper portion of the Endurance spacecraft in SIMION and exposed it to just such a ~50 mV/m externally imposed electrical field.



The above figure shows a cross-section through this 3D simulation. For simplicity (as this is primarily a sanity check) we have only modeled a single opposing pair of PES booms. Two spacecraft potentials were simulated, one for 0V, and the other at a flight-like -0.5V (shown above). Blue contour lines show negative equipotentials, red lines show positive equipotentials, and the black line shows the 0V equipotential.



The above plot shows a 2D contour plot of the electric field in the vicinity of Endurance. The key feature to note is that all of the spacecraft (modeled as a uniform conductor as measured in the hangar during assembly) remains at an equal potential.

These simulations back up our expectation that the motional electric field from the plasma will not have any effect on the *Endurance* experiment. However, that is not the case for the second motional electric field that must be considered.

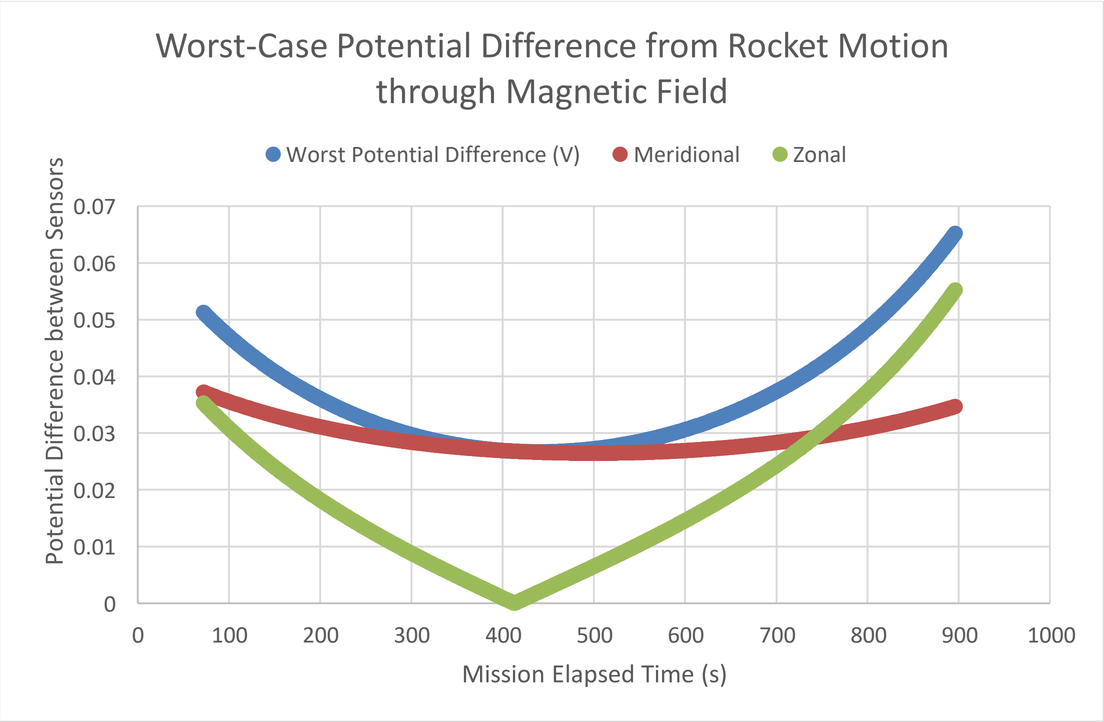
2.) The motion of the rocket relative to background magnetic field

$$E_{motional} = -\vec{V}_{Endurance} \times \vec{B}$$

As the reviewer notes, the motion of the rocket through Earth's magnetic field will also generate its own motional electric field

Unlike the externally imposed static electric field from the plasma, one absolutely would expect this to induce an electrical current in the spacecraft (and thus result in a differential spacecraft "ground"), as one is physically dragging a conductor through Earth's magnetic field. It is therefore very reasonable to ask us to quantify this and justify why it is small.

Fortunately, in addition to her other instruments, *Endurance* carried a magnetometer as a hosted payload (see our mission paper in SSL), which was calibrated (along with the whole spacecraft) in NASA Wallops Flight Facility 22 ft Helmholtz coil magnetic calibration facility. While Endurance is not magnetically clean and the magnetometer was mounted to the aft of the service module, its results are adequate to characterize the ambient dipole field. Taking the velocity from the GPS module aboard *Endurance*, and $\vec{B}$ from the onboard magnetometer, we calculated $E_{motional}$. Then multiplied this field by the 1.7m maximum separation of the PES apertures to determine a worst-case potential difference between the sensor-heads.



