The extension of ionospheric holes into the tail of Venus

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Abstract

Ionospheric holes are Cytherian nightside phenomena discovered by the NASA Pioneer Venus Orbiter, featuring localized plasma depletions driven by prominent and unexplained enhancements in the draped interplanetary magnetic field. Observed only during solar maximum, the phenomenon remains unexplained, despite their frequent observation during the first 3 years of the mission and more than 30 years having elapsed since their first description in the literature. We present new observations by the European Space Agency Venus Express showing that ionospheric holes can extend much further into the tail than previously anticipated (1.2 to 2.4 planetary radii) and may be observed throughout the solar cycle and over a wide range of solar wind conditions. We find that ionospheric holes are a manifestation of a deeper underlying phenomenon: tubes of enhanced draped interplanetary magnetic field that emerge in pairs from below the ionosphere and stretch far down the tail. We speculate on two possible explanations for the magnetic fields underlying the phenomena: magnetic pileup due to stagnation of ionospheric flow and internal draping around a metallic core.

1. Introduction

One of the most intriguing mysteries that endures from the Pioneer Venus Orbiter (PVO) [Colin, 1980] is that of ~1000 km wide “holes” in the nightside ionosphere. First described by Brace et al. [1980], a sketch of the phenomenon can be seen in Figure 1. Ionospheric holes have the following characteristics:

1. A strong sunward or antisunward enhancement in magnetic field of 10–50 nT compared to the adjacent regions [Brace et al., 1980; Luhmann and Russell, 1992].
2. A concurrent diminution in electron and ion density by at least a half and up to an order of magnitude [Brace et al., 1982].
3. A low plasma beta (ratio between thermal plasma pressure and the magnetic pressure, $\beta < 1$) [Brace et al., 1982].
4. Dual electron populations: a $2 \times 10^3$ K (0.17 eV) core and $1.2 \times 10^4$ K (1 eV) component [Brace et al., 1982].
5. Holes occur in pairs (although typically only one was encountered in a given orbit) with oppositely polarized field enhancements, one sunward and the other tailward.
6. The location and magnetic polarity of the holes are consistent with a draping of the interplanetary magnetic field (IMF) [Marubashi et al., 1985].

The most dominant feature of the holes is the strong sunward or antisunward enhancement in magnetic field. Brace et al. [1982] demonstrated that the holes form as a result of the internal magnetic pressure dominating over plasma pressure. Later, Marubashi et al. [1985] demonstrated that the location of the holes and magnetic polarity within (sunward/antisunward) are consistent with a draping of the interplanetary magnetic field (IMF). Additionally, Marubashi et al. [1985] reported many instances of magnetic enhancements in the ionosphere identical to that associated with holes but without any attendant plasma depletion. Later, Luhmann and Russell [1992] described observations of the magnetic signatures of holes at the very lowest altitudes (~145 km) explored by PVO. This is significant, since the plasma depletions associated with holes are not generally observed below ~200 km, the altitude where the ion collision frequency exceeds the ion gyrofrequency and the plasma becomes demagnetized [Grebowsky and Curtis, 1981]. This same study concluded that the collected observations of ionospheric holes by PVO gave "the impression of well-defined
Figure 1. Sketch showing ionospheric holes and orbits of the NASA Pioneer Venus Orbiter (PVO) and the European Space Agency (ESA) Venus Express (VEX).

flux tubes stretching tailward from far below periapsis.” If this interpretation is correct, then it should theoretically be possible to observe the extension of ionospheric holes into the tail. The origin of these enhanced fields underlying the phenomena is unknown, and thus the holes have remained fundamentally unexplained for over 30 years.

Given that the direction and position of holes is controlled by the orientation of the IMF, Brace et al. [1982] and Marubashi et al. [1985] suggested formation mechanisms for these enhanced magnetic flux tubes based on draping of the IMF around the ionosphere. The general problem with such theories is that they invoke that the draped field lines wrap around the planet without penetrating the ionosphere. However, the field lines inside the holes encountered by PVO did not show signs of bending to wrap around the planet: they remained oriented sunward/antisunward down to the very lowest altitudes (150 km) [Luhmann and Russell, 1992]. Thus, in order to encircle the planet and not penetrate the ionosphere, the field lines in the ~1000 km diameter ~50 nT holes would have to kink abruptly below 150 km and the whole structure compress into a horizontal layer only tens of kilometers thick that encircles the planet. This is problematic, since if conservation of magnetic flux is imposed, this invokes a structure with internal field strength of ~1000 nT and internal magnetic pressure ~400 nPa. Such a layer could not be balanced by the local 0.3 nPa plasma pressure on the nightside ionosphere (n = 1.5 x 10^4 cm^-3 [Howard et al., 1974; Aleksandrov et al., 1976] and T_e ~ 1000 K, T_i ~ 500 K, [Knudsen et al., 1979]). Nor is there any evidence that these magnetic structures could be self-supported, helical, force-free flux ropes [e.g., Zhang et al., 2012]. It is therefore very unlikely that the ionosphere can support such a structure, implying that the magnetic flux tubes associated with the holes go beneath the ionosphere and diffuse into the atmosphere and crust [e.g., Luhmann, 1991].

