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Key Points:
- We report the discovery and first quantitative extraterrestrial measurements of an ionospheric ambipolar electric field at the planet Venus
- A persistent, stable, and global phenomenon, accelerating any ion lighter than 18 amu to escape velocity
- Planets can lose heavy ions to space entirely through electrical forces in their ionospheres

Supporting Information:
- Supporting Information S1

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The electric wind of Venus: A global and persistent "polar wind"-like ambipolar electric field sufficient for the direct escape of heavy ionospheric ions

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Abstract Understanding what processes govern atmospheric escape and the loss of planetary water is of paramount importance for understanding how life in the universe can exist. One mechanism thought to be important at all planets is an "ambipolar" electric field that helps ions overcome gravity. We report the discovery and first quantitative extraterrestrial measurements of such a field at the planet Venus. Unexpectedly, despite comparable gravity, we show the field to be five times stronger than in Earth's similar ionosphere. Contrary to our understanding, Venus would still lose heavy ions (including oxygen and all water-group species) to space, even if there were no stripping by the solar wind. We therefore find that it is possible for planets to lose heavy ions to space entirely through electric forces in their ionospheres and such an "electric wind" must be considered when studying the evolution and potential habitability of any planet in any star system.

1. Venus and the Polarization Electric Field

Discovering what processes govern the evolution of atmospheres, and specifically the loss of planetary water and oxygen, is key to determining what makes planets habitable and is a driving science objective behind recent missions including the NASA *Mars Atmosphere and Volatile EvolutioN (MAVEN)* mission, the European Space Agency (ESA) *Mars Express*, and the ESA *Venus Express*. Of all other planets, Venus is in many respects the most Earth-like. Its atmosphere, however, is incredibly dry, with four to five orders of magnitude less water than Earth [*De Bergh et al.*, 1991]. The high deuterium-to-hydrogen ratio [*McElroy and Hunten*, 1969; *Donahue et al.*, 1982; *De Bergh et al.*, 1991] is indicative that this was not always the case, and that Venus once had a substantial quantity of water [*Donahue and Hodges*, 1992; *Hartle et al.*, 1996; *Donahue*, 1999], possibly even forming Earth-like oceans [*Svedhem et al.*, 2007]. Although it is thought that Venus lost much of its water early in its history [*Kulikov et al.*, 2006], one of the major early discoveries of the ESA *Venus Express* [*Svedhem et al.*, 2009] mission was that the primary ion species escaping down the comet-like plasma tail were H^+ and O^+ ions in a water-like stoichiometric ratio of 2:1. Thus, regardless of the original water inventory, atmospheric escape mechanisms at Venus today appear to be far more effective at driving water and oxygen loss than at nearby Earth, with a comparable size and gravity. Without an intrinsic magnetic dipole field [*Zhang et al.*, 2008; *Bridge et al.*, 1967], the prevailing wisdom has been that atmospheric loss is dominated by mechanisms resulting from stripping by the solar wind [*Dubinin et al.*, 2011]. However, one planetary-driven mechanism thought to play a supportive (but important) role in both atmospheric evolution [*Barabash et al.*, 2007b; *Dubinin et al.*, 2011], and the enrichment of light (H^+, D^+) ion escape [*Hartle and Grebowsky*, 1990, 1993, 1995; *Barabash et al.*, 2007b] is that of a long hypothesized "ambipolar" electric field (also referred to as a "polarization" electric field at Venus [*Barabash et al.*, 2007b]).

