Assessing Coulomb Collision Contributions to Photoelectron Deceleration above Earth's Polar Caps

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Key Points:

- We report the first measurement of coulomb collisions slowing photoelectrons escaping from Earth's atmosphere.
- This effect was previously masked by a spacecraft wake disturbance during the transition from supersonic to subsonic plasma wave speeds.
- Fully kinetic models are needed for precision studies of coulomb collision effects as existing analytical models overestimate energy shifts.

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Abstract

NASA's *Endurance* rocket mission resolved a subtle energy shift in photoelectrons escaping from Earth's polar caps, from which the first successful measurement of Earth's ambipolar electrostatic field was made. Preflight models predicted that coulomb collisions with thermal electrons could add an extra energy shift of up to 1 eV. However, no such additional shift was reported in the initial analysis. Here, we identify a previously unreported effect related to the spacecraft wake, which introduced a systematic $+0.25eV$ energy shift that countered and masked the shift from coulomb collisions. After applying an in-flight calibration for this wake effect, we find a total photopeak energy shift consistent with the combined influence of the ambipolar field and the subtler $-0.37eV$ coulomb shift, predicted by the fully kinetic STET model. Further analysis of these recalibrated measurements yields an ambipolar field estimate in close agreement with the initial analysis.

Plain Language Summary

When solar extreme ultraviolet (EUV) radiation strikes neutral atoms in the atmosphere high-energy photoelectrons are released that can escape Earth's gravity. NASA's *Endurance* mission, with its high-resolution Photoelectron Spectrometer (PES), resolved a subtle energy shift in these photoelectrons as they escaped from Earth. Initial PES data analysis found that the energy shift was entirely consistent with Earth's global ambipolar electrostatic field. However, preflight models also predicted that coulomb collisions (elastic collisions between photoelectrons and lower-energy thermal electrons), would create an additional shift ontop of that from the ambipolar field. However, no evidence for this additional shift was reported. In this study, we find that a previously unknown spacecraft effect canceled and masked this coulomb collisional effect. We also show that preflight models substantially overestimated this effect. After in-flight calibration, the measured shift matched predictions from the combined ambipolar field and a weaker coulomb shift, as estimated by the fully kinetic STET model.

1 Introduction: Photoelectrons and Coulomb Collisions

Electrons in Earth's ionosphere consist broadly of two populations. They are dominated ($> 99.9\%$) by a thermal (or "core") population ($< 1eV$), which is restrained from escaping from Earth by a global "ambipolar" electrostatic field (G. A. Collinson et al., 2024). Additionally, there exists a hot suprathermal population ($1eV$ to $\sim 100eV$), primarily generated between 130km-300km (depending on solar zenith angle) by photoelectron emission from the neutral atmosphere as a result of solar EUV radiation (Doering et al., 1976; Peterson et al., 1977; G. A. Collinson, Glocer, Pfaff, et al., 2022). Photoelectrons have more than enough energy to overcome gravity and escape to space, and have been observed at large distances down the magnetotail (Coates et al., 1985).

The energy spectrum of photoelectrons from any planetary atmosphere exhibits numerous discrete spikes (called "photopeaks") (Lee et al., 1978, 1980a, 1980b; Jasperse & Smith, 1978). This is a result of the intense solar He-II emission line at 30.4nm which bombards the neutral gas with an excess of photons at one discrete energy. Consequently, photoelectrons are ejected at a range of discrete peaks, the energy of which is that of the photon ($40.78eV$) minus the work function of the specific electron orbital from which they escaped. The result is that planetary ionospheres radiate electrons at discrete and known energies, rigidly dictated by atomic physics. As a result, He-II photopeaks have been used throughout the solar system as tracers of parallel electrical potentials (Coates et al., 1985, 2015; G. Collinson et al., 2015; G. A. Collinson et al., 2016, 2023; Xu et al., 2018). If the photopeaks are observed at a different energy from which they are known to have been created, it is usually assumed this is primarily due to their falling from an electric potential drop between their source in the atmosphere and the spacecraft.

However, in theory photoelectrons should receive an additional retardation from coulomb collisions with the thermal electron population (Spitzer, 1950; Cicerone & Bowhill, 1970; Swartz et al., 1971; Khazanov et al., 1997). As photoelectrons corkscrew upwards along magnetic field lines, they are predicted to scatter elastically with the cold thermal electrons, transferring (and losing) some of their energy. As a result, one expects to observe an additional decrease in photoelectron energy with increasing altitude from coulomb collisions.