The European Space Agency (ESA) Venus Express [Svedhem et al., 2007] is the first Cytherian explorer since PVO with the scientific instrumentation required for further study of ionospheric holes. In addition to a Magnetometer (MAG) [Zhang et al., 2006], it carries both an Electron Spectrometer (ELS) and Ion Mass Analyzer (IMA) as part of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) investigation [Barabash et al., 2007a]. However, whilst PVO’s periapsis was initially close to the equator, the periapsis of Venus Express is over the geographic north pole (see Figure 1). Thus, Venus Express orbits very much higher than PVO when above the ±45° magnetic latitudes where ionospheric holes are known to occur [Marubashi et al., 1985]. Whilst all events described in this paper were in the ionotail (not the ionosphere), we have opted to retain the nomenclature of “ionospheric holes” in describing this phenomenon for consistency with previous studies.

In this paper we present the results of a search for the continuation of ionospheric holes into the Cytherian ionotail by the Venus Express. Our scientific questions were as follows: Do ionospheric holes extend into the ionotail? If so, under what conditions are they observed? What are the magnetic and ionic properties inside an ionospheric hole? What is the underlying process that is driving the phenomenon? And finally, can
the collected *Pioneer Venus Orbiter* and *Venus Express* observations offer any additional clues to explain the origin of the magnetic enhancements underlying ionospheric holes?

This paper is laid out as follows. In section 2 we describe our search for ionospheric holes and our selection criteria. In section 3 we present our results, with full data sets from our best example event in section 3.1 and the consistency of our events with a draping of the interplanetary magnetic field (IMF) in section 3.2. In section 4 we discuss our observations and why they have led us to conclude that they are the extension of ionospheric holes into the tail. In section 4.1 we discuss why only 11 events were identified in the tail, when they were commonly encountered during the first 3 years of the PVO mission. In section 4.2 we discuss three possible explanations for the formation mechanism of ionospheric holes (one of which we discount due to its inconsistencies with the new observations). Finally, in section 5, we summarize our findings and conclude that the fundamental underlying phenomenon is a magnetic structure embedded within the tail.

2. Instrumentation and Event Selection Criteria

Our search for ionospheric holes employed three instruments: the *Venus Express* Magnetometer (MAG) [Zhang et al., 2006], Analyzer of Space Plasmas and Energetic Atoms (ASPERA) Electron Spectrometer (ELS), and ASPERA Ion Mass Analyzer (IMA) [Barabash et al., 2007a]. Like many of the components used in the construction of the *Venus Express*, the ASPERA suite is composed of flight spares from the preceding two spacecraft in her class, the ESA *Rosetta* and ESA *Mars Express*. As a result, ASPERA-ELS was never originally intended for flight, and it was known to have a sensitivity that was almost 6 times lower than expected due to misalignments of the electron optics during manufacture [Collinson et al., 2009]. Whilst this has been corrected for in calibration, this lower than desired sensitivity means that in low-flux regions, extracting meaningful moments such as density and temperature is often very challenging [e.g., Collinson et al., 2012]. Additionally, the electron populations inside ionospheric holes measured by PVO’s Langmuir Probes (Orbiter Electron Temperature Probes (OETP)) (a 0.17 eV core and “hot” 1 eV component [Grebowsky and Curtis, 1981]) are below the lower energy limit of the instrument. Thus, it is challenging to make direct quantitative comparisons between ASPERA-ELS and the PVO OETP data. The *Venus Express* Ion Mass Analyzer (ASPERA-IMA) [Barabash et al., 2006] is a top-hat electrostatic analyzer equipped with electrostatic deflector plates which allow the sensor to scan ±45°, with a temporal resolution of 196 s for a full 3-D scan. ASPERA-IMA has a magnetic separator which enables it to distinguish H⁺, He⁺⁺, He⁺, and heavy ions with M/q 20–80 amu/q, which in the tail of Venus are mostly oxygen [Barabash et al., 2007b].

Our criteria for event selection were very strict, in that candidates had to exhibit every known feature of the ionospheric holes observed by PVO: (1) The event must exhibit an unambiguous enhancement in field strength (|B|), such that the event is the strongest magnetic feature in the tail and clearly enhanced with respect to the background field. (2) The event must be a magnetic enhancement, not a temporary reversal in polarity, which would likely indicate a brief current sheet crossing. (3) The event must be associated with a concurrent decrease in the flux in both electrons and ions. And (4) the event is surrounded on both sides by cold ionotail plasma.

We visually inspected every *Venus Express* encounter with the Cytherian wake from 2006 to 2012 where data were available from all three instruments and found 11 candidate events which match these criteria. Each has been given an identifying number assigned in chronological order.

3. Results

3.1. An Ionospheric Hole in the Ionotail of Venus

At approximately 05:22:30 Greenwich Mean Time (GMT) on 19 May 2010, *Venus Express* encountered an anomaly that currently represents our best example of the extension of an ionospheric hole in the Cytherian ionotail. In this section, and in Figure 2, we present full data sets from this event. Data covering a close-up of the event are presented in Figures 2a–2d, whereas Figures 2e–2h show data from the entire encounter with Venus, so that conditions inside the ionospheric hole can be more easily contrasted against the rest of the tail.