The ionosphere of any planet consists of ions and electrons in approximately equal numbers. In the absence of electrical forces, electrons, being three to four orders of magnitude lighter than ions, would easily escape

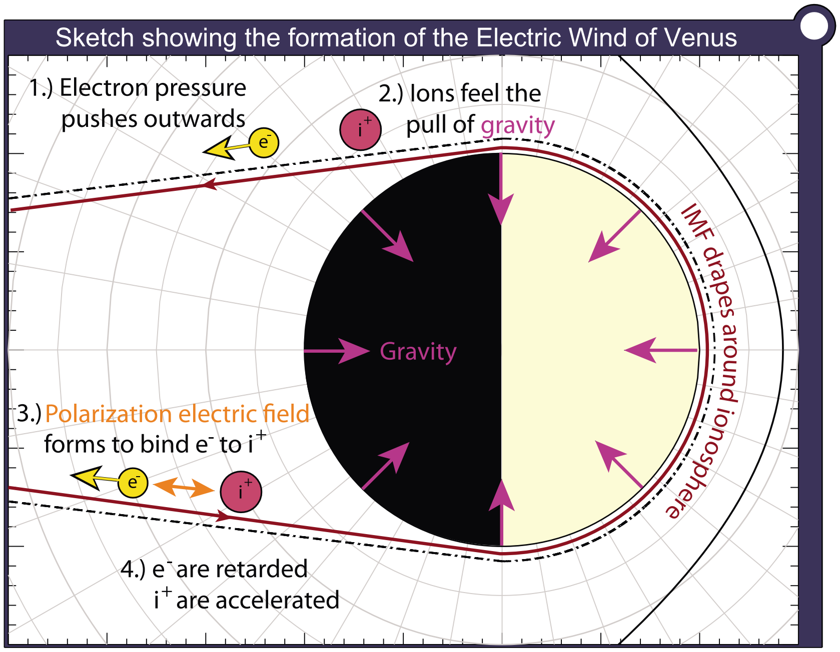

Figure 1. The induced magnetosphere of Venus and formation of the electric wind.

the pull of gravity guided along the draped magnetic field. However, the Coulomb force restricts their motion away from the ions. As the electrons pull away, an ambipolar electric field forms to resist their separation, preventing a net charge from forming and satisfying quasineutrality (see Figure 1). The more energetic the electrons, the stronger the electric field must be to restrain them. "Superthermal" (1–70 eV) photoelectrons, generated by photoionization of the atmosphere, play an especially potent role in generating this field [*Lemaire*, 1972] even though they make up a small fraction of the total electron population [*Khazanov et al.*, 1997]. The potential drop that results from this electric field assists terrestrial atmospheric escape [*Moore et al.*, 1997] since it reduces the potential barrier required for heavier ions (such as O^+) to escape and accelerates light ions (such as H^+) to escape velocity. An identical physical process is also hypothesized to occur in the solar wind [*Lemaire and Scherer*, 1973] (and in the stellar winds from all stars [*Scudder and Karimabadi*, 2013]), although it is very difficult to measure and thus has remained theoretical. This potential drop is critical to the formation of Earth's "polar wind," which flows outward along open magnetic fields above our polar caps [*Hanks and Holzer*, 1968]. However, given that that the scientific term "polar wind" also encompasses other acceleration mechanisms, and that at an unmagnetized planet it would not be confined to the poles, we adopt the nomenclature of "electric wind" as a shorthand to refer to this specific mechanism: the ambipolar electric field, electric potential drop, and outflow of decelerated electrons and accelerated ions.

Although vital to our understanding of the evolution of our atmosphere, this field is extremely challenging to measure given its small magnitude. The few attempts made to measure it in Earth's ionosphere were only able to estimate an upper bound on the electric potential drop (i.e., the total drop *below* the observing spacecraft) of $\lesssim 2$ V [*Coates et al.*, 1985; *Fung and Hoffman*, 1991]. In addition to these weak ionospheric fields, larger (≈ 20 V) [*Kitamura et al.*, 2012; *Winningham and Gurgiolo*, 1983; *Wilson et al.*, 1997] parallel potential drops are frequently observed *above* spacecraft (i.e., between ≈ 3800 km and infinity [*Kitamura et al.*, 2012]). However, these higher-altitude potential drops occur entirely above the bulk of our ionosphere and are not to be confused with the ionospheric ($\lesssim 500$ km) potential drops discussed in this study.