While coulomb collisions in general are a well-established phenomenon, to our knowledge, this net slowing effect on Photoelectrons has never been successfully resolved observed experimentally. This is because until recently, no electron spectrometer has existed with sufficient resolution to fully resolve the He-II photopeaks, let alone the subtle slowing by the coulomb collisions with the thermal core electron population. The closest to date was *Atmospheric Explorer E*, which measured photopeaks to $1.5\%\Delta E/E$. Analysis of AE-E data by Lee et al. (1980b) found an order of magnitude agreement between the observed energy loss due to coulomb collisional scattering and theory, which was deemed satisfactory given the large number of assumptions neccesary in their calculations. Furthermore, Lee et al. (1980b) were not able to separate out the effect of the ambipolar field in their calculations.

NASA's *Endurance* sounding rocket (yard №47.001) (G. A. Collinson, Glocer, Pfaff, et al., 2022) launched May 11th 2022 to an altitude of 768km, carrying the new Photoelectron Spectrometer (PES) instrument, with an unprecedented energy resolution of $0.5\%\Delta E/E$. PES successfully resolved one of the brightest He-II photopeaks throughout the majority of its 15 minute suborbital flight. PES measured an energy shift of this photopeak of $-0.55 \pm 0.09eV$ between the photoproduction region (250km) and apogee, exactly what was expected from the ambipolar field of Earth under the specific conditions of the flight (G. A. Collinson et al., 2024).

No clear evidence was reported of an additional photopeak energy shift from coulomb collisions. This was in contrast to preflight predictions using the GLOW two stream mode (Solomon, 2017), which suggested as much as $\sim -1eV$ of additional energy decrease could be seen from coulomb collisions alone (G. A. Collinson, Glocer, Pfaff, et al., 2022). As per Solomon (2017) GLOW models the shift associated with coulomb collisions using the analytical formulation by Swartz et al. (1971), which does not take into account key physical effects such as pitch-angle scattering. Given that such an additional $\sim -1eV$ shift would have been readily observable to PES, it was concluded that the formulation by Swartz et al. (1971) must be substantially overestimating the effect. The close agreement between the observed photopeak shift and that predicted for an ambipolar field suggested that the slowing effect by coulomb collisions must in reality be more subtle. G. A. Collinson et al. (2024) thus used a simple linear trend in their calculations to not risk not overfitting the PES data, and assumed that any photoelectron deceleration by coulomb collisions must in reality be small and within the uncertainty of the measurement

In this paper, we examine fine details of the structure of the observed shift in photoelectrons measured by the *Endurance* PES instrument, searching for evidence of the additional energy decrease expected from coulomb collisions. We use the fully kinetic Superthermal Electron Transport (STET) model (Khazanov et al., 2014) to self-consistently model the additional shift from coulomb collisions, finding it to be far smaller ($-0.37eV$ at apogee) than predicted by the Swartz et al. (1971) analytical model used in GLOW.

This paper is organized as follows. In section 2, we give a brief summary of the *Endurance* mission and the instruments used in this study. In section 3, we closely examine the vertical structure of the shift in photoelectrons, finding the need for an additional in-flight calibration for a hitherto unknown observational effect which provided a systematic (and unphysical) +0.25eV increase in photoelectron energy between 550 km and 620 km. In section 4, we perform an additional in-flight calibration and compare the observed en-

ergy decrease against that expected from two effects: ambipolar field (predicted from in-situ data from another instrument) and coulomb collisions (from the fully kinetic STET model). In section 5, we summarize our findings and present our conclusions.

2 NASA Rocketship 47.001 *Endurance*

In this section we give a brief summary of the *Endurance* rocket mission and the instruments relevant to this study. For a detailed description of the mission design and the PES instrument see G. A. Collinson, Glocer, Pfaff, et al. (2022). For a summary of the main results see G. A. Collinson et al. (2024).

2.1 Mission Overview

The *Endurance* rocketship launched at 01:31 GMT on May 11th 2022 from Ny Ålesund, Svalbard. The entire flight occurred on open magnetic field lines in Earth's north polar cap. *Endurance* was a three axis stabilized spacecraft, aligned with Earth's magnetic field to within 3.5° degrees.

Figure 1a shows a time versus altitude plot of the mission. The color coded timeline above gives a summary of the main events. The primary mission was divided between 70 s of uninterrupted science collection (blue, Fig. 1a), followed by 10 s where the attitude control system was free to fire and realign the rocketship with Earth's magnetic field (yellow, Fig. 1a). The cold gas produced by these firings interfered with every instrument apart from the camera. However, all the gas rapidly dispersed before commencement of the next science collection, and did not contaminate science measurements.