3.1.1. Overview of Planetary Encounter

Figures 2a and 2e show a color-coded timeline of the encounter. The highly elliptical ~24 h polar orbit of the *Venus Express* was aligned such that it made a pass from local midnight to midday, as shown in Figure 1. The encounter began in the solar wind, downstream from Venus at 3:55:00 (blue on the timeline). The spacecraft
Figure 2. Event №7—A hole embedded within a very typical Cytherian ionotail, as observed by the ESA Venus Express on 19 May 2010. (a–d) Close-up of the event, covering the period from 05:18:45 to 05:36:00 Greenwich Mean Time. (e–h) The period from 03:55:00 to 06:10:00 Greenwich Mean Time so that the conditions inside event №7 can be more easily contrasted against those during the rest of the Venus encounter.
crossed the bow shock and spent over an hour in the magnetosheath (red on the timeline), evident from the shocked solar wind protons and electrons in Figures 2g and 2h. The spacecraft then crossed the magnetic pileup boundary into the calm wake in the shadow of Venus (purple on the timeline, labeled “ionotail”). Here the shocked sheath plasma disappears, and ASPERA-IMA observes a cold ionospheric outflow of protons and heavy ions [Barabash et al., 2007b] at $\sim$20 eV (Figure 2h). The flux of ionospheric electrons intensifies as Venus Express crosses the ionopause at $\sim$5:47:00 where $\sim$20 eV photoelectrons can be observed [Coates et al., 2008]. The spacecraft then reemerges into daylight and crosses the ionopause, sheath, and upstream bow shock in quick succession before entering the upstream solar wind.

This is a very typical and otherwise unremarkable Venus Express tail encounter, with two notable exceptions. Firstly, the ambient magnetic field in the ionotail was much weaker than usual (the importance of this will be discussed later in detail in section 4.1). Secondly, an anomaly was encountered (gold on timeline), consistent with PVO observations of ionospheric holes. We shall now describe our observations of this event in more detail.

3.1.2. MAG

Figure 2b shows magnetic observations of event №7 at a resolution of 32 samples per second. These data are in the Venus Solar Orbital (VSO) coordinate system, where the $x$ axis points sunward from the center of the planet, the $y$ axis points backward along the tangent to the orbit of Venus, and the $z$ axis completes the right-handed set, pointing upward away from the ecliptic. Note that the periodic, regular bursts (very evident during the event in Figure 2b) are a known instrument noise in the data set and should be disregarded.

During the event, the total magnetic field strength ($|B|$) increases sharply from the mean background of $2.7 \pm 1.2$ nT to a plateau at $9.1 \pm 0.6$ nT. The main component of this increase is an enhancement in $+B_x$. Note from Figure 2f that this represents a clear and unambiguous enhancement with respect to the rest of the tail, and after the event the magnetic field returns to the same orientation and strength as before. These observations are very consistent with PVO magnetometer observations during ionospheric holes [e.g., Marubashi et al., 1985; Luhmann and Russell, 1992, and references therein].

3.1.3. ASPERA-ELS

Figures 2c and 2g show data from ASPERA-ELS, with spectrograms of differential energy flux above and the integrated total flux below. During the event, the total electron flux measured by ELS decreases from $\approx 5 \times 10^{-13}$ to $\approx 2 \times 10^{-13}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$. This is qualitatively consistent with the “troughs in electron density” reported by Brace et al. [1982] and with the selection criteria of Hartle and Grebowsky [1990], who required at least a factor of 2 decrease in density. As mentioned above, a direct qualitative comparison with PVO OETP measurements is difficult since the expected 0.17 eV and 1 eV populations [Grebowsky and Curtis, 1981] are below the energy range of ASPERA-ELS. Additionally, obtaining plasma moments in this diffuse region is challenging due to the low sensitivity of ELS (6 times lower than intended [Collinson et al., 2009]). However, since (as will shortly be demonstrated) IMA measured a decrease in ion density, we infer that the decrease in electron flux observed by ELS is due to a $>$2 decrease in electron density, as was observed by PVO inside ionospheric holes.

The absence of $\sim$27 eV photoelectrons [Coates et al., 2008] inside or adjacent to event №7 (or any other of the holes encountered by the Venus Express) is suggestive of no magnetic connection to the terminator (i.e., magnetic connection to the nightside of the planet on both sides of the hole). However, photoelectrons have never been observed in the tail at distances $> 1.45R_V$ [Coates et al., 2011], and event №7 and the majority of holes were above this altitude. Thus, whilst lower down the presence of photoelectrons is a marker for magnetic connection to the terminator, at these distances, their absence is less conclusive.

