



This is a repository copy of *A statistical study of ionospheric boundary wave formation at Venus*.

White Rose Research Online URL for this paper:  
<http://eprints.whiterose.ac.uk/134525/>

Version: Accepted Version

---

**Article:**

Chong, G.S., Pope, S.A. [orcid.org/0000-0001-8130-4222](https://orcid.org/0000-0001-8130-4222), Walker, S.N. et al. (3 more authors) (2018) A statistical study of ionospheric boundary wave formation at Venus. *Journal of Geophysical Research: Space Physics*, 123 (9). pp. 7668-7685. ISSN 0148-0227

<https://doi.org/10.1029/2018JA025644>

---

**Reuse**

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



[eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk)  
<https://eprints.whiterose.ac.uk/>

# A statistical study of ionospheric boundary wave formation at Venus

Ghai Siung Chong<sup>1</sup>, Simon A. Pope<sup>1</sup>, Simon N. Walker<sup>1</sup>, Rudy A. Frahm<sup>2</sup>, Tielong Zhang<sup>3,4</sup>,  
Yoshifumi Futaana<sup>5</sup>

<sup>1</sup>ACSE, University of Sheffield, Sheffield, UK.

<sup>2</sup>Southwest Research Institute, San Antonio, Texas, USA.

<sup>3</sup>Harbin Institute of Technology, Shenzhen, China.

<sup>4</sup>Space Research Institute, Austrian Academy of Sciences, Graz, Austria.

<sup>5</sup>Swedish Institute of Space Physics, Kiruna, Sweden.

## Key Points:

- The ionospheric boundary is not always smooth. It is often observed to exhibit a wavelike appearance.
- Characteristics of the boundary wave are consistent with a Kelvin-Helmholtz Instability induced wave.
- Draping patterns of magnetic field lines set up favorable conditions for boundary wave excitation.

---

Corresponding author: Ghai Siung Chong, [gschong1@sheffield.ac.uk](mailto:gschong1@sheffield.ac.uk)

## Abstract

Previous missions to Venus have revealed that encounters with plasma irregularities of atmospheric origin outside the atmosphere are not uncommon. A number of mechanisms have been proposed to discuss their origins as well as their roles in the atmospheric evolution of Venus. One such mechanism involves an ionopause with a wavelike appearance. By utilizing the magnetic field and plasma data from Venus Express (VEX), we present the first observational statistical analysis of the ionospheric boundary wave phenomena at Venus using data from 2006 to 2014. Results from the minimum variance analysis of all the photoelectron dropout events in the ionosphere reveal that the ionopause of Venus does not always appear to be smooth, but often exhibits a wavelike appearance. In the northern polar region of Venus, the normal directions of the rippled ionospheric boundary crossings lie mainly in the terminator plane with the largest component predominantly along the dawn-dusk ( $Y_{VSO}$ ) direction. The average estimated wavelength of the boundary wave is  $212 \pm 12$  km and the average estimated velocity difference across the ionopause is  $104 \pm 6$  km/s. The results suggest that the rippled boundary is a result of Kelvin-Helmholtz Instability. Analysis reveals a correlation between the normal directions and the locations of the boundary wave with respect to Venus. This indicates the draping of magnetic field lines may play a role in enhancing the plasma flow along the dawn-dusk direction, which could subsequently set up a velocity shear that favors the excitation of ionospheric boundary wave by the KHI along the dawn-dusk direction.

## 1 Introduction

Due to the absence of an intrinsic magnetic field [Russell *et al.*, 1980; Luhmann and Russell, 1997], the solar wind interaction with Venus is highly dynamic. The Venusian ionopause, which is a boundary separating the shocked solar wind plasma and ionospheric plasma, is subjected to a number of plasma instabilities. The two main instabilities are the Rayleigh-Taylor Instability (RTI) (also known as the Interchange Instability [Arshukova *et al.*, 2004]) and the Kelvin-Helmholtz Instability (KHI). The Interchange Instability only grows when there is a non-monotonic plasma pressure gradient at the subsolar region [Arshukova *et al.*, 2004]. The KHI is a macroinstability that is principally generated by the strong shear flows across a boundary [Chandrasekhar, 1961] and is an important mode of energy transfer at Venus [Futaana *et al.*, 2017]. Important factors to the generation of KHI waves include the velocity, density and temperature gradients [Amerstorfer *et al.*, 2007;

49 *Amerstorfer et al.*, 2010; *Ferrari et al.*, 1982; *Huba*, 1981; *Biernat et al.*, 2007; *Wolff et al.*,  
 50 1980; *Price*, 2008]. Even though the KHI is considered the more dominant instability for  
 51 wave excitation, there are occasions when terms such as the magnetic field stress, gravity,  
 52 and boundary curvature are more significant, and can give rise to other instabilities, for  
 53 example the RTI or flute instability [*Elphic and Ershkovich*, 1984].

54 This wavelike appearance of the ionopause is an important characteristic of Venus  
 55 and plays a significant role in its atmospheric evolution. For instance, when the Venu-  
 56 sian ionospheric boundary is excited by the KHI, the boundary wave can grow, become  
 57 nonlinear and subsequently reach a turbulent phase with non-regular structures [*Amer-  
 58 storfer et al.*, 2010]. The vortices formed in the turbulent phase can eventually break up  
 59 to create “atmospheric bubbles” (sometimes referred to as “plasma clouds”) [*Brace et al.*,  
 60 1982; *Wolff et al.*, 1980; *Thomas and Winske*, 1991]. These bubbles of atmospheric plasma  
 61 will be convected downstream together with the solar wind bulk flow. At the same time,  
 62 magnetic “flux ropes” [*Russell*, 1990] can also be formed and scattered within the iono-  
 63 sphere [*Wolff et al.*, 1980]. The estimation of the ion loss rate due to the convection of  
 64 atmospheric bubbles is of the order of  $10^{26}$  ions  $s^{-1}$  [*Brace et al.*, 1982; *Amerstorfer et al.*,  
 65 2010] which is higher than the rate of pick up  $\approx 10^{25}$  ions  $s^{-1}$  [*Lammer et al.*, 2006] and  
 66 sputtering processes  $\approx 10^{24}$  ions  $s^{-1}$  [*Luhmann and Kozyra*, 1991]. It is widely accepted  
 67 that the detachment of plasma clouds resulting from ionospheric boundary surface waves  
 68 is one of the principal atmospheric loss processes at Venus [*Lammer et al.*, 2006; *Wolff  
 69 et al.*, 1980; *Svedhem et al.*, 2007a; *Elphic et al.*, 1980]. Other atmospheric escape mech-  
 70 anisms operating at Venus include the thermal escape (or Jeans escape) [*Jeans*, 1955;  
 71 *Chamberlain*, 1963], photo-dissociation [*McElroy et al.*, 1982; *Rodriguez et al.*, 1984], ac-  
 72 celeration due to the  $\mathbf{J} \times \mathbf{B}$  force [*Russell*, 1986] and ionospheric holes [*Hartle and Gre-  
 73 bowsky*, 1993].