Just after apogee (768km), *Endurance* performed a pitch over maneuver (green, Fig. 1a), rotating by 180˚ so that the instruments on the bow of the rocketship would look into the ram direction on the downleg portion of the flight.

2.2 *Endurance* instruments used for this study

The primary instrument used in this paper is the photoelectron spectrometer (PES), a new technology developed for the mission (G. A. Collinson et al., 2018; G. A. Collinson, Glocer, Chornay, et al., 2022). PES simultaneously measured two data products every 10s. A standard energy resolution ($15\%\Delta E/E$) survey between 10eV and 1keV, and a high resolution ($0.5\%\Delta E/E$) scan between $20.3eV$ and $25.85eV$ to attempt to resolve the most prominent He-II photopeaks, of which it successfully caught one, dominated by the $N_2 A^2\Pi_u$ atomic transition. PES was a pure energy spectrometer, with two fixed look directions, field aligned and anti-aligned. In this paper we only use the high resolution measurements of photoelectrons escaping from Earth's ionosphere (i.e. aft-facing during upleg and prior to pitch-over, bow-facing after pitch-over to loss of signal).

This study also uses data from the *Endurance* Swept Langmuir Probe (SLP). This is a traditional needle probe mounted at the very bow of the spacecraft. A voltage sweep was applied once every 5 seconds during the flight, and the current measured by the probe recorded. From this, we may determine the density and temperature of ionospheric thermal electrons ($< 1eV$). These two parameters can be combined to calculate electron pressure, and hence predict the strength of Earth's ambipolar electric field according to equation 1.

$$E_{||} = \frac{\nabla P_E}{n_e q} \tag{1}$$

SLP also measured the electrical potential difference between the spacecraft and the ambient plasma. This spacecraft vs. plasma potential is crucial to calibrate PES, since pho-