Similarly, recent investigations of the ionospheric potential drop at other worlds (specifically Mars [*Collinson et al.*, 2015] and Titan [*Coates et al.*, 2015a] have also only been able to put an upper limit of $< \pm 2$ V due to instrumentational limitations and the field's diminutive strength. Although an ambipolar electric potential has never been successfully measured in a planetary ionosphere, there is abundant indirect evidence for the presence of an electric wind at Venus. *Hartle and Grebowsky* [1990, 1993, 1995] theorized the presence of an ambipolar electric field from observations of escaping H^+ and D^+, by the NASA Pioneer Venus

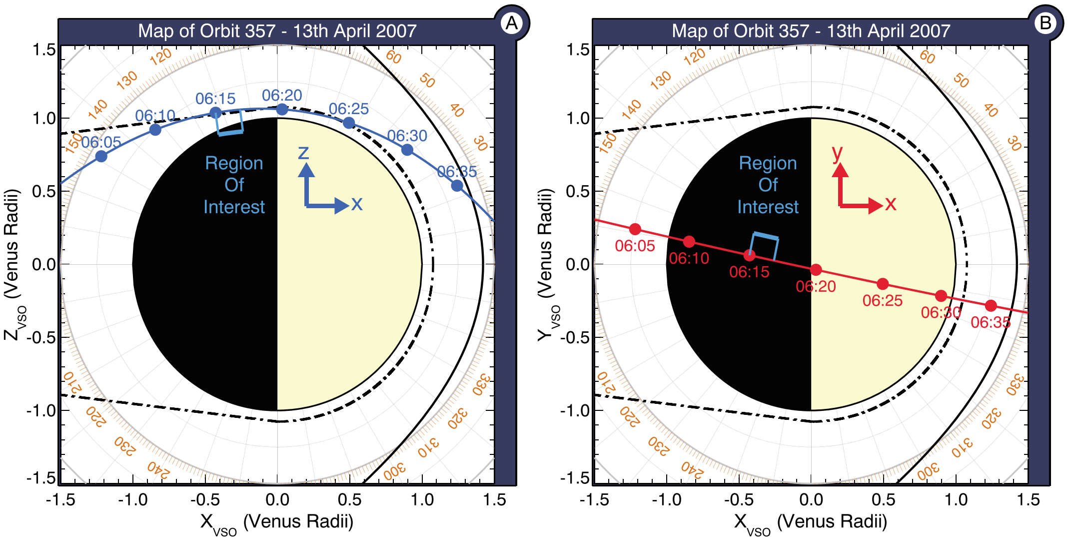

Figure 2. Map of orbit № 357 of the ESA *Venus Express* in Venus Solar Orbital coordinates where *X* points toward the Sun, *Y* is perpendicular to *X* and points in the opposite direction to the planet's velocity vector, and *Z* completes the right-handed system pointing up out of the plane of the Cytherean ecliptic. The progress of the spacecraft is marked at 5 min intervals in Greenwich Mean Time. (a) *x* versus *z* view from the "side" of the planet, (b) *x* versus *y*, the "top down" view over the north geographic pole. Approximate locations of the bow shock [*Slavin et al.*, 1980] (solid line) and ionopause [*Martinecz et al.*, 2008] (dashed line) are included for orientation.

Orbiter and presumed that this electric field dominated light ion escape. Additionally, the observation of hot superthermal photoelectrons (created in the dayside ionosphere [*Coates et al.*, 2008] and observed in the magnetotail of Venus [*Tsang et al.*, 2015; *Coates et al.*, 2011, 2015b]) was also presented as indirect evidence that a "polar wind like" process may be occurring [*Tsang et al.*, 2015; *Coates et al.*, 2011, 2015b]. Similar outflows of photoelectrons and associated outflowing ions have also been observed in the induced magnetotails of Mars [*Frahm et al.*, 2006, 2010; *Coates et al.*, 2011] and Titan [*Coates et al.*, 2007; *Coates*, 2009; *Coates et al.*, 2011; *Wellbrock et al.*, 2012; *Coates et al.*, 2015a] and are also possibly indicative of ambipolar outflow. In addition, the photoelectron and escaping ion fluxes were used to estimate the relevant electric wind-related escape rates at Titan [*Coates et al.*, 2012], Mars [*Frahm et al.*, 2010], and Venus [*Coates et al.*, 2015b].