74 The concept of ionospheric boundary waves at Venus has long been studied in a  
 75 number of model simulations. *Wolff et al.* [1980] showed that the ionospheric boundary  
 76 is unstable to KHI and illustrated the formation of flux ropes and atmospheric bubbles  
 77 as a result of the ionospheric surface wave. *Terada et al.* [2002] used a two-dimensional  
 78 global hybrid model to investigate the KHI at Venus and showed that the ionopause in the  
 79 subsolar region is unstable to KHI. *Biernat et al.* [2007] studied the growth of the KHI  
 80 at the Venusian ionopause and found that KHI can evolve regardless of the solar wind  
 81 conditions. *Amerstorfer et al.* [2010] and *Amerstorfer et al.* [2007] showed that a density

82 increase can influence the growth rate of KHI and characterized the evolution of the KHI  
83 into three main phases, i.e. linear, nonlinear and turbulent phases. However, *Möstl et al.*  
84 [2011] showed that the ionopause is not able to reach the nonlinear vortex phase during  
85 either low or high solar activity due to the stabilizing density jump across the ionopause.  
86 In addition to Venus, the development of the KHI has been studied at other planets, in-  
87 cluding Mars [*Penz et al.*, 2004], Mercury [*Sundberg et al.*, 2010], Earth [*Nykyri and Otto,*  
88 2001], Saturn [*Masters et al.*, 2009] and so on.

89 The continuous process of plasma loss resulting from ionospheric boundary wave  
90 events over a prolonged period of time plays a significant role in contributing to atmo-  
91 spheric loss at Venus. However, observational studies are rather limited and only short  
92 periods of Pioneer Venus Orbiter (PVO) data (one to two orbits of data) have been uti-  
93 lized. Using PVO data, *Luhmann* [1990] reported one of the earliest observations of an  
94 ionospheric boundary wave which is interpreted as the “terminator wave”, based on the  
95 significant field behavior change within  $15^\circ$  of the terminator. The authors suggested a  
96 possible mechanism by the reverse orientation of the Interplanetary Magnetic Field (IMF)  
97 in the ionosphere and suggested its association with the formation of flux ropes. *Brace*  
98 *et al.* [1980] observed wavelike structures and interpreted them as PVO passing through  
99 the ionospheric surface wave, which can be due to the altitude changes of the Venusian  
100 ionopause. *Brace et al.* [1983] reported trans-terminator ionospheric waves into the night-  
101 side and suggested a potential wave energy by the plasma pressure gradient driven inter-  
102 change instabilities or the ion-neutral drag driven shear instabilities. *Walker et al.* [2011]  
103 and *Pope et al.* [2009] suggested that nonlinear vortex-like structures observed in the mag-  
104 netosheath region using Venus Express (VEX) magnetic field data were associated with  
105 the strong shear flow across the ionopause. However, the altitudes of these observations  
106 are not consistent with the nominal ionopause altitude. *Chong et al.* [2017] presented ev-  
107 idence for the ionospheric boundary exhibiting a wavelike appearance for a single VEX  
108 pass along the terminator.

109 To study the dynamics and characteristic distributions of the ionospheric boundary  
110 wave on Venus, a statistical analysis is conducted in this paper. Analysis of the avail-  
111 able magnetic field and plasma data from the instruments on board of VEX from 2006  
112 to 2014 reveals that the observations of such phenomena are not uncommon. Investigation  
113 of boundary wave formation is fundamental to our understanding of the atmospheric loss  
114 mechanisms operating and hence the atmospheric evolution of Venus and unmagnetized

115 planets in general. The paper is structured as follows: The instrumentation is summarized  
 116 in Section 2; The observations and data analysis of the ionospheric boundary wave are  
 117 presented in Section 3; The characteristics of the boundary wave and its possible genera-  
 118 tion mechanisms are discussed in Section 4; The summary and conclusions are presented  
 119 in Section 5.

## 120 **2 Instrumentation: Venus Express**

121 VEX had an elliptical polar orbit with periapsis ranging from 130 to 463 km at a  
 122 latitude of about  $78^\circ\text{N}$ . The apoapsis distance was around 66,000 km and VEX had an or-  
 123 bital period of 24 hours [Titov *et al.*, 2006; Svedhem *et al.*, 2007b]. The magnetic field was  
 124 measured by the VEX Fluxgate Magnetometer (MAG) [Zhang *et al.*, 2006]. 1 Hz MAG  
 125 data are used for the statistical analysis in this paper. These data have been cleaned to re-  
 126 move the dynamic stray fields [Pope *et al.*, 2011] and corrected for offset [Leinweber *et al.*,  
 127 2008]. The data have been rotated into the Venus Solar Orbital (VSO) coordinate frame;  
 128 with  $+X_{VSO}$  in the Venus-Sun direction,  $+Y_{VSO}$  perpendicular to  $+X_{VSO}$  and in the direc-  
 129 tion of the orbital motion of Venus, and  $+Z_{VSO}$  is orthogonal to complete the right hand  
 130 set of axes.

131 The electron spectrometer (ELS) and ion mass analyser (IMA) are part of the Anal-  
 132 yser of Space Plasmas and Energetic Atoms (ASPERA-4) on board of VEX [Barabash  
 133 *et al.*, 2007]. ELS provides electron energy spectra in several modes, two of which is used  
 134 in this study: an electron spectrum between 0.9 eV to 15 keV is generated every 4 sec  
 135 with an approximate energy resolution ( $\Delta E/E$ ) of 7% (the energy resolution is energy and  
 136 sector dependent) and an electron spectrum between 9 eV to 250 eV is generated every 1  
 137 sec with an approximate energy of 7%. The ion measurements provided by the IMA cover  
 138 the energy range 0.01-36 keV/q with a sampling time of 192 seconds and an energy reso-  
 139 lution ( $\Delta E/E$ ) of 7%.