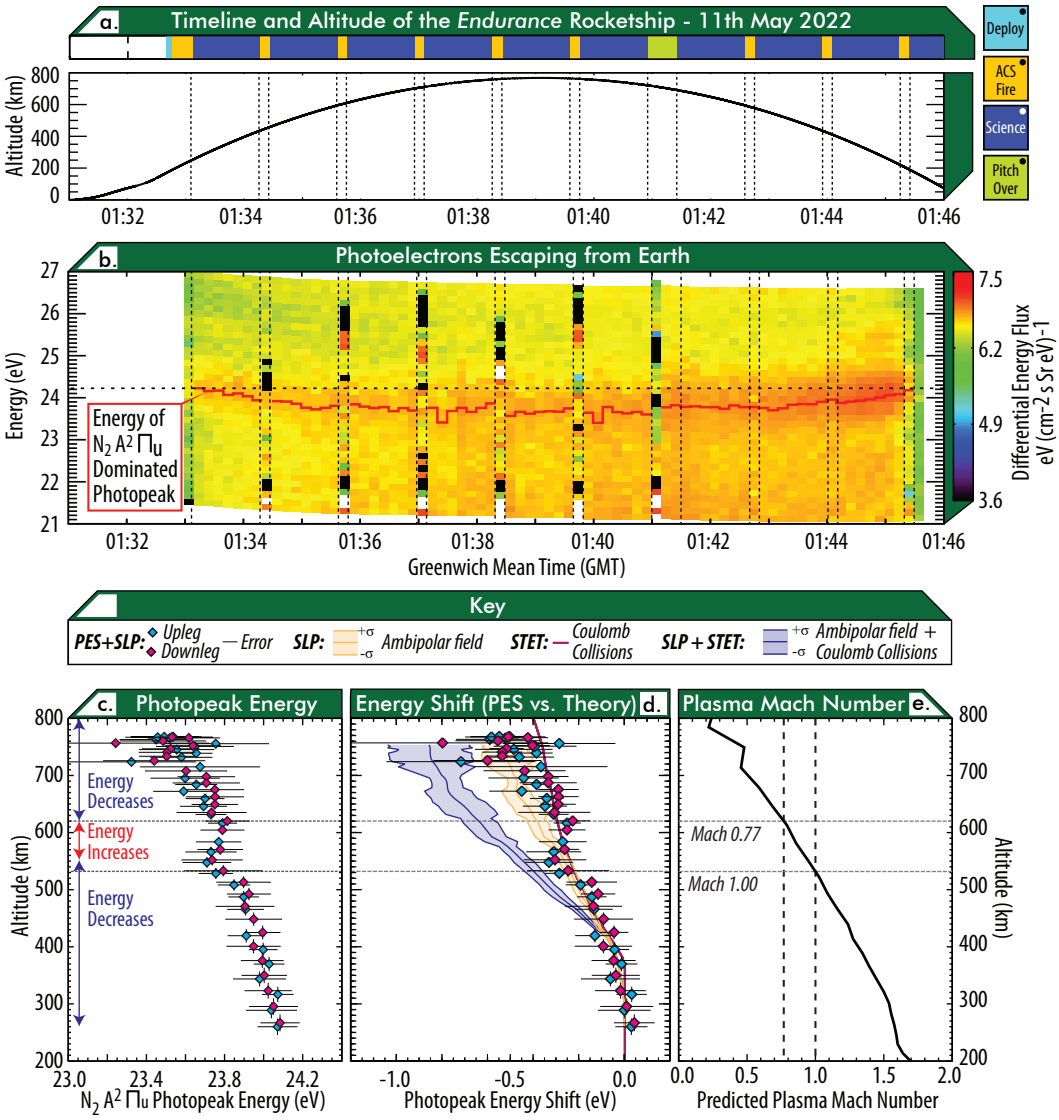

Figure 1. a.) Color coded timeline of the *Endurance* mission and plot of time vs. altitude of the rocketship. b.) High-resolution spectrogram showing the evolution of differential flux of the primary He-II photopeak during the flight, corrected for spacecraft potential. c.) Energy vs. Altitude of the primary He-II photopeak, corrected for spacecraft potential. d.) Comparison between the energy shift of the He-II photopeak and i.) the predicted shift from the ambipolar field from SLP (gold), ii.) the energy shift from coulomb collisions alone from the STET model (maroon), and the combined shift from both effects (purple). e.) Calculation of the evolution of Plasma Mach number with altitude according to Gombosi and Rasmussen (1991).

toelectrons escaping from the ionosphere fall through two potential drops: Earth's electrical potential, and the spacecraft potential. It is crucial to remove the spacecraft effects in order to accurately measure Earth's ambipolar field and to search for the subtle energy shift of the photopeaks due to coulomb collisions. All PES data shown in this study have been corrected for spacecraft potential by SLP.

3 Analysis of the altitude structure of the He-II Photopeak

Figure 1b shows a time vs. energy spectrogram of PES high-resolution measurements of outflowing photoelectrons. These data have been corrected for spacecraft potential as measured by SLP, as per G. A. Collinson et al. (2024). A bright He-II photopeak was observed throughout the flight, presumed to be dominated by the $N_2 A^2\Pi_u$ transition at 24.09 eV. The peak energy of this photopeak was determined by fitting a gaussian distribution to each scan. A general trend towards lower energies near apogee was observed over the flight. Figure 1c shows a plot of energy versus altitude of the peak energy from this gaussian fit, showing measurements on upleg (blue) and downleg (pink).

Figure 1d shows the magnitude of the shift in energy of the He-II photopeak from its production energy ($24.09eV$). The gold curve shows the predicted energy shift from the ambipolar field of Earth according to the SLP instrument, using equation 1. From this very close agreement, G. A. Collinson et al. (2024) concluded that the only source of the shift apparent in photoelectron energy was from the ambipolar field.

3.1 Apparent initial non-detection of an additional energy shift from coulomb collisions

Pre-flight simulations using the GLOW two-stream model predicted that an additional shift of as much as 1eV would be present due to coulomb collisions (G. A. Collinson, Glocer, Pfaff, et al., 2022). However, GLOW does not self-consistently model this effect, and it predicts this additional shift from an analytical model (Swartz et al., 1971). Additionally, *Endurance* is the first mission to resolve photopeaks with sufficient resolution to empirically test this aspect of the model. The 1eV of additional shift predicted by GLOW would have been readily seen by PES. Thus the most likely explanation for this apparent non-detection is that the analytical model underpinning this calculation in GLOW is substantially overestimating the shift due to coulomb collisions.

For the purposes of G. A. Collinson et al. (2024), which was to calculate an average potential drop over the entire flight, it was assumed that any additional coulomb collisional shift must be far smaller than predicted by GLOW, and were being swallowed by the uncertainties in the measurement. We shall test this assumption in this paper.