The plot above shows the difference between spacecraft "ground" between the apertures of the furthest PES sensors arising from $E_{motional}$. The exact value will depend on the orientation of the booms with respect to the magnetic field. Fortunately, *Endurance's* near-vertical trajectory aligned quite closely with the near-vertical magnetic field lines near the poles. Thus, $E_{motional}$ was very small, and the resulting potential difference was also small when compared to the other sources of measurement error, and very small compared to Earth's potential $(0.55V)$.

This (thankfully small) source of error has been incorporated into our error analysis (see discussion later on error budget in response to this reviewer's questions).

The authors discuss a "global electrostatic energy field" but what exactly is this field relative to? What is true ground?

There is no true ground *per se* for planetary electrostatic fields (or in astrophysics in general), all that matters to the plasma is the potential drop through which they fall. As such the zero potential can be defined at any location that is convenient. The measurement presented in the paper is an integrated measurement of $E_{||}$ between the peak of photoproduction $(250 - 300km)$ and apogee. The zero potential is chosen to be at the peak of the photoproduction region.

How was true ground maintained on a rocket moving through a charged plasma?

Measurements were made in respect to a spacecraft potential which floated with respect to the plasma (ϕ_{SC}). We have now clarified in the manuscript that this common spacecraft chasis ground was the same for all instruments

> "All exposed surfaces of *Endurance* were checked for electrical continuity prior to launch to ensure the spacecraft chassis would provide a common electrical ground to all instruments and thus evenly distribute ϕ_{SC}"

In response to this comment and comments by the first reviewer, the methodology section now includes a section describing how the difference between the spacecraft potential and plasma (ϕ_{SC}) was measured and calibrated out.

Little detail is given concerning the sensitivity of the instruments.

For full details on Endurance's instrument suite, please see section 4 of our mission paper in Space Science Reviews [Collinson, Glyn, et al. "The Endurance Rocket Mission: Gauging Earth's Ambipolar Electric Potential." Space Science Reviews 218.5 (2022): 39].

We have also included a new section in the methods describing the instruments (in response to comments from both reviewers) and we have listed their sensitivities. For PES this is tied to the geometric factor of the sensor which was 1.8×10^{-3} $(cm^2\ sr\ eV/eV)^{-1}$ for all 8 sensors combined. As per Fig 5. This corresponded to a noise floor of the PES instrument was at a differential energy flux of about 10^4. We have clarified the densities which SLP is sensitive to

> "SLP operates in plasma densities between $1 \times 10^3\ cm^3$ and $1 \times 10^7\ cm^3$"

We have described the frequency ranges at which FIELDS is sensitive to

> "Four spherical sensors with embedded pre-amps captured electrostatic and electromagnetic modes at frequencies between $5\ Hz$ to $5\ MHz$."

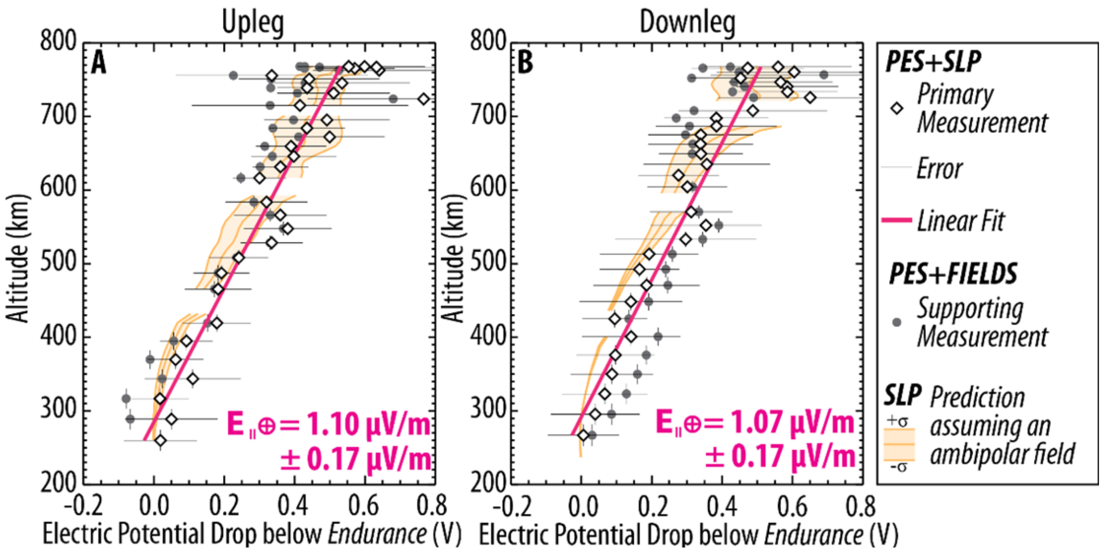
Error estimates are provided, but most of the error bars overlap on Figure 1.