3.1.4. ASPERA-IMA

Figures 2d and 2h show data from ASPERA-IMA. There are two spectrograms: the top (red) shows protons, and the bottom (blue) shows heavy planetary ions. Throughout the wake, both spectra show the cold, low energy ionospheric outflow described by Barabash et al. [2007b]. During the event, there is a marked diminution in the flux of ions. Below the spectrograms are plots of particle density (in cm$^{-3}$) and temperature (in K), again with protons shown in red and heavy ions in blue. During the event there is a marked decrease in the density of all species, consistent with Marubashi et al. [1985] who reported decreases in O$^+$ number density between 1 order of magnitude and greater than 3 orders of magnitude, beyond which O$^+$ populations were below the sensitivity of the PVO-OIMS instrument. We observe a decrease in planetary...
ions of 2 orders of magnitude during event №7 and a decrease in proton density by approximately 1 order of magnitude.

Inside all events (including event №7), magnetic pressure dominated over plasma pressure consistent with analysis of ionospheric holes by Brace et al. [1982]. Pressure ratios for events №1 to №8 are shown in the rightmost column of Table 1 (The remaining events were too brief to calculate reliable plasma pressures with the 192 s temporal resolution of ASPERA-IMA). Two ratios are shown. First is the ratio between the total plasma pressure (thermal and dynamic) of the two main species (H\(^+\) and O\(^+\)) and the magnetic pressure, as in equation (1).

\[
\frac{\text{Plasma Magnetic}}{\text{Magnetic}} = 2 \mu_0 B^{-2} \left( n_H k_B T_H + n_O k_B T_O + m_H n_H v_H^2 + m_O n_O v_O^2 \right)
\]  

Second is the plasma “beta” (\(\beta\)), the ratio between thermal plasma pressure and the magnetic pressure, as in equation (2).

\[
\beta = 2 n k_B T \mu_0 B^{-2}
\]

The mean ratio between plasma and magnetic pressure for all events was 1.3\times10^{-2}, and the mean plasma \(\beta\) was 3.3\times10^{-3}.

### 3.2. Location of Events in the Solar Wind Magnetic System: Consistency With IMF Draping

One of the signature properties of ionospheric holes is that their location and magnetic polarity are consistent with a draping of the interplanetary magnetic field (IMF) [e.g., Marubashi et al., 1985], and thus the holes do not stay in one fixed geographic location. Because of this, PVO did not encounter holes on every encounter with the nightside ionosphere and often would encounter only one of the pair, since the geographic locations of the holes are controlled by the highly variable IMF orientation. Thus, although Venus Express only ever encountered one hole on any given orbit, this is most likely due to the rarity of events. Given the requirement for conservation of magnetic flux, it seems most probable that as holes occur in pairs in the ionosphere, they continue in pairs into the ionotail, as suggested by Brace et al. [1987].

The locations of the Venus Express events were transformed into the Solar Wind Magnetic (SWM) coordinate system, as used by Marubashi et al. [1985] and Phillips and Russell [1987]. The \(X_{\text{SWM}}\) points opposite to the solar wind velocity vector, \(Y_{\text{SWM}}\) is rotated to lie in the plain of the IMF, and \(Z_{\text{SWM}}\) completes the right-handed set. As with previous investigations of ionospheric holes [e.g., Marubashi et al., 1985; Luhmann and Russell, 1992], with no spacecraft in the immediate vicinity of Venus to monitor upstream conditions, we are forced to use a technique whereby the Venus Express proxies as its own solar wind “monitor.” IMF and solar wind proton velocity vectors were averaged for 15 min immediately outside of the two bow shock crossings (inbound and outbound), with preference given to the solar wind measurements closest to the event.

### Table 1. Properties of Ionospheric Holes Encountered by the Venus Express in the Cytherian Ionotail

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Duration</th>
<th>Cross Section</th>
<th>Field Strength (nT)</th>
<th>Pressure Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>№</td>
<td>(dd/mm/yyyy)</td>
<td>(≈ in min)</td>
<td>(km)</td>
<td>(Inside)</td>
<td>(Outside)</td>
</tr>
<tr>
<td>1</td>
<td>03/12/2006</td>
<td>13</td>
<td>2833</td>
<td>0.47</td>
<td>10.9±1.5</td>
</tr>
<tr>
<td>2</td>
<td>26/12/2006</td>
<td>7</td>
<td>1859</td>
<td>0.31</td>
<td>14.3±1.7</td>
</tr>
<tr>
<td>3</td>
<td>27/10/2008</td>
<td>6</td>
<td>1724</td>
<td>0.28</td>
<td>12.4±1.8</td>
</tr>
<tr>
<td>4</td>
<td>07/02/2009</td>
<td>12</td>
<td>3059</td>
<td>0.51</td>
<td>17.3±1.4</td>
</tr>
<tr>
<td>5</td>
<td>01/06/2010</td>
<td>10</td>
<td>2738</td>
<td>0.45</td>
<td>19.4±2.0</td>
</tr>
<tr>
<td>6</td>
<td>12/05/2010</td>
<td>6</td>
<td>1576</td>
<td>0.26</td>
<td>18.3±1.9</td>
</tr>
<tr>
<td>7</td>
<td>19/05/2010</td>
<td>6</td>
<td>1452</td>
<td>0.24</td>
<td>9.1±0.6</td>
</tr>
<tr>
<td>8</td>
<td>12/04/2011</td>
<td>5</td>
<td>1311</td>
<td>0.22</td>
<td>10.7±1.2</td>
</tr>
<tr>
<td>9</td>
<td>27/07/2011</td>
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<td>11.7±0.5</td>
</tr>
<tr>
<td>10</td>
<td>07/11/2011</td>
<td>4</td>
<td>1099</td>
<td>0.18</td>
<td>15.6±1.2</td>
</tr>
<tr>
<td>11</td>
<td>05/03/2012</td>
<td>2</td>
<td>542</td>
<td>0.09</td>
<td>18.2±0.4</td>
</tr>
<tr>
<td>Mean</td>
<td>-</td>
<td>≈7</td>
<td>1738</td>
<td>0.29</td>
<td>14.4±1.3</td>
</tr>
</tbody>
</table>