Although an electric potential drop should theoretically occur at any planet or moon with an atmosphere, without an understanding of the magnitude of the potential, it is not possible to determine the role and relative importance that the electric wind plays in atmospheric escape.

2. Measuring the Electric Potential of a Planet

The ionosphere of Venus is a rich source of hot photoelectrons [*Coates et al.*, 2008], which were observed escaping down the plasma tail on practically every orbit of the European Space Agency's (ESA) *Venus Express* at altitudes of up to 2.3 Venus radii (r_V) [*Coates et al.*, 2015b]. Photoelectrons are key to both the generation and measurement of the electric wind. The energy spectra of Cytherean photoelectrons exhibit bright spectral peaks resulting from the photoionization of atomic oxygen by ultraviolet (He-II 30.4 nm) photons including two peaks at 22.3 eV and 23.7 eV, resolved by our instrument as a single merged peak at 23 eV [*Coates et al.*, 2008, 2011], in addition to a third peak at 27.2 eV. The energy of photopeaks is dictated by atomic physics. Therefore, any observed shift in their energy can be used to determine the presence, polarity, and magnitude of an external electric potential drop between the ionosphere where the photoelectrons are generated and the detector onboard the spacecraft [*Coates et al.*, 1985, 2015a; *Collinson et al.*, 2015].This potential drop has two components: one associated with the electric wind and the other due to spacecraft charging.

To measure the strength of the electric wind using the ESA *Venus Express*, we therefore require the following: (1) The spacecraft must be in the right location: on an open magnetic field line connected to both the solar wind and ionosphere. (2) The spacecraft must carry an electron spectrometer capable of resolving any shift in known spectral features. (3) The spacecraft must carry a magnetometer so that electrons can be binned by “pitch angle” (the angle of observation relative to the magnetic field), so that we examine only field-aligned electrons coming from the ionospheric source. (4) We require a measurement of the electrostatic potential due to spacecraft charging in order to determine what portion of the observed potential drop is due to the electric wind. (5) The spacecraft potential must remain constant for the 60 s integration required to gain sufficient counting statistics with our instrument.