The main data plot (Fig 1 in the previous draft, Fig 2 in the current draft) of potential drop vs. altitude contains two measurements. The first is our primary measurement whereby PES data are corrected for the absolute spacecraft potential by SLP. It is from this data product which we derive the potential drop and parallel electric field quoted in the paper.

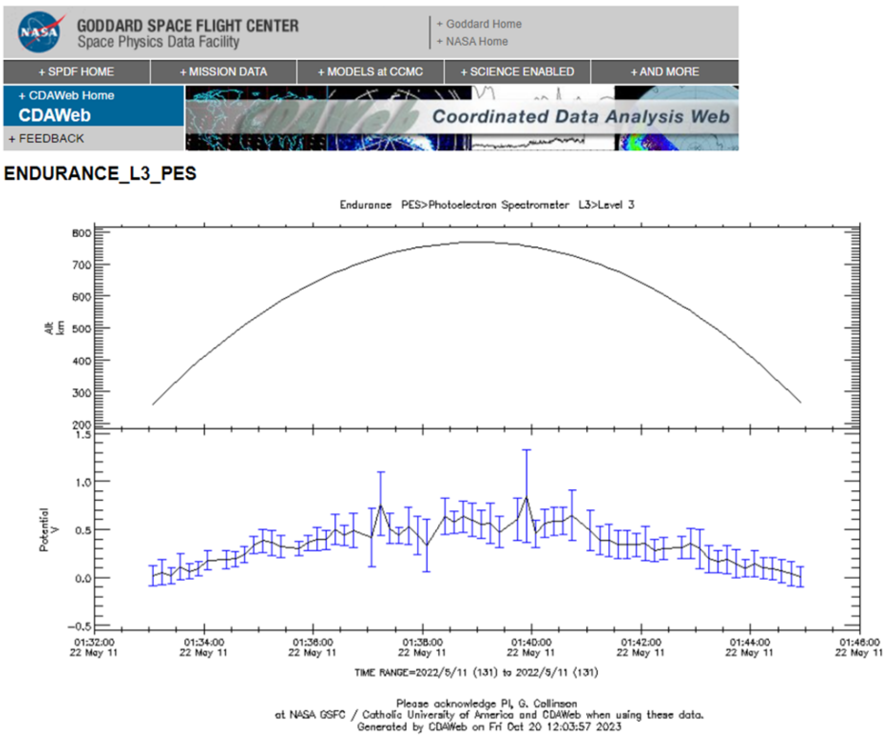
The secondary/supporting measurement is the same PES data but corrected by the relative spacecraft potential from the FIELDS instrument. The point of including this data is more of a cross-check for us that even with a completely independent measurement of spacecraft potential we still get consistent results (which we were relieved to see that we did).

In the previous draft, we plotted error bars from both measurements (primary and secondary). Since the errors overlap, this made the overall error appear larger to the eye.

We have revised the plot showing only the errors on the primary measurement so that the reader can more clearly see the trend and error in the potential drop data. We have also lost the vestigial linear fit to the secondary/supporting measurement (used in our analysis, but not discussed in the paper).



For the purposes of this review, we also include a time-series plot below from the primary measurement which hopefully more clearly shows that the errors are reasonable.



Also, how were the error bars quantified throughout the study (are they all +/- 1-sigma of presumably binned measurements?)

This comment made us go back and expand on our description of how error bars were quantified (See supplementary section "*Method of calculation of potential drop from He-II photopeak measurements*"). We have revised our error budget description in the methodology section and expanded it to include the VxB from the motion of the rocket. Please see the relevant passage below.