For this study we used the fully kinetic Superthermal Electron Transport (STET) model (Khazanov et al., 2014) configured for an open field line as in Glocer et al. (2017) to more accurately predict the extra photopeak energy shift from coulomb collisions. We moreover configure the model to use the observed thermal electron density from the SLP and ran STET at a very high energy resolution to ensure a good fidelity result. The structure of the thermosphere for the model was in good agreement with that measured by the *Endurance* Bayard-Alpart Ionization Gauge (G. A. Collinson, Glocer, Pfaff, et al., 2022). STET self-consistently calculates the gyroaveraged electron distribution function as a function of energy, pitch angle, and position along the field line. This calculation includes production and transport of photoelectrons along a magnetic field line, and explicitly calculates coulomb collisions (Khazanov et al., 2014). Details of the collisional operator used in STET are provided in Khazanov (2010). STET predicts a total shift of $-0.37eV$ at apogee from coulomb collisions alone (Fig. 1d, maroon line).

The purple curve in Fig. 1d takes the ambipolar field calculation from the SLP instrument and adds to it the additional coulomb energy shift predicted by STET. We note the following features of this prediction. Between 250km and 380km, no additional shift from coulomb collisions is predicted. This is because photoelectrons are still being produced throughout these altitudes and thus the photopeaks are still at their energy of photoemission. Between 430km and ~600km, the two curves (Fig. 1d gold vs. purple) slowly diverge due to an additional energy shift from coulomb collisions. Above ~600km, the gradient of the two curves approximately match. This is because by these altitudes *Endurance* had flown out of the bulk of the ionosphere and coulomb collisions are so infrequent that the energy shift is dominated by the ambipolar field.

3.2 Investigation of an anomalous increase in photoelectron energy between 550km and 620km

A closer analysis of the fine structure of the PES data is required before we may search for evidence of the effect of coulomb collisions. Between ~250 km and 550 km (upleg and downleg), the measured energy of the primary photopeak decreases in energy, a trend one would generally expect from either ambipolar field, coulomb collisions, or a combination of both (purple, Fig. 1d). However, between 550 km and 620 km, this trend reverses, with the photopeak unexpectedly increasing in energy (Fig. 1c). Given that this was observed on both upleg and downleg (separated by ~150 km downrange distance), it is extremely unlikely that this increase in energy is random, and is in all probability a real effect.

There is no known natural phenomenon which should cause an apparent energy increase of photoelectrons at these altitudes. The most plausible explanation is if there is an additional spacecraft effect (beyond spacecraft potential) which is altering the energy of photoelectrons as they approach the PES sensors. The data (Fig. 1c) suggest that whatever this spacecraft effect is, was in a stable state below 550 km, in a different stable state above 620 km, and gradually transitioned in-between.

We posit that this effect is related to the plasma wake of *Endurance*, and in particular, how it changed between the transition from supersonic to subsonic flight. All spacecraft create a wake as they travel through the plasma (or as the plasma flows over them). The vast majority of spacecraft are supersonic with respect to the ambient plasma, generating a shockwave around them just like a jet fighter or the Concorde supersonic transport. *Endurance* however was a ballistic sounding rocket, with velocity varying between $3.0 km/s$ at 250 km, and $0.4 km/s$ near Apogee. We hypothesize that the increase in photopeak energy between 550 and 620 km is an effect arising from the transition between supersonic and subsonic flight, and a fundamental change in the nature of the plasma wake of the spacecraft.

If this theory is correct, the altitudes at which *Endurance* was transonic should match the altitudes at which the photoelectron shift occurred (550 km to 620 km). In other words, *Endurance* should be supersonic below ~550km and subsonic above 620km.

To calculate the mach number (M) for the plasma wake of *Endurance*, we take the rocket velocity (V_r) and divide by the wave speed in the ambient plasma (a) at a given altitude, according to equation 2.

$$M = \frac{V_r}{a} \tag{2}$$

Where we take a from Gombosi and Rasmussen (1991), in the approximation neglecting heat flow as below in equation 3.