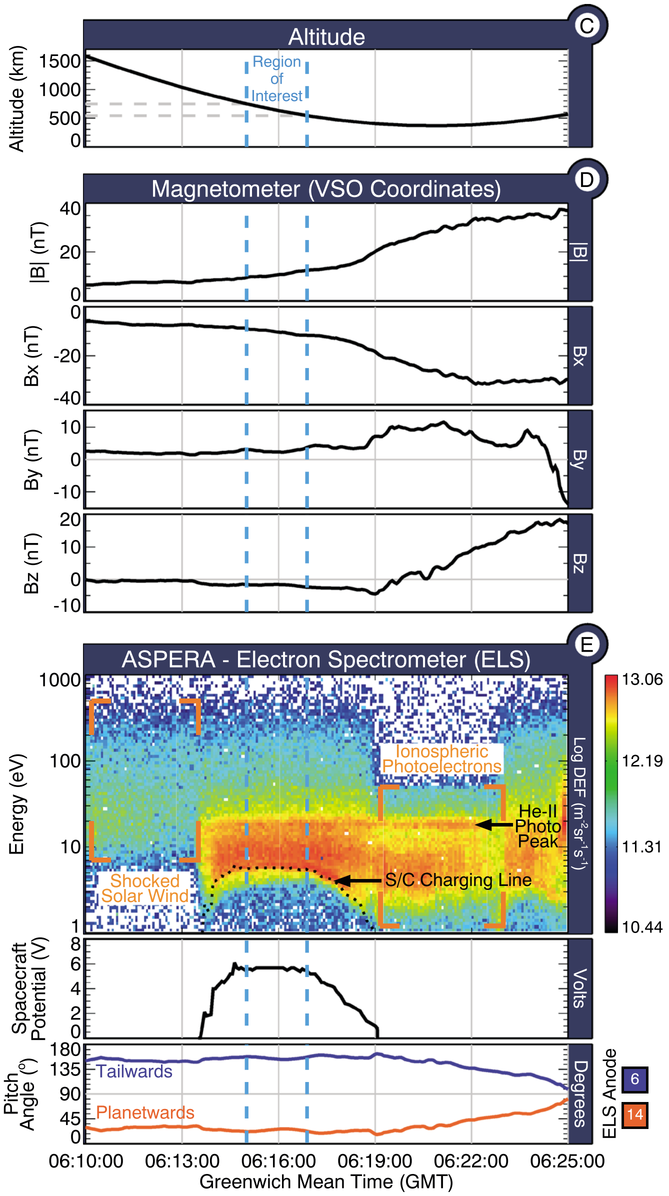

Figure 3. Magnetic and particle observations from the ESA *Venus Express* on 13 April 2007. (a) Spacecraft altitude for context, (b) magnetic observations from the Venus Express Magnetometer, and (c) ASPERA-ELS electron spectrogram (time versus energy), with the color scale showing the log of the differential energy flux, integrated over all 16 anodes; spacecraft potential measured from the spacecraft charging line, providing a known and stable electrostatic environment during the region of interest; and the pitch angle of ELS anodes 14 and 6, showing a fortuitously good and stable pitch angle coverage during the region of interest.

3. Evidence for an Electric Potential: Orbit № 357

Figure 2 shows a map of orbit № 357, representing our current best example satisfying our measurement criteria, and Figure 3 shows *Venus Express* co-incident observations from near periapsis. The spacecraft, orbiting in a highly elliptical 24 h polar orbit, was flying on a midnight-midday pass with periapsis in the ionosphere over the north geographic pole. Shortly after the *Venus Express* flew into daylight there was a brief window (06:15 Greenwich Mean Time (GMT) to 06:17 GMT) where it was possible to make a direct measurement of electric potential drop at Venus. This region of interest was additionally fortuitous in that magnetic conditions (Figure 3b) were calm, resulting in stable magnetic connectivity to the same approximate region of the ionosphere during our electron observations. Before 06:14 GMT, the only particles measured by the Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) Electron Spectrometer (ELS) [*Barabash et al.*, 2007a; *Collinson et al.*, 2009] (Figure 3c) were a hot population of shocked solar wind electrons. At lower altitudes (>06:19 GMT) this population disappears, indicating that the spacecraft was no longer in magnetic connection to the solar wind, and instead ELS measured solely ionospheric photoelectrons with the He-II photopeak visible as a line in the spectrogram (Figure 3c). This photoelectron population is highly typical in terms of spectral features and flux [*Cui et al.*, 2011]. In the region of interest, both populations are observed, and therefore the *Venus Express* was in the right place, with the right magnetic connection to both ionosphere and solar wind, to observe the electric wind.