Horizontal error bars come from four sources. Firstly, the inherent $0.5\%\ \Delta E/E$ energy resolution of the sensor. Secondly, the estimated error in the measurement of spacecraft potential from SLP (and FIELDS for the supporting cross-check measurement). Thirdly, errors in the peak fitting which arise largely from poisson noise in the data. This error source was most prevalent above 700km (e.g. in the exosphere) as the N_2 $A_2\ \Pi_u$ photopeak became increasingly degraded through coulomb collisions on their journey up from the photoproduction region (Fig 3d). Fourthly, the error arising from the weak electrical current induced within the structure of the conductive *Endurance* spacecraft from its motion through Earth's magnetic field ($E_{motional} = -\vec{V}_{Endurance} \times \vec{B}$). These induced currents will result in a slight potential difference between the common electrical ground of the PES sensors, and hence an error in their measurement of the energy of the photopeaks. Fortunately however, when measurements of $\vec{V}_{Endurance}$ from the on-board GPS receiver were combined with the onboard magnetometer [1], this final error was found to be very small ($< 0.05V$).

Are there any known calibration errors or offsets in the measurements?

The short answer is yes, but it is corrected for in flight.

The full answer is that the high resolution of the PES has two known sources of calibration offsets. The first offset comes from the conversion between the digital command sent to the optics supply and the analog voltage applied. This was found to be highly linear and every sensor was calibrated on the bench to within ~1%.

REDACTED

In addition, there is a known fixed energy offset in the electron optics. Simulations predict this to be a small, in the region of 0.05 eV at 25eV (please see plot from simulations above from our in-preparation instrument paper for PES).

It is vital to keep in mind that the measurement of Earth's potential comes from the *relative* change in the energy of the He-II photopeak. This optical offset is *fixed*, affecting all 78 scans made by PES during the flight identically. Thus, one could theoretically completely ignore this offset and it would not affect science closure of this paper, as it will not impact the *relative* change in the energy of the He-II photopeak during the flight. However, we opted to correct for this offset in our data analysis and plot in terms of absolute energy.

It was found to be very challenging to precisely measure this optics offset in the laboratory. The high-resolution mode of PES had a maximum energy of 30eV. During lab calibration our data indicated that this fixed optics offset was very small ($\approx 0.02V$), but we also found we were unable to generate a truly mono-energetic and parallel beam below <30eV. We thus opted to correct for this offset in flight, since natural photoelectrons make a far more accurate benchmark of electron energy emission.

Endurance flew through the photoproduction region (250-300km) twice, on the upleg and downleg. In this region photopeaks are generated isotopically all around the spacecraft at a fixed energy that is well known and dictated by atomic physics (see references in the paper). This provided a highly precise electron emission line from which to compare and cross-calibrate during passage through the photoproduction region. In the photoproduction region, the difference between photopeak measurement and emission comes from two sources. 1.) The $\approx -1V$ potential difference between plasma and spacecraft (ϕ_{SC}); 2.) The $\approx 0.05V$ offset from the optics. Thus, this small offset manifests in our data analysis as a $\approx 5\%$ component of uncertainty in the absolute measurement of spacecraft potential. Please see extended data S1e which shows the variation in absolute spacecraft potential by SLP with error bars.

What about spatiotemporal differences along the trajectory? Single point rocket observations seem insufficient to warrant claim of discovery of such an electrostatic field. Simultaneous multipoint observations of voltage differences larger than the intercalibration error between the different sensors might be necessary.

Spatiotemporal differences are a valid concern when studying many parallel E fields, especially the kinetic-scale structures mentioned by the reviewer which are unstable and evolve rapidly. Fortunately, this is not the case for planetary ambipolar fields. To address this comment, the following sentences have been added to the main body of the manuscript to acknowledge and diffuse this (which we shall subsequently discuss in more detail below in 3 parts)

> "The launch occurred during geomagnetically quiet conditions to have as few perturbations in the environment as possible during the observations. The trajectory was designed so that one would not expect a measurable difference in the ambipolar field along the trajectory. Furthermore, one would not expect any temporal changes in the ambipolar field during the $\approx 13\ min$ science collection."