\(a\)Insufficient ion data to calculate reliable plasma pressure inside events.
Figure 3 shows maps of the events in the SWM coordinate system. Figure 3a shows the $x$-$y$ plane and Figure 3b the $y$-$z$ plane. For comparison, Figure 3c shows a map of PVO ionospheric holes in SWM coordinates reproduced from Marubashi et al. [1985]. The colored lines correspond to the locations of the events. We observe a clear grouping and spatial separation between events in that tailward (red, $-B_x$) enhancements are found toward the $+y$ hemisphere and sunward (blue, $+B_x$) events toward the $-y$ hemisphere. This is exactly as would be expected for a draping of IMF field lines, consistent with PVO observations of ionospheric holes (shown below in Figure 3c). The only exception, event №9, was associated with a significant ($86^\circ$) shift in IMF clock angle between inbound and outbound solar wind measurements. Thus, the location of this outlier is suspected to be erroneous.

4. Discussion

Our search uncovered 11 events consistent with all known properties of the PVO ionospheric holes:

1. There is an unambiguous localized enhancement in magnetic field, the main component being $\pm B_x$.
2. There is a concurrent decrease in electron flux and ion density.
3. The location and polarity of the magnetic enhancements are consistent with draping of the interplanetary magnetic field, consistent with Marubashi et al. [1985] and Luhmann and Russell [1992].
4. The events are strongly dominated by enhanced magnetic pressure, with $\beta < 0.01$, consistent with Brace et al. [1982].
5. The depleted plasma within the events is composed of cold ionospheric outflow, consistent with Hartle and Grebowsky [1990].

Thus, we conclude that ionospheric holes extend much further into the tail than previously encountered. The ionospheric holes encountered by Pioneer Venus Orbiter were of longitudinal extents between 600 and 1800 km.
with a proportional correlation between stronger solar wind dynamic pressure and larger physical size [Mahajan and Oyama, 2001; Hoegy and Grebowsky, 2010]. The fourth column of Table 1 shows the spatial extent (perpendicular to the Sun-Venus line) of the 11 new events encountered by the Venus Express. With only a single spacecraft, it is very challenging to determine their shape or whether Venus Express was crossing at the widest point or merely clipped the edge. This, combined with the limited statistics of this survey, makes accurate qualitative comparisons with the sizes of holes reported in the ionosphere by PVO very challenging. However, we observe that the mean size (1738 km) is large when compared to those observed in the ionosphere, and furthermore, three of the 11 events (Nos. 1, 4, and 5) were much larger (~3000 km) than those reported by PVO. In addition to their larger size, the magnetic enhancements associated with holes are weaker in the tail (mean of ~14.4 nT, see Table 1, versus 20–30 nT). As a first-order test to examine whether magnetic flux is conserved in the holes from the ionosphere into the tail, we can use the known values for the maximum size of holes in the ionosphere ($R_1 = 1800$ km), and the mean field strengths in the ionosphere ($B_1 \approx 28$ nT) and ionotail ($B_2 \approx 14$ nT), to predict the maximum size of the hole in the tail ($R_2$), according to flux conservation equation (3).

$$R_2 = R_1 \sqrt{\frac{B_1}{B_2}} = 1800 \sqrt{\frac{28}{14}} \approx 2.5 \times 10^3 \text{ km}$$

Given the many assumptions made and that the size of the holes is poorly constrained, this is not inconsistent with the measured value of $3 \times 10^3$ km, and thus we conclude that our observations are consistent, to the first order, with the conservation of magnetic flux inside the holes in the ionosphere and tail.

4.1. On the Scarcity of Ionospheric Holes Identified in the Tail

Ionospheric holes were only observed by PVO when surrounded by a dense, high beta (i.e., low $|B|$) nightside ionosphere. Holes were observed frequently during the first 3 years of the mission, during which time the periapsis was actively maintained at ~150 km. After 3 years, such maneuvers were not possible due to lack of propellant, and periapsis drifted to 2300 km (above the nightside ionosphere) due to solar gravitational perturbations. During the late mission preentry phase where PVO again sampled the nightside ionosphere, conditions were low density, chaotic, and disturbed with no evident hole crossings, resembling the “disturbed” nightside ionospheres encountered in the early mission phase [e.g., Cravens et al., 1982]. The absence of holes in this later phase is in apparent contradiction to the first 3 years of the mission, when statistical analysis by Hoegy and Grebowsky [2010] suggested that they were always present (although not necessarily encountered on every orbit). Given that Marubashi et al. [1985] reported numerous instances of magnetic flux tubes without attendant plasma depletions, we posit that whilst the flux tubes may indeed be always (or at least commonly) present, a detectable plasma hole will not form in the ionosphere unless local conditions are conducive to do so. Whilst ionospheric holes were a common and persistent feature during the first 3 years of the Pioneer Venus Orbiter mission, only 11 events have been unambiguously identified in Venus Express data. In this section we describe our investigation into this disparity.