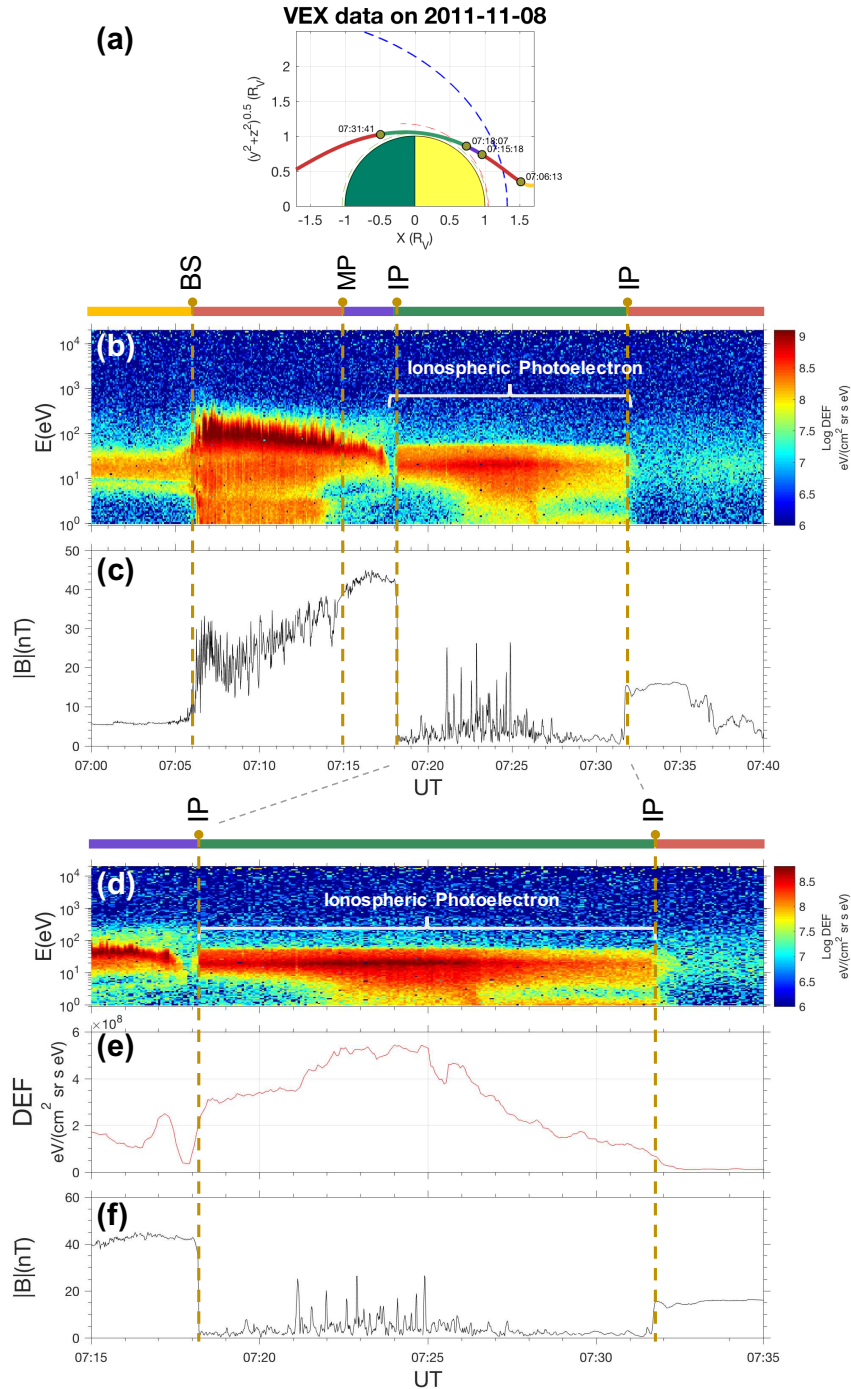
140 In contrast to PVO, which was able to sample the Venusian ionosphere in the sub-  
 141 solar region over the period of solar maximum, the high latitude elliptical polar orbit of  
 142 VEX provides an opportunity to study the dynamics of the Venusian ionosphere in the  
 143 northern polar region of Venus across nearly a full solar cycle with rather quiet solar ac-  
 144 tivity [Futaana *et al.*, 2017].

### 3 Observations and data analysis

#### 3.1 Photoelectron Dropouts

Figures 1 and 2 show the (a) VEX trajectory, (b) and (d) the electron energy-time spectrogram of differential energy flux, (c) and (f) the 1Hz magnetic field magnitude and (e) average electron energy flux at 22eV from VEX orbits on 08 Nov 2011 and 02 Oct 2011 respectively. Data in (e) is smoothed using a moving average filter of 7 data points. The location of the bow shock is highly variable due to the variations in the solar Extreme Ultraviolet (EUV), solar wind Mach number, and IMF orientation [Zhang *et al.*, 2008a]. Here the observed altitudes of the bow shock on both orbits are comparably different than the nominal bow shock locations [Zhang *et al.*, 2008a,b]. On the inbound leg of the orbit occurring on 08 Nov 2011, the bow shock was crossed at around 07:06 UT (at an altitude of 3395 km) with shocked solar wind appearing in the magnetosheath region around Venus. The broad energy intensity of these electron populations can be seen to become narrower towards the magnetic barrier at around 07:15 UT where the magnetic field magnitude increases until the inbound ionopause was crossed at around 07:18 UT. The ionosphere region is identified by the observation of the ionospheric photoelectron population at 21-24eV and at 27eV [Coates *et al.*, 2008; Cui *et al.*, 2011]. This can also be observed as an increase of the electron energy flux (averaged at ~22eV) in Figure 1(e). These photoelectron populations are mainly due to the photo-ionization of atmospheric oxygen by solar HeII 30.4 nm photons [Coates *et al.*, 2008]. VEX then crossed the ionopause and bow shock (not shown here) on its outbound pass, which can be similarly characterized as described above.

The VEX observations of the bow shock through to the magnetic barrier region on 02 Oct 2011 are similar to those on 08 Nov 2011. However, the behavior of the ionosphere on these two orbits are quite different. This is easily seen by comparing Figures 1(d) and 2(d). For instance, the ionospheric photoelectron population on 08 Nov 2011 is observed continuously within the ionosphere. In contrast, there were ten separate intervals when the ionospheric photoelectron population disappeared while VEX was in the ionosphere region on 02 Oct 2011. These will be termed “photoelectron dropout” events throughout this paper. These ten intervals of photoelectron dropouts can also be clearly reflected from the dips in the average electron energy flux at 22eV in Figure 2(e). The photoelectron dropout events on 02 Oct 2011 are not uncommon. After excluding the orbits where



167 **Figure 1.** An example of the crossing of an unmagnetized ionosphere with continuous observations of

168 ionospheric photoelectron population from 07:18 UT to 07:32 UT on 08 Nov 2011. (a) The VEX trajectory

169 plot in  $R_V$  (Venus radii) which is colored in yellow, red, purple and green respectively to show the differ-

170 ent regions (unshocked solar wind, magnetosheath, magnetic barrier and ionosphere) in which VEX was

171 passing. These regions are also reflected by the colored bar above Figure 1(b) and (d). The nominal alti-

172 tudes of bow shock (BS), induced magnetopause (MP) and ionopause (IP) represented using blue, red and

173 green dashed lines respectively [Zhang *et al.*, 2008a,b] are plotted in (a). The actual crossings of the bow

174 shock and ionopause are marked with golden circles and their respective times. (b) The electron energy-