1. Theory predicts that the Ambipolar field should be persistent and static during the flight.

As is hopefully now much clearer in our revised manuscript, ambipolar fields arise from the natural pressure gradient on the topside of the ionosphere [Wahlund et al., 1992; Wu et al., 1992, Godbole et al., 2022]. One of the key findings of this paper is the experimental demonstration that Earth's ambipolar field can be correctly derived from these parameters. As this reviewer pointed out earlier, the system is in a steady state due to the speed at which electrons can move along field lines. This means these parameters change slowly over the course of the day, but not on the ~7 min timescale of Endurance's two measurements of the ambipolar field (upleg and downleg). Additionally, *Endurance* was deliberately launched during a period of quiet geomagnetic activity (please see later in this response), so that the ionosphere would be similarly stable. Thus, one would not expect Earth's ambipolar field to vary in either time or space along the trajectory of *Endurance.*

Endurance's trajectory was designed to fly as parallel as possible to both the open/closed field line boundary and the terminator, so no substantial spatial differences would be expected in the structure of the ambipolar field.

2. Supporting evidence from *in-situ* measurements

Measurements of potential drop below Endurance (Fig 2., this draft) were extremely consistent on both upleg and downleg, consistent with the electric field structure being persistent, stable, and static (as expected). Likewise, the underlying drivers of the ambipolar field (Ne, te) were consistent on upleg and downleg. Thus there is no evidence for any spatiotemporal differences along the trajectory, nor would we expect there to be from the underlying physics.

3. Simultaneous multipoint observations of the drivers of the ambipolar field throughout the flight are now presented in the manuscript, from which we conclude any spatiotemporal differences along the trajectory are so small as to be within measurement error.

While only single point direct measurements of Earth's potential were available (from PES), multipoint observations of the drivers of the potential (density and electron temperature) were made simultaneously from Endurance-SLP (in-situ) and EISCAT (Radar). These are now included in full for upleg and downleg in the supplemental data section (Fig S3). Figure 1 (map) now marks the location of EISCAT, from which it can be seen that the distance between *Endurance* and EISCAT increased over the flight. The differences between density and electron temperature are so small as to be within errors for much of the flight.

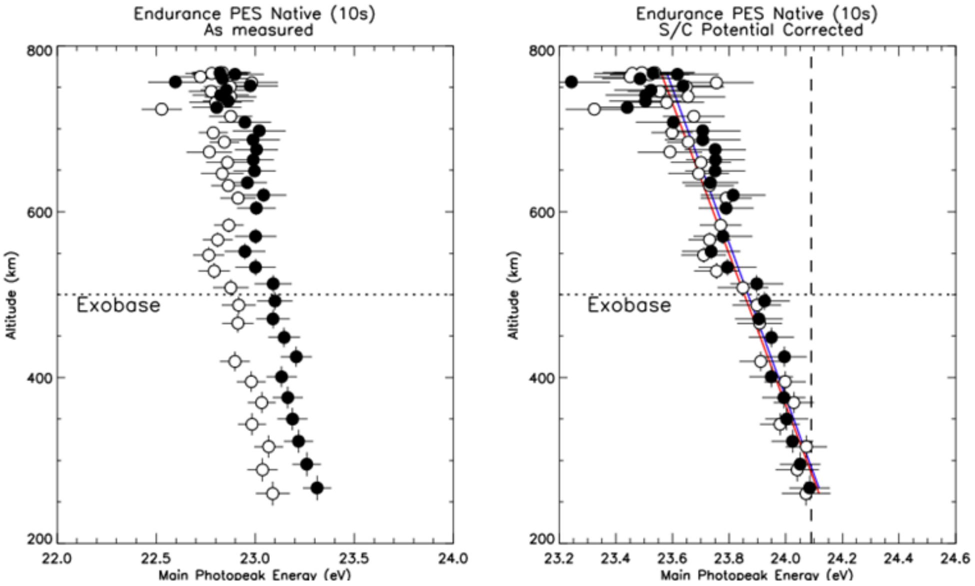
Since Endurance has demonstrated the long-held theory that Earth's electrostatic field is dominated by $E_{\parallel} \approx -\nabla P_e/qn_e$ (Fig 2), and given that profiles n_e and t_e were consistent between EISCAT and Endurance, we may thus conclude that $E_{\|}$ was also consistent, or at least that spatiotemporal differences along the trajectory were very small (as expected).

Error ranges on the data fitting constants (including the derive E-parallel values listed in Fig 1) should also be included.

The manuscript has been revised to read that Earth's electric field $E_{||} \oplus = 1.09 \pm 0.17\ \mu V m^{-1}$ (arising from the linear fit to the potential drop measurement). Thank you for this suggestion.