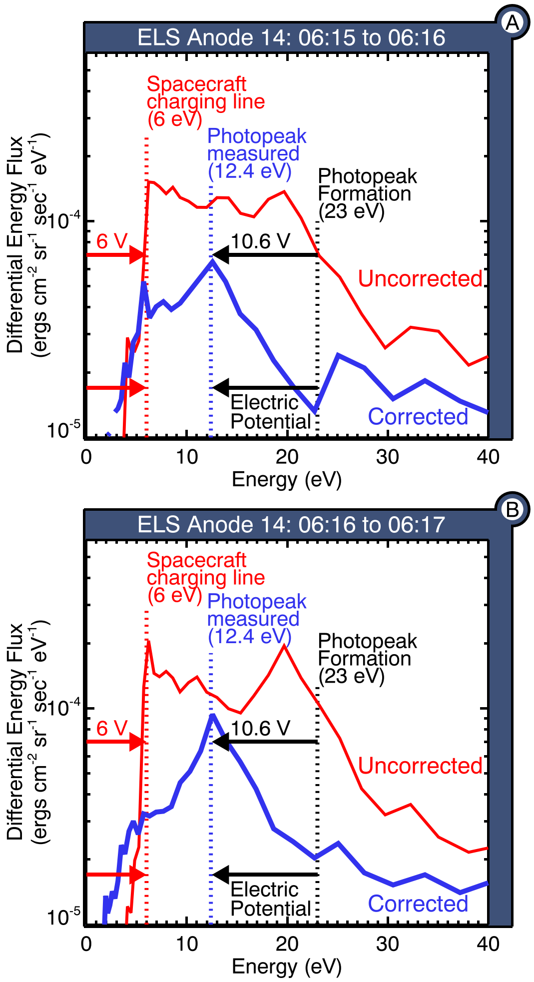

Figure 4. Corrected and uncorrected electron spectra from the region of interest from ELS anode 14, showing key spectral features and the final 12.4 eV spectral shift resulting from a 10.6 V electric potential drop below the ESA *Venus Express*. (a) First ELS integration. (b) Second integration.

Between 06:14 and 06:19 GMT, we observe a spacecraft charging line from which we may determine the electrostatic potential of the spacecraft [*Johnstone et al.*, 1997]. Any electron with energy below the spacecraft potential is accelerated, resulting in a sharp cutoff in the spectrum. Therefore, the energy of this cutoff directly corresponds to the spacecraft potential. In the region of interest, this held stable for 2 min, permitting two 60 s integrations using the ASPERA-4 ELS. Anode 14 was selected to measure the electric wind on the grounds that it had an unimpeded field of view, was looking planetward (see Figure 3d), and had excellent pitch angle coverage to observe photoelectrons outflowing from the ionosphere.

Figure 4 shows the results of these two ASPERA-4 ELS integrations. Original uncorrected spectra as measured at Venus are shown in red. Final spectra corrected for the +6 V spacecraft potential (using Liouville's theorem; see Section S1 in the supporting information) are shown in blue. Having corrected the spectra we may now examine the He-II photopeak for any shift and find that although it must have been generated in the ionosphere at 23 eV, it arrived at the spacecraft at 12.4 eV. We thus find that these ionospheric photoelectrons have been retarded by a significant planetary electric potential of $\Phi_{\text{Venus}} = 10.6$ V.

Although the electrons have lost energy, such an electric potential would impart +10.6 eV to all planetary ions. This is sufficient to counter the gravitational binding energy of even an O^+ ion and directly accelerate it to escape velocity. Although the ASPERA plasma suite carried an Ion Mass Analyzer (IMA) [*Barabash et al.*, 2007a], taking into account the spacecraft potential, the lowest energy that IMA could see in the region of interest was 18 eV and the peak of a 10.6 eV ion distribution would be below its reach. Although their populations could not be fully resolved (full details of ASPERA-IMA observations can be found in Section S2), clear evidence for cold outflowing ionospheric O^+ and H^+ ions was observed on orbit № 357.

4. A Persistent, Global Feature

In order to see if this potential drop was typical, we searched for more instances of the electron spectral conditions required for measurement: specifically, the confluence of solar wind, photoelectrons, and stable spacecraft charging line. Venus Express spends only 5 to 10 min out of each 24 h orbit in a region where it might even be theoretically possible to observe the electric wind. This necessitated a search through two earth-years of data, from which we identified 14 regions of interest, from six orbits, full details of which are shown in Table 1. Although the electric wind could only be measured occasionally, we found that (a) any time

Table 1. Collected *Venus Express* Measurements of the Total Electric Potential Drop[a]

Date of Observation	Start of Region of Interest (GMT)	Altitude (km)	Photopeak Energy (eV)	Potential Drop (V)
2007-03-29	06:27:00	550 km	11.5 eV	11.5 V
2007-04-13	06:15:00	629 km	12.4 eV	10.6 V
	06:16:00	532 km	12.4 eV	10.6 V
2007-12-05	02:40:00	353 km	12.4 eV	10.6 V
2008-02-04	04:45:00	349 km	13.5 eV	9.5 V
	04:46:00	420 km	12.4 eV	10.6 V
	04:47:00	514 km	13.5 eV	9.5 V
	04:48:00	628 km	13.5 eV	9.5 V
	04:49:00	763 km	14.6 eV	8.4 V
2008-03-31	04:05:30	450 km	15.8 eV	7.2 V
2008-04-08	03:56:00	335 km	12.4 eV	10.6 V
	03:57:00	382 km	13.5 eV	9.5 V
	03:58:00	453 km	12.4 eV	10.6 V
	03:59:00	545 km	13.5 eV	9.5 V
	Mean:	**493 km**	**13.1 eV**	**9.9 ± 1.1 V**