4.1.1. Solar Cycle

One difference between the two missions is that whilst all PVO ionospheric holes were observed during solar maximum, the arrival of Venus Express in 2006 coincided with solar minimum, and thus the Sun was dimmer. Solar irradiance is important for ionospheric processes because, broadly speaking, we would expect that the dimmer the Sun, the lower the photoionization rates in the dayside ionosphere, which will reduce the density and thus the conductivity of the ionosphere.

To investigate whether or not there is a correlation between the brightness of the Sun and encountering an ionospheric hole, it is first necessary to consider which wavelengths will be important to photoionization of the Cytherian ionosphere. The primary constituent of the neutral atmosphere is CO$_2$, and the primary constituent of the ionosphere is O$. Figure 4 shows photo cross sections for CO$_2$, O$_2$, and O as calculated by Huebner and Mukherjee [2011]. It can be seen that the wavelengths with the highest cross sections (and thus the most effective in photo dissociation) are all in the ultraviolet spectrum, with a peak of $\approx 10^{-17}$ cm$^{-2}$ at $\approx 50$ nm for all species and another at $\approx 140$ nm for O$_2$. Unfortunately, there is no solar EUV flux monitor at Venus, and so to get a first-order estimate of the relative intensity of these wavelengths on any given day, we are forced to use data taken near the Earth.

Figure 5a shows daily averages of solar irradiance over the course of the Venus Express mission from three separate instruments: (1) 0.1–50 nm from NASA’s Solar and Heliospheric Observatory (SOHO) Solar Extreme...
Photoionization cross sections for CO₂, O₂, and O, from Huebner and Mukherjee [2011], showing the three solar ultraviolet wavelengths analyzed in this study.

Figure 5. (a) Daily average solar irradiance from 2006 to 2013 in three wavelength bands, 0.1–50 nm from SOHO SEM, the 39.5 nm band from SORCE XPS, and the 145.5 nm band from SORCE SOLSTICE. (b) Histograms of solar irradiance during the Venus Express mission. Conditions on the days on which holes were encountered are marked in gold.
we note that no holes were observed when the solar wind was faster than (> 485 km/s). This is qualitatively consistent with Hoegy and Grebowsky [2010], whose statistical study of ionospheric holes observed by PVO found that the holes disappeared at higher solar wind dynamic pressures as the nightside ionosphere became increasingly disturbed.

4.1.3. Background Ionotail Field Strength

This study deliberately set very strict event selection requirements, such that candidate events had to manifest identically to those observed by PVO in the ionosphere. In particular, it was required that the magnetic magnitude ($|B|$) within the event must represent an unambiguous enhancement with respect to the background $|B|$ in the rest of the tail. Figure 7 shows a histogram of all magnetic observations from the tail of Venus between 2006 and 2012. The mean field strength was 11 nT. Note that this is very comparable with $|B|$ inside each of the 11 holes (shown in gold), the mean of which was $14.4 \pm 1.3$ nT. The region in purple shows the range of field strengths immediately outside of each of the 11 events. In all cases, the background tail field strength was much lower than normal, with a mean of $4.72 \pm 2.3$ nT, corresponding to the bottom 13% of the histogram (although this is less obvious from Figure 7 due to the logarithmic scale).

We posit that this explains the disparity in the frequency of observations of holes between PVO and Venus Express: In the ionosphere it is common for there to be large difference between the magnetic pressure inside and outside of the magnetic flux tubes. The field strengths ($|B|$) inside the holes encountered by PVO in the ionosphere were between 10 nT and 50 nT, which is significantly higher than the mean ionospheric background field of $<10$ nT [Luhmann and Russell, 1992]. Thus, no special ionospheric conditions are required for a hole in the ionosphere to create a substantial localized enhancement in magnetic pressure. This enhancement in magnetic pressure drives a reduction in plasma pressure, manifesting as an ionospheric hole.

However, in the ionotail, only under rare conditions is there a significant difference between the magnetic pressure inside and out. Thus, distinct plasma holes (depletions) do not usually survive to higher altitudes: Typically the magnetic pressure within the associated flux tubes is in equilibrium with their surroundings; there is no depletion in local plasma density, and thus the flux tubes are indistinguishable from the rest of the tail. However,
when the background field in the tail is suppressed below ~8 nT, then the ~14 nT magnetic fields within the holes drive an observable decrease in local plasma density, and the holes become visible. This is qualitatively consistent with the global picture presented by Brace et al. [1987], where the holes expand into the tail, ultimately becoming indistinguishable from the rest of the wake. Several mechanisms were observed to suppress the background magnetic field and thus render the holes visible to Venus Express: firstly, calm solar wind conditions, such as event № 7, and secondly, the enhancement of plasma pressure in the tail due to the penetration of hot sheath-like ions into the wake.