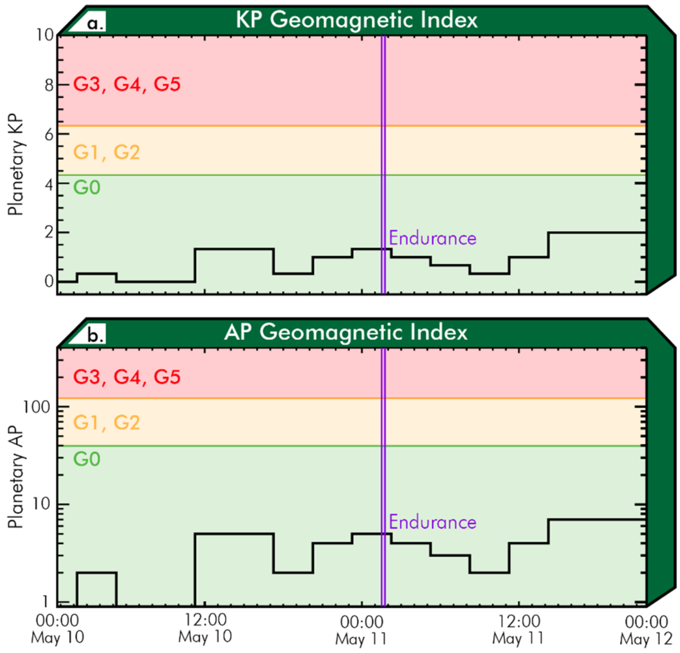
Figure 1: Do the upleg and downleg plots have the same X-axis, most importantly, the same absolute X = 0.0 V point? This is critical to any kind of confidence here in the results

Yes. The measurements are completely self-consistent on the upleg and downleg arriving back at the same absolute X = 0.0V point after the flight. Please see the working plot below showing upleg and downleg before and after correction for s/c potential measurement.



No evidence is provided showing quiet geomagnetic conditions during this event

KP and AP data have been included as supplementary data (please see plot below for convenience). In brief, planetary KP was ~1.33, planetary AP was 5. The G-scale was very comfortably G0. We have color coded the activity regimes for the benefits of the wider scientific community.



Lines 33-34: This statement is too suggestive that the cold ions are the cause of strong storms; that is not true at all. An abundance of cold ions in the magnetosphere and enhanced ionospheric outflow are correlated with more intense geomagnetic activity, yet correlation is not causation. This statement needs to be edited for clarification.

We agree with the reviewer that a reasonable reading of this sentence might be to imply a known direct causative relationship between cold ions and enhanced activity. We have attempted to clarify this statement while keeping the scientific thrust of what we were trying to say.

> “These results have important implications for the origin, composition, and mass-loading of plasma in Earth’s magnetosphere, which is crucial to accurately modelling the impact of space weather, geomagnetic storms [11], and their societal impacts [12] [13] [14] [15].”

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

Second review of: Measurement of Earth's Electric Potential
By G. A. Collinson et al.

Summary:

The authors have done an excellent job in addressing all the concerns that I raised in my previous review. These include adding a number of references to previous studies, and updating the Methods section to include a brief description and layout of the Endurance instrumentation used in this paper, namely the PES, SLP, and FIELDS package. The language surrounding the N2+ (A 2Pi_u) in the main text has been revised slightly to reflect the "He-II photopeak" which is more generic and permits for a superposition of other emission lines, and this is also reflected in the Methods section discussion about He-II photopeaks.

A new section was added to Methods describing how the corrections for spacecraft potential were performed. As suspected, the authors took great care to correct for the spacecraft potential based on the technique described in their previous paper (Collinson et al. [2016], SI), and additionally cross-checked this potential on the upleg and downleg separately based on an independent estimate of the absolute potential based on the measured energy of the photopeak compared to its generation energy.

The "U" I was referring to (in terms of capitalization) was in the word "Using" on the previous manuscript L91. In the revised version, this word now appears on a new line (L99) and is correctly capitalized.

This addresses all my concerns and I am happy to recommend the manuscript in its present form for publication. Congratulations to the authors.

Referee #2 (Remarks to the Author):

I want to thank and commend the authors for their thorough and detailed responses to the reviews.

I am more than satisfied with the responses and no longer have any concerns. I recommend that these exciting new results be published in Nature.

-Drew Turner