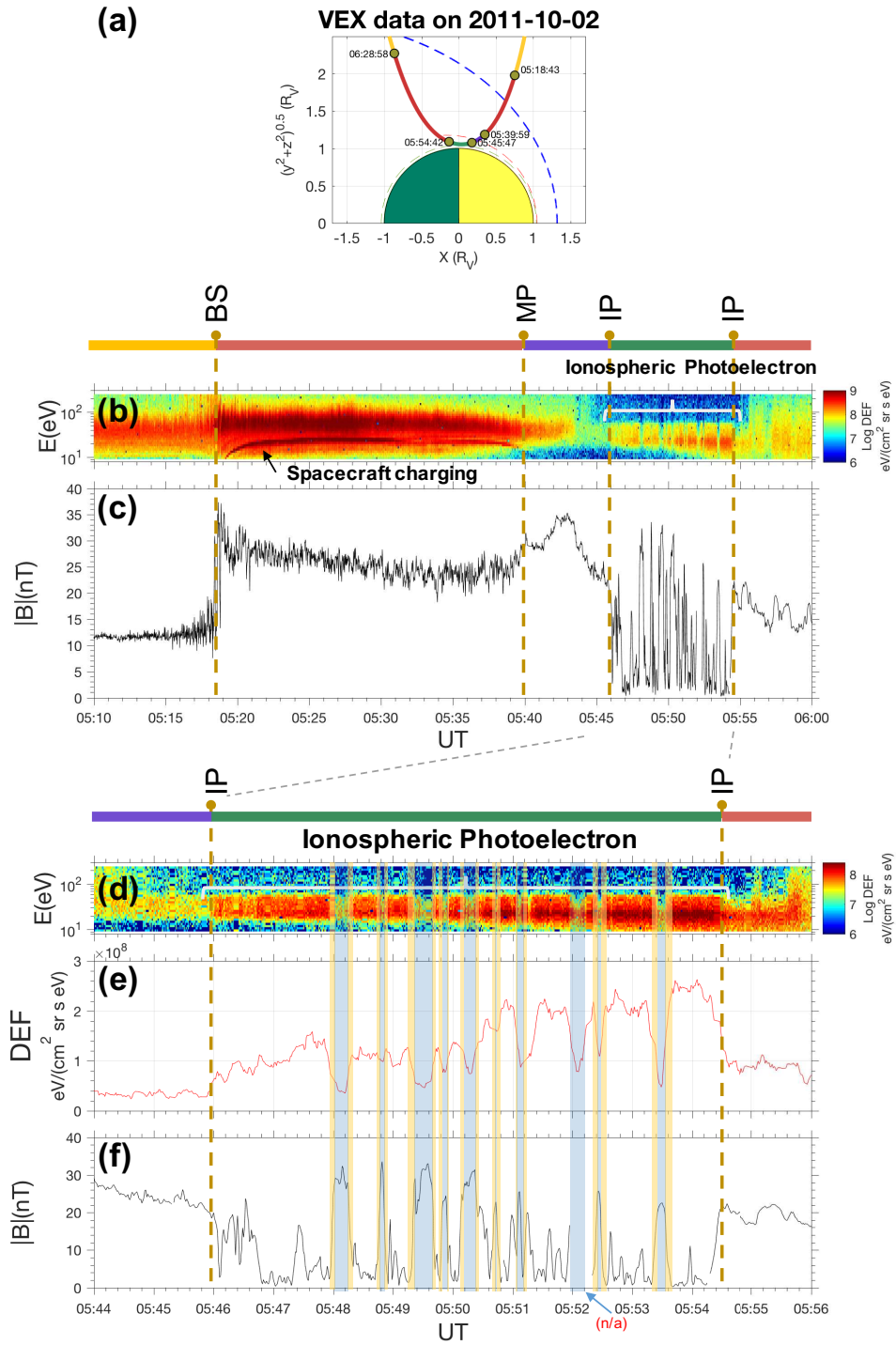
175 time spectrogram of differential energy flux and (c) 1-Hz magnetic field magnitude plots from 07:00 UT to

176 07:40 UT. Descriptions of (d) and (f) are same as (b) and (c) but from an expanded timescale 07:15 UT to

177 07:35 UT which focus mainly in the ionosphere region. (e) The average electron energy flux at 22eV (7-point

178 smoothed).





179 **Figure 2.** An example of an unmagnetized ionosphere perturbation with intervals of missing photoelectron  
 180 population (“photoelectron dropouts”) while VEX was still within the inbound and outbound ionopause on 02  
 181 Oct 2011. Description of the figure has the same format as Figure 1 and the ionosphere perturbation is from  
 182 05:46:00 UT to 05:54:30 UT. All ten photoelectron dropouts are shaded in blue. There is missing magnetic  
 183 field data in the photoelectron dropout interval labeled “n/a”. The yellow shaded regions correspond to the  
 184 dip-to-peak and peak-to-dip magnetic field fluctuations immediately adjacent to the photoelectron dropouts  
 185 regions.

196 the ELS and/or MAG data are unavailable when VEX was in the ionosphere, as well as  
 197 orbits when ionospheric photoelectron populations are not observed at all, around 23%  
 198 (495 orbits) show at least one or more intervals of photoelectron dropouts out of the re-  
 199 maining 2141 orbits from Apr 2006 to Nov 2014.

200 Throughout this study, the first observation of photoelectrons during an orbit is iden-  
 201 tified as the inbound ionopause crossing and the last observation of photoelectron popula-  
 202 tion is identified as the crossing of the outbound ionopause. The ionosphere is the region  
 203 between the inbound and outbound ionopause.

204 It can be seen from Figure 2 (apart from one interval labeled “n/a” which is associ-  
 205 ated with a gap in magnetic field data and which will be omitted from the following anal-  
 206 ysis), each of the nine blue-shaded photoelectron dropout intervals on 02 Oct 2011 cor-  
 207 respond to an increase in the magnetic field magnitude. Compared to the ionospheric re-  
 208 gions of low field magnitude, the larger magnetic field magnitude regions are comparable  
 209 to that observed in the magnetic barrier region just before the first ionopause crossing. In  
 210 addition, the electron energy intensity during the photoelectron dropout intervals are also  
 211 comparable to the intensity in the magnetic barrier region as seen from Figure 2(d) and  
 212 (e). Note that for the purposes of readability, the plot of average energy flux in Figure 2(e)  
 213 is 7-point smoothed. As a result, the presented energy fluxes of a couple of photoelectron  
 214 dropout intervals appear to be larger than the flux intensity in the magnetic barrier.

215 The occurrence of the photoelectron dropouts implies that while VEX was in the  
 216 ionosphere (where ionospheric photoelectron population should be constantly observed),  
 217 there were periods when VEX detected electron population similar to those in the mag-  
 218 netic barrier region. However, to travel from the magnetic barrier to the ionosphere region  
 219 or vice versa, VEX would be expected to cross the ionopause.

### 220 **3.2 Ionospheric boundaries crossings**

221 To assess if these photoelectron dropout events on 02 Oct 2011 relate to ionopause  
 222 crossings all of the 18 (yellow-shaded) regions adjacent to the periods in which photoelec-  
 223 tron dropout events were observed were investigated using Minimum Variance (MV) anal-  
 224 ysis [Sonnerup and Scheible, 1998]. MV analysis is implemented over the dip-to-peak and  
 225 peak-to-dip field fluctuations to determine if they are ionopause crossings. In the case that  
 226 they are boundary crossings, MV analysis is used to find the boundary normal directions.

**Table 1.** A summary of the results of the Minimum Variance Analysis applied to the Venus Express data from 02 Oct 2011 for all the photoelectron dropout intervals shown in Figure 2.

Time (UT)		MV Direction			$\lambda_{int}/\lambda_{min}$	$ B_n / B $	$ \Delta B / B $	$\theta_{B_n-B}$ (deg)	Data Point
From	To	X	Y	Z					
'05:47:56'	'05:48:03'	0.187	0.979	0.081	23.04	0.00	0.92	89.8	8
'05:48:15'	'05:48:21'	0.070	0.574	-0.816	5.07	0.01	0.74	89.3	7
'05:48:42'	'05:48:49'	0.096	0.956	-0.276	42.67	0.07	0.93	86.0	8
'05:48:49'	'05:48:55'	0.066	0.986	-0.156	1305.10	0.06	0.89	86.7	7
'05:49:15'	'05:49:22'	0.207	0.882	0.423	18.97	0.01	0.95	89.4	8
'05:49:35'	'05:49:42'	0.012	-0.607	0.795	10.54	0.01	0.68	89.6	8
'05:49:47'	'05:49:50'	0.369	0.868	-0.333	8.66	0.05	0.92	87.3	4
'05:49:53'	'05:50:50'	0.109	0.868	-0.485	92.38	0.14	0.89	82.2	8
'05:50:04'	'05:50:11'	0.142	0.942	0.303	34.09	0.00	0.93	89.8	8
'05:50:22'	'05:50:36'	0.177	0.866	-0.469	4.26	0.09	0.79	85.1	15
'05:50:37'	'05:50:42'	0.047	0.738	-0.674	50.77	0.14	0.89	81.8	6
'05:50:43'	'05:50:48'	0.070	0.989	0.129	10.01	0.10	0.63	84.2	6
'05:50:55'	'05:50:59'	0.324	0.839	0.438	32.14	0.12	0.86	83.3	5
'05:51:07'	'05:51:11'	0.111	0.960	0.258	31.27	0.10	0.76	84.2	5
'05:52:20'	'05:52:25'	0.083	0.778	-0.622	46.53	0.07	0.87	85.8	6
'05:52:27'	'05:52:34'	0.096	0.551	-0.829	3.50	0.02	0.91	89.0	8
'05:53:19'	'05:53:25'	0.260	0.472	-0.842	6.07	0.09	0.97	84.9	7
'05:53:33'	'05:53:39'	0.246	0.623	-0.743	10.46	0.03	0.89	88.1	7