4.2. The Origin of Ionospheric Holes
Numerous theories have been put forward over the last three decades to attempt to explain the origin of the magnetic enhancements underlying ionospheric holes. To date, whilst many ideas have been suggested [e.g., see Luhmann and Russell, 1992; Hoegy and Grebowsky, 2010, and references therein], open questions remain and no consensus has been reached on the origin of ionospheric holes. Whilst closure on this question is outside the intended scope of this study (and a topic for future investigation), in this section we use collected Venus Express and PVO observations to eliminate one existing theory and briefly discuss two other possible mechanisms.

4.2.1. Elimination of “Ionospheric Channel” Theory
Perez-de-Tejada [2004] suggested a possible mechanism whereby the holes form as a result of the erosion of the ionosphere by the solar wind. In this theory, the solar wind impacts and strips away the ionosphere through momentum transfer at the magnetic “poles” (in SWM coordinates: \(x, y = 0; |z| > \pm 1R_V\)), resulting in “channels” of heated, low-density plasma extending tailward from the poles. If this were the case, then ionospheric holes should contain thermalized \(\approx\) keV solar wind protons. An example of such a population can be seen in the proton spectrogram of Figure 2h, when Venus Express was crossing through the sheath (red on the timeline, Figure 2e). However, the only plasma population evident within the holes is normal cold \(\approx 20\) eV ionospheric outflow (gold on the timeline). We found no evidence for an additional \(\approx\) keV solar wind population, and no difference in the peak energy of the ionospheric outflow, contrary to the Perez-de-Tejada [2004] solar wind erosion theory. Additionally, this theory implies that the stronger the solar wind dynamic pressure, the more frequently holes should be observed. However, this is not the case (see Figure 6c). We thus conclude that this theory is not consistent with our observations and should be discounted as a formation mechanism for ionospheric holes. We do not exclude the possibility that such a process may occur at Venus as a distinct and separate phenomenon and is a topic for future investigation.

4.2.2. Pileup of Dayside to Nightside Ionospheric Flow
One possible formation mechanism which would permit penetration of the magnetic flux tubes below the ionosphere is if the holes are a magnetic pileup boundary in the nightside ionosphere. At Venus, ionospheric plasma flows from the day to night across the terminator [Brace et al., 1983]. Thus, we speculate that a magnetic pileup may occur between this inflow from the dayside and the plasma in the tail, as sketched in Figure 8a. The resulting magnetic enhancements are not shielded by the ionosphere and penetrate, making contact with the surface. A historical example of such an ionospheric pileup theory was presented by Grebowsky et al. [1983], who suggested that holes could result from the transition from high-\(\beta\) dayside plasma to low-\(\beta\) nightside plasma. When \(\beta = 1\), magnetic pressure dominates, shutting off the day-to-night flow and resulting in a sunward/antisunward pileup layer.

As solar wind dynamic pressure increases, day-to-night flow becomes disturbed, ultimately resulting in a “disappearing” (i.e., absent) ionosphere [Cravens et al., 1982], where the density is significantly depleted throughout the nightside. Thus, if the holes are a result of the pileup of this flow, then they should disappear when it shuts off at higher solar wind dynamic pressures. There are two such observations possibly consistent with this picture: firstly, from this study, the absence of holes when the solar wind velocity was > 485 km/s (see Figure 6a) and secondly, the correlation between increasing solar wind dynamic pressure and decreasing frequency of observation of holes by PVO [Hoegy and Grebowsky, 2010]. Both these studies only counted an event as a hole when there was both a magnetic enhancement and a local plasma depletion. However, it is difficult to detect an unambiguous localized plasma depletion when the global density is already virtually nil. Thus, given the selection criteria of these studies, it is perhaps unsurprising that no holes were observed during these conditions, and thus, this correlation may be due to sampling bias.

4.2.3. IMF Internal Draping Around a Planetary Core
Finally, we briefly speculate on an alternate theory that would explain the PVO observations of the apparent emergence of enhanced draped IMF from below the ionosphere. A sketch of the hypothesis is presented
Figure 8. Sketch showing two theories to try and explain the formation of ionospheric holes. (a) Theorized pileup between day-to-night flow of ionospheric plasma and tail plasma. (b) The theorized pileup of interplanetary magnetic field at the core/mantle boundary, resulting in the formation of enhanced magnetic flux tubes, which under favorable nightside conditions results in localized plasma depletion.

in Figure 8b. This new theory requires three assumptions. Firstly, let us assume that, as predicted in hybrid modeling by Lipatov [1978, 2002] and from PVO observations under high solar wind dynamic pressure by Luhmann [1991], the ionosphere is sufficiently resistive that the IMF may penetrate to the surface and interior and can induce a signal deep inside the planet. Secondly, let us assume that Venus, like Earth, is a highly differentiated planet with a rocky mantle and conductive metallic core (as predicted by radial density modeling by Zharkov [1983] and Phillips and Malin [1983]). Thirdly, let us assume that having reached the surface, the IMF penetrates the crust and rocky mantle, just as it passes through the lunar mantle [e.g., Kivelson and Russell, 1995; Halekas et al., 2011, and references therein].