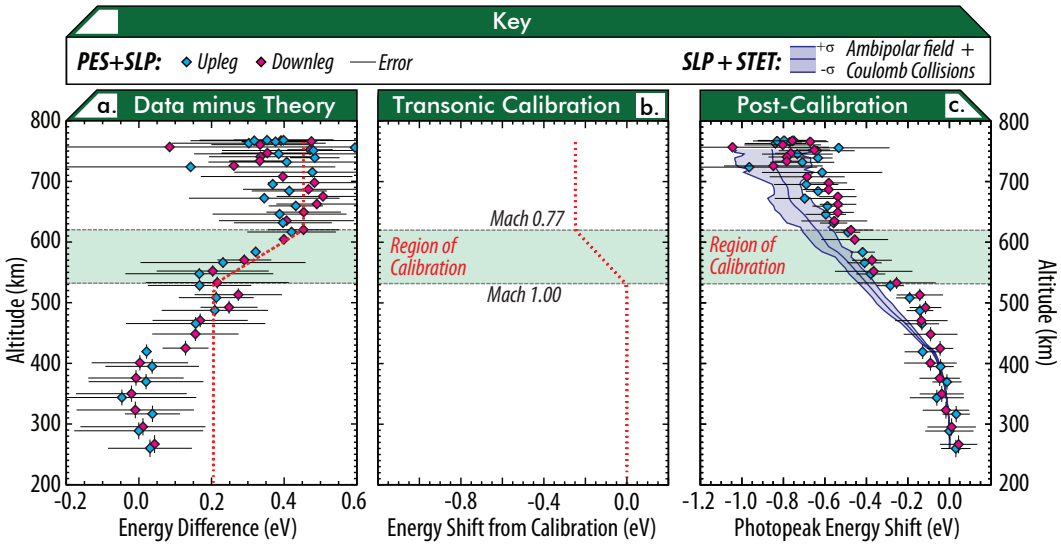

Figure 2. a.) Difference between the measured shift in photoelectrons by PES and predicted combined shift from ambipolar fields (from SLP) and coulomb collisions (from STET). b.) Transonic calibration factor vs. altitude. c.) Magnitude of the shift in the He-II photopeak vs. altitude, as Fig. 1d but with in-flight transonic calibration.

$$a = (3a_e^2 + 3a_i^2)^{0.5} \tag{3}$$

Where a_e and a_i are defined as below in equations 4 and 5.

$$a_e^2 = \frac{kT_{e||}}{m_i} \tag{4}$$

$$a_i^2 = \frac{kT_{i||}}{m_i} \tag{5}$$

Fig. 1e shows a plot of plasma Mach number versus altitude for the conditions encountered during the flight of *Endurance*. We used data from the EISCAT Svalbard Radar collected during the rocket flight in this calculation (see G. A. Collinson et al. (2024), extended Figure 6). Supersonic flight is predicted up to ~530km, near the altitude at which photoelectrons begin to unexpectedly increase in energy. The altitude range up to 620 km corresponds to a transonic region where plasma Mach number drops down to Mach 0.77. Fig. 1e is this consistent with the hypothesis that this altitude range is associated with a substantial change in the character of the plasma wake, and presumably collapse of the supersonic shockwave generated by the spacecraft.

4 Results

4.1 In-flight Transonic Calibration

Understanding the specific physics of how the transonic transition is affecting the apparent energy of the photopeaks, and why specifically this effect appears to stop below Mach 0.77, would require additional modeling, and is beyond the scope of this study (although we speculate briefly in Section 5). However since PES consistently measured this

effect on both upleg and downleg, we choose to calibrate it out of the PES data. One approach to measure the additional energy offset from this transonic effect would be to measure the total net increase in energy between 550km and 620km. However, this neglects the fact that what is being measured by PES in this altitude region is a combination of an energy increase from the spacecraft wake and a presumed decrease from both ambipolar field and coulomb collisions. We thus chose the baseline of our calibration to be the predicted shift expected from these combined known effects.

Figure 2a shows the difference between the measured energy shift from PES (as in Fig. 1d) and the combined energy shift expected from the ambipolar field (from SLP) and the coulomb collision shift (from STET). Below 420 km, PES observations align closely with theory, showing a near-zero energy difference. Above 620 km, there is a constant offset between the measured and predicted values. The energy difference between theory and observations remains constant, meaning the gradient of the PES measurements aligns with theoretical expectations. This suggests that, at higher altitudes where coulomb collisions are minimal, the observed PES energy shift from 620 km to apogee is largely governed by the ambipolar field, as predicted by theory.

Between 420 km and 620 km, the data gradually diverges from theoretical predictions. There could be numerous causes of this, not the least that STET is still over-estimating the effects of coulomb collisions. Applying a correction factor across this entire altitude range might risk overfitting, so we limit the in-flight calibration to altitudes between 530 km and 620 km. This range begins at the predicted altitude where *Endurance* drops below Mach 1 (Fig. 1e) and spans the region where an unphysical increase in photoelectron energy was observed (Section 3.2).