[a] Times denote the beginning of a 60 s ASPERA-4 ELS integration; altitude denotes the minimum altitude of the spacecraft during the measurement. The energy is that of the He-II generated photoelectron peak, corrected for spacecraft potential, and the potential is that of the total integrated potential drop below the spacecraft.

it was possible to measure an electric potential drop, one was observed, and (b) the magnitude of this drop was very consistent, with a mean value of $\Phi_{\text{Venus}} = +9.9\,\text{V} \pm 1.1\,\text{V}$.

Figure 5 shows a map of the location where these observations occurred. We find that this force drives escape from all electric latitudes, whereas at magnetized planets, it is confined to the magnetic poles. For each orbit we sampled data from the solar wind as near to the region of interest possible (the standard technique when no second spacecraft is available [*Collinson et al.*, 2014]), finding no evidence for any bias in upstream conditions. Given this, and the consistency in its strength, our collected observations indicate that the electric wind is a persistent, stable, and global phenomenon, flowing tailward from behind the entire terminator.

5. The Importance of the Electric Wind

Contrary to all expectations [*Hartle and Grebowsky*, 1993], the electric potential drop in the ionosphere of Venus is at least five times greater than the upper limits we have in Earth's topside ionosphere [*Coates et al.*, 1985; *Fung and Hoffman*, 1991]. Although parallel electric potentials of comparable magnitude have been observed at Earth [*Kitamura et al.*, 2012; *Winningham and Gurgiolo*, 1983; *Wilson et al.*, 1997], all occur at much higher altitudes (3800 km → infinity) [*Kitamura et al.*, 2012], far above the bulk of the terrestrial ionosphere where they cannot directly act upon ionospheric particles. We therefore discover that it is possible for two terrestrial planets with similar sizes, surface gravities, and ionospheres [*Brace et al.*, 1983] to have significantly different polarization electric fields. Based on models developed for Earth [*Khazanov et al.*, 1997], we speculate that one possible contributing factor in explaining its unexpected strength may be a higher proportion of photoelectrons at Venus due to its closer distance to the Sun and higher photoionization rates. The greater the admixture of photoelectrons, the greater the electric field needs to be to restrain then and satisfy quasineutrality. For a first-order approximation of this ratio at Venus, we used a model derived from the NASA Pioneer Venus Orbiter Langmuir probe measurements [*Theis et al.*, 1980] to estimate thermal electron densities. When compared to superthermal densities measured by ASPERA-ELS, it corresponds to a ratio between 0.1 and 1%. This would be a very high fraction for Earth [*Khazanov and Liemohn*, 1996], and according to *Khazanov et al.* [1997], this would translate to a potential drop of approximately 7 V. This is reasonably consistent with our measurements and supports our hypothesis that the higher admixture of superthermal electrons at Venus is a contributor to the enhancement of the polarization electric field. For full details of how this approximation was made, see Section S3, and for the source code of the *Theis et al.* [1980] model (converted into IDL from the original Fortran), see Section S4.