Thus, assuming that the ionosphere, atmosphere, crust, and mantle are sufficiently “transparent,” for the advection of the IMF to induce a current in the core, the result is a secondary pileup of IMF at the subsolar core boundary, producing a pair of oppositely polarized draped IMF flux tubes that emerge radially from the surface. Under the right ionospheric/ionotail conditions, the magnetic pressure inside these flux tubes drives a decrease in plasma pressure, resulting in an ionospheric hole. Again, this is purely speculative, and the origin of the magnetic structures underlying the holes remains at topic for future research.

One issue with this theory is that it requires the IMF to induce a signal deep inside the planet under a wide range of solar wind dynamic pressures (Figure 6c) and under normal solar EUV fluxes (Figure 5). It is well known that when solar wind dynamic pressure becomes high enough to overcome ionospheric thermal
pressure the ionosphere becomes magnetized [e.g., Elphic et al., 1980], and it is highly plausible that the IMF can reach the surface with a nonzero component [e.g., Luhmann [1991] briefly speculated a possible connection between the penetration of IMF to the surface and interior and the fields within the holes but did not elaborate further]. However, at present it is unclear whether this is possible under low dynamic pressures when the ionosphere is not magnetized. In particular, two different models, each with their own limitations, have come to opposite conclusions on this question. Hybrid modeling by Lipatov [1978, 2002] suggested that magnetic diffusion was possible under such conditions but did not treat the ionosphere self-consistently. Ma et al. [2013] (which did treat the ionosphere self-consistently) suggested that this was only possible under high solar wind dynamic pressures but was a single-fluid MHD model and thus could not take into account ion-scale effects. At present the assumption of magnetic diffusion under normal solar wind conditions is the biggest challenge to this theory and is thus an important question for future study.

Both the dayside-to-nightside flow pileup and internal draping hypotheses are consistent with the following observations: (1) the apparent emergence of paired magnetic flux tubes from below the ionosphere implied by PVO observations; (2) the location and magnetic polarity (one sunward and the other tailward) of these flux tubes is controlled by the orientation of the IMF (see section 3.2); (3) the order of magnitude increase in magnetic pressure and the low plasma $\beta$ observed by Venus Express (see Table 1); and (4) the magnetic enhancements encountered by the Venus Express ($|B| \approx 14.4 \text{nT}$) are much weaker than those encountered by PVO ($|B| \approx 20–30 \text{nT}$ and as high as 50 nT), consistent with a magnetic pileup where magnetic enhancement is stronger closer to the subsolar point.

5. Conclusions

We reported 2006–2012 Venus Express observations of a rare phenomenon in the ionotail of Venus, consistent with the holes observed in the ionosphere during solar maximum by the 1978–1992 NASA Pioneer Venus Orbiter. We thus show their extension to much higher altitudes (1.2 to 2.4 $R_V$) than previously encountered and that they may be observed throughout the solar cycle and over a wide range of solar wind conditions. The magnetic enhancements were weaker in the tail than those encountered by PVO in the ionosphere, and the flux tubes reached a greater size, consistent with flux conservation. Holes only survive to these high altitudes when the background field in the tail is unusually weak (4.7$\pm$2.3 nT, or $\approx 13\%$ of the time) and are indistinguishable from the surrounding ionotail under typical conditions, consistent with the global picture suggested by [Brace et al., 1987].

All observations are consistent with an encounter with a magnetic structure embedded within the tail: (1) With the exception for a decrease in flux, ASPERA-IMA observed that the plasma inside and outside of the holes have the same spectral signature of cold ionospheric outflow. There is no change in the peak energy and no significant increase in keV particles or any additional plasma populations. This suggests that the attendant plasma depletion is in response to (and being driven by) the magnetic enhancement and not vice versa. (2) Within the limited statistics available, the expansion of the holes into the tail appears consistent with a conservation of magnetic flux. (3) As established by Marubashi et al. [1985], the location and polarity of the fields within our 11 events are controlled by IMF orientation. (4) The unambiguous dominance of magnetic pressure is consistent with Brace et al. [1982], with mean internal plasma $\beta$ of $3.3\times10^{-3}$.

We therefore conclude that the plasma depletions associated with ionospheric holes are only a manifestation of deeper underlying phenomena: tubes of enhanced draped IMF, emerging in pairs from below the very lowest altitudes probed by PVO and stretching far down the tail, consistent with the Luhmann and Russell [1992] flux tube interpretation. This lays a firm foundation for future studies of this phenomenon, wherein the strict event selection criteria set for this survey could be relaxed to not require that the magnetic structure manifest all the plasma signatures of the PVO ionospheric holes.

We considered three possible formation mechanisms for ionospheric holes. First is the Perez-de-Tejada [2004] “ionospheric channel” theory, which we now discount on the grounds of its inconsistencies with ASPERA-IMA observations. Second is the magnetic pileup due to stagnation of ionospheric flow and, finally, a secondary pileup of IMF inside the planet around a conductive metallic core. At present the formation mechanism for the magnetic structures associated with ionospheric holes remains an open question for further study. Both draping mechanisms provide strong motivation for future modeling and data analysis.
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