Table 1 shows the components of the minimum variance directions in the VSO coordinate system, the intermediate-to-minimum eigenvalues ratio ( $\lambda_{int}/\lambda_{min}$ ), the ratio of average magnetic field component along the minimum variance direction ( $B_n$ ) to the larger field magnitudes on either side of the discontinuity ( $|B_n|/|B|$ ), the ratio of the change of the field magnitude to the field magnitude ( $|\Delta B|/|B|$ ), the angle between  $|B_n|$  and  $|B|$ ,  $\theta_{B_n-B}$  as well as the number of data points during the intervals analyzed.

The intermediate-to-minimum eigenvalues ( $\lambda_{int}/\lambda_{min}$ ) of all 18 intervals are greater than 3.5 which implies that the minimum variance direction is well defined. All the  $|B_n|/|B| < 0.14$  (mean value of 0.06) and  $|\Delta B|/|B| > 0.63$  (mean value of 0.86). These values are well within the criteria for tangential discontinuity;  $|B_n|/|B| < 4$  and  $|\Delta B|/|B| \geq 0.2$ , indicating that this boundary represents a tangential discontinuity [Knetter *et al.*, 2004, and references therein]. In addition, all the angles between  $|B_n|$  and  $|B|$ ,  $\theta_{B_n-B} > 81.8^\circ$  (mean value of  $86.5^\circ$ ) which is approximately  $90^\circ$  further indicating all of the nine intervals of photoelectron dropouts are bounded by tangential discontinuities, a typical characteristic of the Venusian ionopause [Wolff *et al.*, 1980].

The same approach is applied to all the dip-to-peak and peak-to-dip field fluctuations immediately adjacent to the intervals of photoelectron dropout identified across the full data set. Note that field magnitude in a magnetized ionosphere is similar to that observed in the magnetic barrier region, unlike for the unmagnetized case. Hence, for the orbits when photoelectron dropouts are observed, the dip-to-peak and peak-to-dip field fluctuations in a magnetized ionosphere cannot clearly be identified. This results in only 371 unique orbits (from a total of 495 events) selected for further analysis. In these 371 orbits, 1043 intervals of photoelectron dropouts are observed, hence 2086 field fluctuations. Since MV analysis is only valid with 3 or more data points, only 1633 field fluctuations (from a total of 2086) which have 6 or more data points are selected. Analysis conducted using more data points would result in smaller data sets, and less data points would result in a higher statistical uncertainty [Sonnerup and Scheible, 1998]. The resulting distributions of the boundary normal directions are similar using between 3 and 9 data points. The use of a minimum of 6 data points is chosen as a compromise between the number of data sets and the statistical uncertainty.

Around 98% (1603 out of 1633 intervals) of all the minimum variance directions have  $|B_n|/|B| < 0.4$  and  $|\Delta B|/|B| \geq 0.2$ , indicating boundaries of tangential discontinuity.

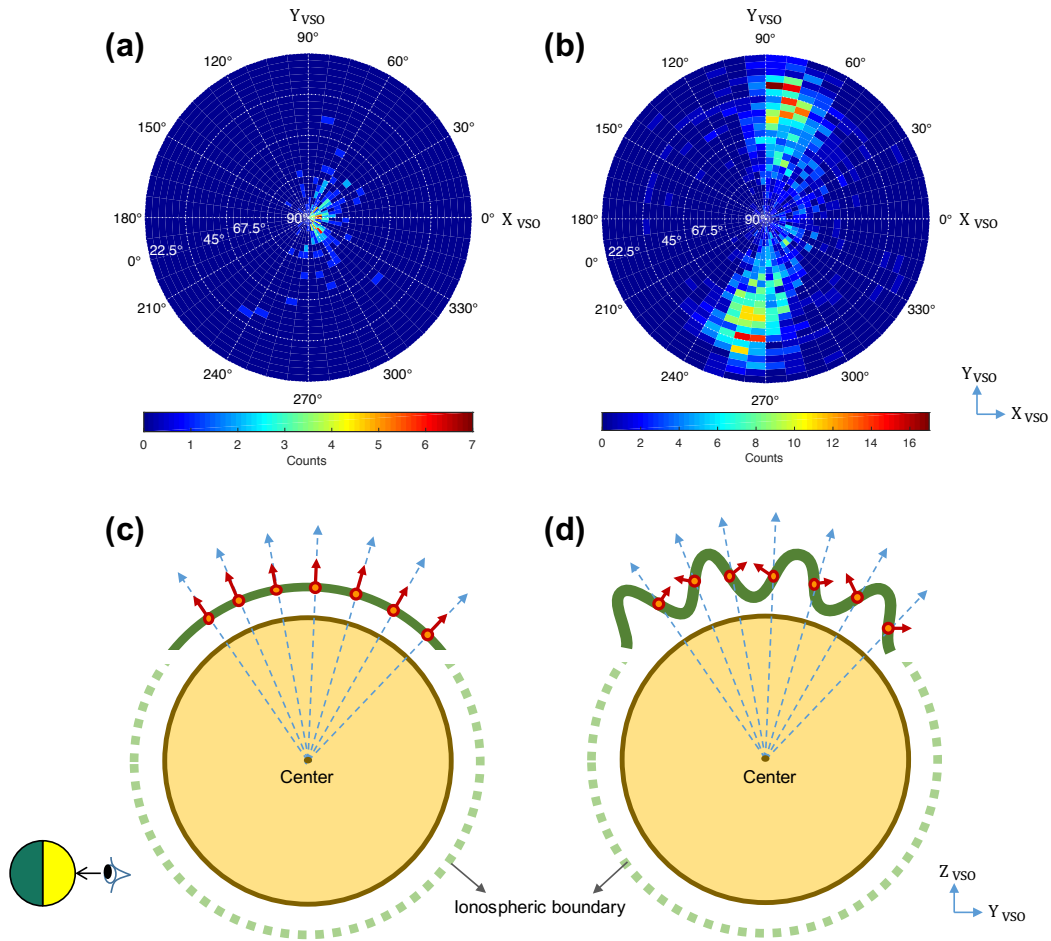
259 Similarly, around 95% (1562 out of 1633 intervals) have  $\theta_{B_n-B} > 75^\circ$  further indicating  
 260 that the analyzed intervals are tangential discontinuities. This is again consistent with the  
 261 characteristics of the Venusian ionopause [Wolff *et al.*, 1980]. Furthermore, more than 88%  
 262 (1446 out of 1633 intervals) have  $\lambda_{int}/\lambda_{min} \geq 3$ , which shows that the minimum variance  
 263 directions are well defined. These results imply that the multiple photoelectron dropout  
 264 events observed during each of these orbits, are due to VEX traversing the ionospheric  
 265 boundary multiple times. For example on 02 Oct 2011, VEX traversed through the iono-  
 266 spheric boundary 9 times on a single trajectory.