The first measurement of an ionospheric ambipolar potential drop is noteworthy, but the unexpected discovery that its magnitude can be so large has profound implications for our understanding of atmospheric loss processes for all planets. Whilst other loss mechanisms are present [*Dubinin et al.*, 2011], the newly discovered

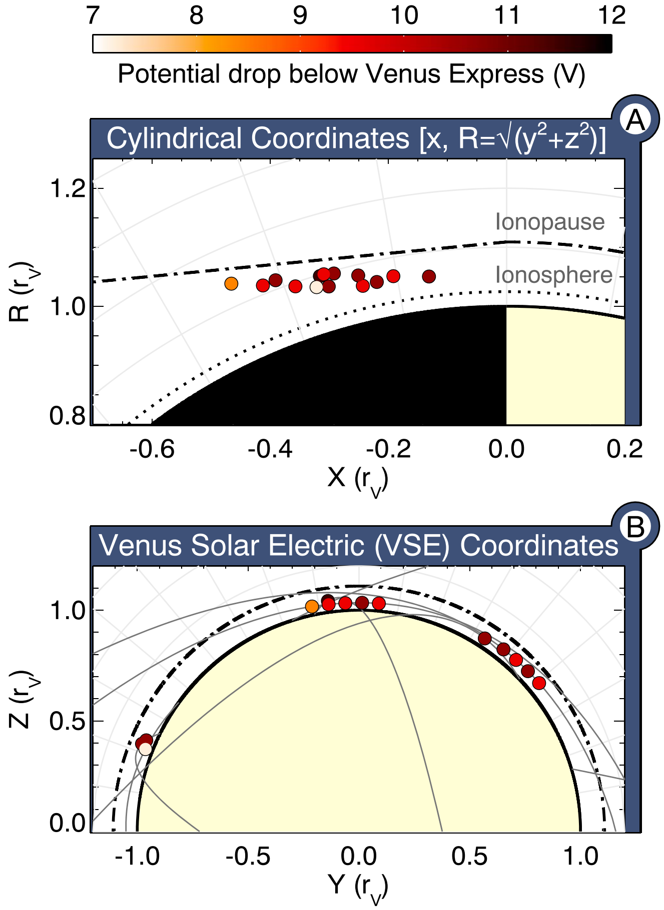

Figure 5. Map of where the total electric potential drop has been measured, in Venus Solar Electric coordinates where *X* points toward the Sun, *Y* is rotated to lie in the plane of the interplanetary magnetic field, and *Z* completes the right-handed system. Units are Venus radii (r_V).

electric potential is quite sufficient all by itself for any ion lighter than 18 amu (which includes O^+ and all water group ions) to overcome gravity and be directly accelerated to escape velocities. Thus we find that it is possible for planets to lose heavy ions to space entirely through electrical forces in their ionospheres and that ambipolar fields can play an even more dominant role in planetary atmospheric escape than previously considered. We also find that, contrary to our current understanding, Venus would still lose heavy ions such as O^+ to space regardless of any atmospheric stripping by the solar wind. Additionally, however, the electric wind will further enhance these other escape processes (such as pickup and acceleration by the motional electric field of the solar wind) by transporting ions from the bulk of the ionosphere (150 km [*Brace et al.*, 1983]) to the ionopause (300+ km [*Martinecz et al.*, 2008]) and above, where these solar wind driven mechanisms can take effect. Thus, given their importance, ionospheric ambipolar fields must therefore always be included in any study of the atmospheric evolution of Venus, Earth, Mars, Titan, or indeed any planet in any star system.

The discovery of a powerful electric wind at Venus, an Earth-like terrestrial planet, also has important consequences for the study of exoplanets by missions such as Kepler. If, for example, the electric potential drop in Earth's (or another Earth-like planet's) ionosphere was a Venus-like +12 V, then a similar direct loss of heavy ions would likely occur, regardless of the presence or absence of a planetary dynamo magnetic field, leading to higher rates of loss. Significant changes to planetary escape rates could impact the ability of a planet to retain an atmosphere [*Zahnle and Catling*, 2013; *Cohen and Glocer*, 2012] and maintain liquid water oceans and increase the likelihood that a planet loses its oceans during the moist greenhouse phase [*Chassefière*, 1997]. Such a strong escape mechanism could also impact the redox evolution of a planetary surface [*Caitling et al.*, 2001]. Given that we believe Venus' stronger polarization field may arise from its closer proximity to the Sun, and that most known exoplanets have been found relatively close to their stars (since these are easier to detect), the possibility of a strong electric wind must be considered when assessing planetary evolution or the potential for habitability on exoplanets.

Acknowledgments
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