Figure 2b presents the transonic in-flight calibration derived from this analysis. No correction is applied below 530 km. Between 530 km and 620 km, the calibration factor increases linearly (fitted to Fig. 2a) to counter the erroneous energy shift from the spacecraft wake. Above 620 km, only a constant offset of $-0.25eV$ is applied. We will now use this calibration factor to correct the PES data for the transonic wake effect.

4.2 Examination of the post-calibration energy shift with altitude of the He-II photopeak

Figure 2c shows a plot of the evolution with altitude in the relative shift of the He-II photopeak after the transonic in-flight calibration (upleg in blue, downleg in pink). Data below 550km are identical to the shift in Fig. 2b. Data above 550 km have undergone the new in-flight calibration from the transonic energy shift correction (Fig. 2b). The total energy shift between 250 km and apogee is $-0.77 \pm 0.11eV$, greater than the $-0.55 \pm 0.09eV$ reported by G. A. Collinson et al. (2024).

As in Fig. 1d, the purple curve in Fig. 2c shows the predicted combined shift from ambipolar field (from SLP measurements) and coulomb collisions (from STET). The newly re-calibrated PES data now agrees within errors of the combined predicted shift, consistent with a combination of both ambipolar field and coulomb collisions were decelerating the photoelectrons. A small systematic offset ($\sim$0.1eV) is apparent in the data above 450km. However, this is well within the measurement error of either the optics of the PES instrument, the spacecraft potential from SLP, or the coulomb collision shift estimation from STET.

5 Discussion and Conclusions

In this study we examined high resolution photoelectron spectra from NASA's *Endurance* sounding rocket. Our goal was to make the first measurement of the subtle additional energy decrease in the photoelectrons from coulomb collisions with the thermal (core)

electron population as they flow from their production region (250km-400km) to the near boundary of the magnetosphere (i.e. near Apogee at 768km). One of the key factors in the design of the mission was minimizing the effect of coulomb collisions. Pre-flight calculations using GLOW predicted that for high solar activity, the photopeaks may be completely eroded by the time they reach apogee. Thus *Endurance* was deliberately flown near solar minimum, and during low solar activity. Thus the measurements presented here likely represent a case of minimal coulomb collisional effects. The PES instrument carried aboard *Endurance* is the first electron spectrometer with sufficient energy resolution to be capable of observing this subtle effect. However, a previous analysis of PES data by G. A. Collinson et al. (2024) found the total shift in the photoelectrons to be entirely consistent with that expected only from Earth's ambipolar electrostatic field, and reported no such additional shift from coulomb collisions.

5.1 In-flight Transonic Calibration

Before we could begin our search for the slowing of photoelectrons from coulomb collisions, we discovered an additional correction was required from a hitherto unreported spacecraft effect. Specifically, as the spacecraft slowed to subsonic speeds, the energy of photoelectrons was observed to unphysically increase by $+0.25eV$ between Mach 1 and Mach 0.77. This effect was observed again in reverse on the downleg as *Endurance* accelerated through the Transonic regime to supersonic flight. Further modeling is required to understand the detailed physics behind this additional energy shift associated with the Transonic transition. We posit one possibility is that the spacecraft wake could be causing a systematic offset in the measurement of spacecraft potential. Another explanation could be that the supersonic wake is physically slowing the photoelectrons (above Mach 1), possibly from an additional weak electric potential drop associated with the shockwave. Understanding the physics behind this effect, and why it dissipates around Mach 0.77 is a prime topic for future modeling studies. What is clear though is that the photopeak energy should not increase naturally over this altitude. Thus, for the purposes of this study we performed an in-flight calibration to remove this spacecraft effect. Note that data below 530km are untouched by this calibration, and data above 620km are only shifted by a constant $-0.25eV$.

Future rocket missions seeking to make high resolution measurements of photoelectrons should keep an eye out for this previously unreported spacecraft effect when the spacecraft goes transonic.

5.2 Refined Calculation of Ambipolar Field from Calibrated Data

In this section we make three calculations of Earth's ambipolar field: 1.) Above 620km where coulomb collisions are minimal, 2.) Below 530 km where there is no transonic correction, and 3.) An average calculation over the entire flight to compare directly with the initial result by G. A. Collinson et al. (2024). In all cases we make a linear fit to the shift in PES data vs. altitude to determine the gradient, and hence calculate the parallel electric field.