267 Moreover, the dip-to-peak and peak-to-dip field fluctuations occur on the time scale  
 268 of a few seconds. Since the decay of the magnetic field in the ionosphere is on a timescale  
 269 from minutes to several hours [Luhmann *et al.*, 1984], the possible scenario of VEX trav-  
 270 eled through patches of magnetized and unmagnetized regions of the ionosphere consecu-  
 271 tively can be ruled out.

### 272 3.3 Ionospheric boundary waves

287 In addition to the previous analysis, a total of 251 VEX passes with ionospheric  
 288 boundary crossings that are similar to the case presented on 08 Nov 2011 (no photoelec-  
 289 tron dropout) are collected. The criteria used to select these passes were (1) no obser-  
 290 vations of photoelectron dropout events, (2) only gradual ionospheric crossings without  
 291 magnetic intermediary and (3) clear passes from high field magnetic barrier to low field  
 292 unmagnetized ionosphere. Results of MV analysis of the ionospheric boundary show that  
 293 the minimum variance directions are very well defined with more than 96% (242 out of  
 294 251) of the directions having  $\lambda_{int}/\lambda_{min} \geq 3$ . The results also suggest that the crossings  
 295 are ionospheric boundary with more than 98% (247 out of 251) having  $\theta_{B_n-B} > 75^\circ$  and  
 296 around 100% (250 out of 251) having  $|B_n|/|B| < 0.4$  and  $|\Delta B|/|B| \geq 0.2$ .

297 All of the normal directions for the 238 (out of 251) ionopause crossings with  $\lambda_{int}/\lambda_{min} \geq 3$   
 298 and number of data points  $\geq 6$  are binned in a three dimensional polar statistical his-  
 299 togram with an azimuthal  $\phi$  bin size of  $7.5^\circ$  and elevation  $\alpha$  bin size of  $3.75^\circ$  in Fig-  
 300 ure 3(a).  $\phi$  and  $\alpha$  are the angles between the locational radial vector from the center of  
 301 the planet and the X-Z  $v_{SO}$  and X-Y  $v_{SO}$  planes respectively.  $\phi$  ranges from  $0^\circ$  to  $360^\circ$ .  
 302 While  $\alpha$  ranges from  $-90^\circ$  (southern polar point) to  $+90^\circ$  (northern polar point). The col-  
 303 orbar at the bottom of the histogram is the number of ionopause crossings in each bin.



273 **Figure 3.** All of the normal directions of the ionospheric boundary crossings are binned in a three dimensional polar statistical histogram for ionospheric boundary crossing cases with (a) no observation of photoelectron dropout events as well as (b) observations of photoelectron dropout events with an azimuthal  $\phi$  bin size of  $7.5^\circ$  and elevation  $\alpha$  bin size of  $3.75^\circ$ . (a) and (b) are computed from a total of 238 and 1446 events respectively with criteria of  $\lambda_{int}/\lambda_{min} \geq 3$  and number of data points  $\geq 6$ . The colorbars at the bottom of the histograms are the number of ionopause crossings in each bin. Illustrative diagrams that show the projections of normal directions of ionospheric boundary crossings (especially in the northern polar regions where all of the boundary crossings are observed) for (c) a smooth ionospheric boundary and (d) an ionospheric boundary that exhibits a wavelike appearance. The green line represents the ionospheric boundary. The blue dashed arrows represent vectors projected radially from the center of Venus through its local locations. The red arrows represent the normal directions of the boundary crossings projected from their local locations which are denoted by the orange colored dots. Note that the illustration of the symmetric ionospheric boundary is visualized on the basis that the nominal ionopause altitude is not Solar Zenith Angle dependent [Zhang *et al.*, 2008b].

304 For ease of comparison, all minimum variance directions with negative  $Z_{VSO}$  components  
 305 are rotated into the positive  $Z_{VSO}$  direction and the local positions of the boundary cross-  
 306 ings are shifted to the northern polar point ( $\alpha = 90^\circ$ ) so that all directions can be visu-  
 307 alized and compared in a single directional hemisphere. As seen in Figure 3(a), around  
 308 91% (217 out of 238) of the boundary normal directions fall in the elevation range of  $\alpha >$   
 309  $67.5^\circ$ .

310 For a spherically smooth Venusian ionospheric boundary in the dayside and the  
 311 polar regions as illustrated in Figure 3(c), the normal directions of boundary crossings  
 312 should be aligned radially from the center of Venus at their local locations. This is re-  
 313 flected in the results in Figure 3(a). As the locations of boundary crossings are shifted to  
 314 the northern polar region, the close proximity between the boundary normal directions and  
 315 the radial directions (from the center of Figure 3(a)), implies that ionospheric boundary is  
 316 smooth and quasi-spherical in the Y-Z  $V_{SO}$  plane (i.e. Figure 3(c)).

317 However, this scenario of smooth Venusian ionospheric boundary is not reflected in  
 318 the results obtained for the photoelectron dropout events. In Figure 3(b), all of the 1446  
 319 well defined boundary normal directions from the photoelectron dropout intervals are  
 320 binned in a similar three dimensional polar statistical histogram. Figure 3(b) shows that  
 321 the bins are more populated in the azimuthal range of  $60^\circ < \phi < 120^\circ$  and  $240^\circ < \phi < 300^\circ$   
 322 as well as in the elevation range of  $\alpha < 45^\circ$ . In comparison to the smooth boundary case  
 323 presented in Figure 3(a), only around 23% (333 out of 1446) of the boundary normal  
 324 directions fall in the elevation range of  $\alpha > 67.5^\circ$ . This shows that instead of pointing  
 325 radially outward from the center of Venus, the majority of the normal directions of the  
 326 boundary crossings lie in the Y-Z  $V_{SO}$  plane, with the most dominant component along  
 327 the  $Y_{VSO}$  axis. In contrast to Figure 3(a), the results from Figure 3(b) imply that, for a  
 328 single orbital trajectory exhibiting multiple crossings of the ionospheric boundary, the  
 329 ionopause crossings from the photoelectron dropout cases do not result from a smooth  
 330 ionospheric boundary, but an ionospheric boundary that can exist as a ripple along the  
 331 Y-Z  $V_{SO}$  plane and which may propagate in a direction dominantly along the  $Y_{VSO}$  axis.  
 332 This is illustrated in Figure 3(d). All the minimum variance directions are obtained from  
 333 a variety of VEX trajectories with a range of azimuthal angles (not shown here), i.e. the  
 334 result of consistent minimum variance directions shown here are not biased towards any  
 335 particular VEX orbit.

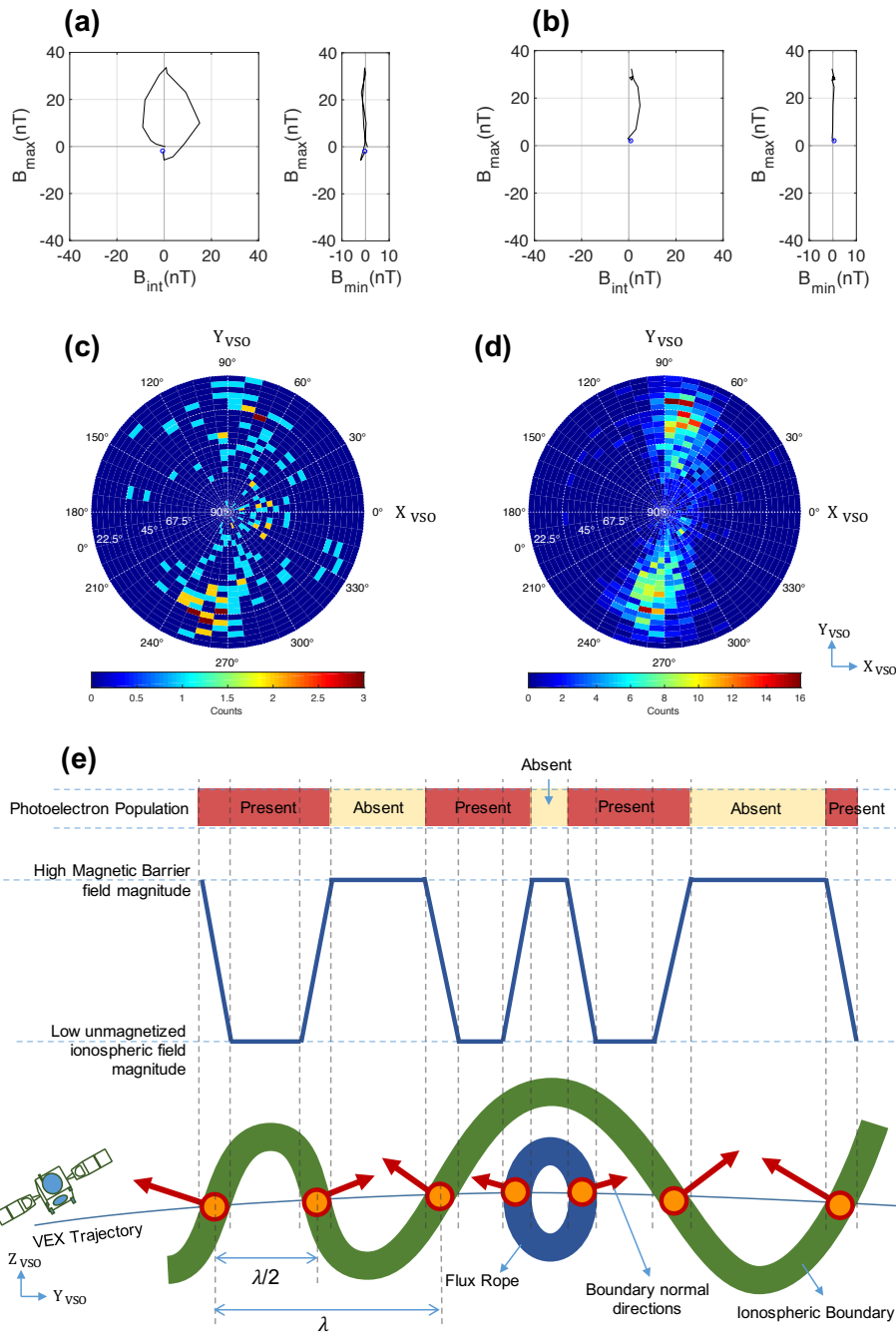
### 3.3.1 Flux ropes

Crossings of magnetic flux ropes [Russell and Elphic, 1979; Russell, 1990; Wolff et al., 1980] should be, in theory, in an idealized hydromagnetic state, similar to crossings of the Venusian ionospheric boundary. Both are tangential discontinuity boundaries [Spreiter et al., 1970; Wolff et al., 1979]. Based on its unique “potato chip” shaped hodogram as a key identifier [Russell, 1990], a total of 132 magnetic flux ropes resulting in 264 dip-to-peak and peak-to-dip field changes are identified in this statistical analysis. The second photoelectron dropout event on 02 Oct 2011 that corresponds to a dip-to-peak-to-dip field change from 05:48:41 to 05:48:55 is identified as a flux rope. The hodogram (with  $\lambda_{int}/\lambda_{min} \approx 55$ ) has a “potato chip” shape as shown in Figure 4(a). In addition, the hodogram of the boundary crossing (with  $\lambda_{int}/\lambda_{min} \approx 55$ ) from 05:47:56 to 05:48:09 (just before the flux rope is encountered) is shown in Figure 4(b). The start of both hodograms are marked with blue circles. In comparison to the “potato chip” shape hodogram in Figure 4(a), the hodogram shown in Figure 4(b) does not indicate field rotation and thus this is not a flux rope.

177 of these 264 dip-to-peak and peak-to-dip field changes have  $\lambda_{int}/\lambda_{min} \geq 3$  and number of data points  $\geq 6$ . Similar to Figure 3(b), the minimum variance directions of only the flux rope crossings as well as photoelectron dropout events excluding the flux ropes, are binned in a three dimensional polar histogram, with an azimuthal  $\phi$  bin size of  $7.5^\circ$  and elevation  $\alpha$  bin size of  $3.75^\circ$  in Figure 4(c) and Figure 4(d) respectively. Compared to the non flux rope cases in Figure 4(d), the boundary normal directions of the flux ropes in Figure 4(c) are slightly more randomly orientated. However, the majority of them can still be observed to lie along the  $Y_{VSO}$  axis.

In summary, the analysis of all the ionospheric boundary crossings from 2006 to 2014 reveals that the Venusian ionospheric boundary is not always smooth. In particular, 23% (495 orbits) of all the available orbits shows that the ionopause can often exhibit a wavelike appearance in the northern polar region, where all of the boundary crossings are observed. Figure 4(e) presents an illustrative diagram to show how the wavelike characteristic of the Venusian ionospheric boundary can be visualized from the simultaneous observations of photoelectron dropout events (top panel) and the changes in magnetic field magnitude (middle panel).





351 **Figure 4.** Hodogram of (a) a flux rope from 05:48:41 to 05:48:55 and (b) an ionospheric boundary crossing  
 352 from 05:47:56 to 05:48:09 on 02 Oct 2011. All the normal directions of the boundary crossings are binned  
 353 in a three dimensional polar histogram for ionospheric boundary crossings cases of (c) only flux ropes and  
 354 (d) all photoelectron dropout intervals excluding flux ropes for comparison. (c) and (d) are computed from a  
 355 total of 177 and 1269 events respectively. (e) An example illustrative diagram showing how the ionospheric  
 356 photoelectron dropout events (top panel) and the changes in magnetic field magnitude (middle panel) can be  
 357 related to the possible VEX trajectory through multiple ionospheric crossings and flux ropes (bottom panel).  
 358 The red arrows represent the normal directions of boundary crossings projected from their local locations,  
 359 which are denoted by the orange colored dots.  $\lambda$  and  $\lambda/2$  denote estimated half-width and full width of the  
 360 ionospheric boundary wave.