5.2.1 Ambipolar field above 620km

Above 620km the effect of coulomb collisions is predicted by STET to be very small, and thus PES data from these altitudes are ideal for searching for a clean measurement of Earth's ambipolar field (which should be the dominant source of the energy shift in photoelectrons). Note that while this is only a fraction of the total altitude explored by *Endurance*, more than half of the PES measurements were collected above 620 km (from ~01:36 GMT to just after ~01:42 GMT, Fig. 1b), so there is ample data from this region to analyze.

For the purposes of measuring a parallel electric field, all that is needed is the relative shift in photopeak energy (not the absolute shift). Analysis on data above 620km would yield the same result with or without the transonic calibration, since in this region the only correction factor is a constant $-0.25eV$ energy offset, and the gradient of the measured energy shift is unaffected. We find that the relative shift in photopeaks measured by PES above 620 km closely matches theory (Fig. 2a data minus theory constant above 620km), and thus is extremely consistent with what is expected for Earth's ambipolar field. The total potential drop inferred from these measurements was ~ 0.23, corresponding to a parallel electric field of $1.6\mu Vm^{-1}$ between 620km and 768 km.

5.2.2 Ambipolar field below 530km

Below 530km, data are unaffected by the transonic correction, and is thus another altitude region where a clean measurement of Earth's ambipolar field should be possible. In this region however, STET predicts that the total shift in photoelectrons ($\sim 0.22V$) is dominated by coulomb collisions. Taking the PES data, subtracting the shift at each altitude from STET, and applying a linear fit (not shown for brevity) yields a mean shift of $\sim 0.08eV$, corresponding to an electric field of $0.45\mu Vm^{-1}$ between 250km and 530km. This weaker electric field at low altitude is consistent with the prediction by SLP (Fig. 1d).

5.2.3 Average field over the flight

If we accept the entire corrected dataset shown in Fig. 2c, we can subtract the coulomb collision shift predicted by STET to estimate the contribution solely from the ambipolar field throughout the flight. Caution must be taken with this approach, as STET was also involved in the transonic calibration, making this analysis partially circular above 530km. Nonetheless, with this caveat, subtracting STET's predicted coulomb collision shift at each altitude and applying the same linear fit as G. A. Collinson et al. (2024) (not shown for brevity) yields an estimated potential drop of $\sim 0.49V$, corresponding to an electric field of $0.97\mu Vm^{-1}$. This average falls between the high-altitude and low-altitude only estimates presented above. This result is also consistent within errors with the original calculation by G. A. Collinson et al. (2024) and thus generally supports the conclusions presented there. A safe conclusion from this analysis of the entire corrected dataset is that the effect of coulomb collisions was indeed much smaller than predicted by the pre-flight GLOW simulations and remained within the uncertainties of the original measurement.

5.3 Assessment of the energy shift from Coulomb Collisions

Modeling the effects of coulomb collisions on photopeaks is notoriously difficult and requires a very careful approach (Khazanov, 2010). We find that for precision (sub-electronvolt) measurements, a fully kinetic model is needed to accurately determine the effect of coulomb collisions. Our post-flight prediction by the kinetic STET model ($-0.37eV$) is less than the pre-flight prediction by G. A. Collinson, Glocer, Pfaff, et al. (2022) ($\sim -1eV$) which used the GLOW two-stream model (which as per Solomon (2017) handles coulomb collisions using the analytical formulation of Swartz et al. (1971)). A key factor distinguishing these approaches is that STET includes the simultaneous treatment of pitch-angle scattering and energy loss. We posit that treating these two processes together may be important for accurately capturing the precise energy shift of photoelectrons from coulomb collisions. However, for most applications where sub-electronvolt resolution is not required, GLOW would still be a resonable approximation, giving an order of magnitude agreement to the coulomb collisional shift observed by *Endurance*.

During the flight of *Endurance*, the transonic energy shift (hitherto unknown) of $+0.25eV$ was countering and masking much of the shift from coulomb collisions. The recalibrated

data were found to be consistent over the entire flight (250km to 768km) with a combination of the dominant shift from Earth's Ambipolar field and the weaker shift from coulomb collisions of $-0.37eV$ predicted by STET. During conditions of solar maximum the effect of coulomb collisions could likely be stronger, but the measurements here were selected to occur at low solar activity to deliberately minimize this effect.

6 Open Research

Endurance data are available from the NASA Goddard Space Flight Center Space Physics Data Facility `https://cdaweb.gsfc.nasa.gov`, by selecting "Sounding Rockets" as the data source.

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