## 4 Discussions

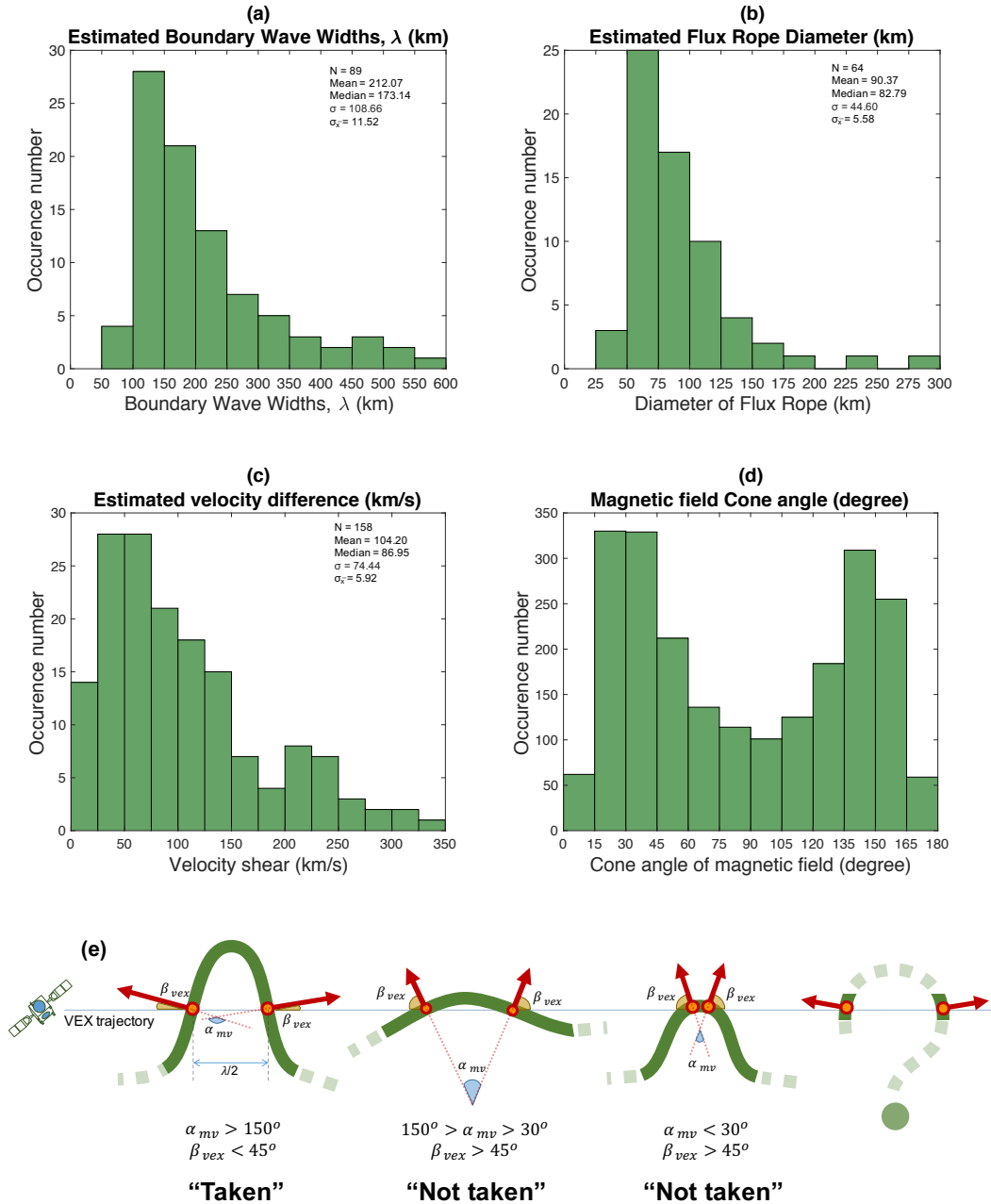
Due to the polar orbit of VEX, the ionosphere is only sampled in the northern polar region, hence the ionospheric boundary wave events are observed in a rather small range of locations with elevation  $> 39^\circ$  and with 90% of the observations made at  $> 61^\circ$ . Its periapsis ranges from around 166 km to 1025 km, with 90% of the passes made below 475 km. The boundary wave events are observed everywhere in this small range of locations and do not show any particular preferred location.

### 4.1 Kelvin-Helmholtz Instability as a boundary wave generation mechanism

#### 4.1.1 Boundary wave widths

With the assumption that the boundary wave is stationary with respect to the spacecraft velocity (VEX has velocity  $\sim 9.5$  km/s around the periapsis), both the sizes of boundary wave billows and flux ropes can be estimated from the duration of their crossings along with their respective minimum variance orientation. The half-width of the boundary wave,  $\lambda/2$  as illustrated in Figure 5(e) is estimated by the product of the VEX velocity and the time spent between two consecutive boundary crossings. The estimation is made under two criteria: (1) Only two consecutive boundary crossings when  $\alpha_{mv}$ , the angle between their respective boundary normal directions, is less than  $30^\circ$  or greater than  $150^\circ$ , are selected to eliminate the crossings of boundary waves that are still in the linear growth phase; i.e. only developed waves are selected, (2) only boundary crossings when  $\beta_{vex}$ , the angle between the spacecraft velocity vector and the boundary normal vector is less than  $45^\circ$  are selected to eliminate the boundary crossings of the ‘near-tips’ of the waves as illustrated in Figure 5(e) and to eliminate the boundary which is crossed at a large angle by the VEX. These criteria yields a total of 89 boundary wave events. Note that the data of VEX, a single spacecraft mission, could only allow the estimations of the boundary normal directions but not the shape of the boundary wave. Hence the ionopause is expressed in a dashed line shaped question mark in the last (fourth) schematic diagram in Figure 5(e) indicating an undefinable shape. [Brace *et al.*, 1982]

A histogram of the estimated widths of the boundary wave  $\lambda$ , of the 89 events with a bin size of 50 km is presented in Figure 5(a). The distribution of the boundary wave widths is a single peak positively skewed distribution with a median value of 173 km and a mode class of 100-150 km. Mode class is the most frequent range of values in a dis-



404 **Figure 5.** (a) A histogram of the estimated ionospheric boundary wave widths,  $\lambda$  from a total of 89 events  
 405 from 2006 to 2014. Bin size is 50 km. Range: from 87 km to 550 km. (b) A histogram of the estimated flux  
 406 rope diameter from a total of 64 events. Bin size is 25 km. Range: from 48 km to 295 km. (c) A histogram  
 407 of the estimated velocity difference across the ionospheric boundary from a total of 158 events. Bin size is  
 408 25 km/s. Range: from 5 km/s to 341 km/s. (d) A histogram of the magnetic field cone angle in the magnetic  
 409 barrier region from a total of 2216 events. Bin size is  $15^\circ$ . Cone angle is defined as  $\cos^{-1}(B_x/B)$ . (e) Illus-  
 410 trative diagrams showing the criteria used in estimating the boundary wave widths and the flux rope diameter.  
 411 The criteria are  $\alpha_{mv} < 30^\circ$  or  $> 150^\circ$  and  $\beta_{vex} < 45^\circ$ . The red arrows represent the normal directions of  
 412 boundary crossings projected from its local locations which are denoted by the orange colored dots. The iono-  
 413 spheric boundary is represented by green lines.  $\beta_{vex}$  is the angle between the spacecraft velocity vector and  
 414 the boundary normal vector.  $\alpha_{mv}$  is the angle between the boundary normal directions from two consecutive  
 415 crossings.

420 tribution. It ranges from 87 km to 550 km and has an average width,  $\lambda$  of  $212 \pm 12$  km.  
 421 The lower 0.25 and higher 0.75 quantiles are 135 km and 255 km respectively. Additional  
 422 analysis conducted with criterion  $\beta_{vex} < 30^\circ$  yields only 41 events but results in a similar  
 423 average width,  $\lambda$  of  $219 \pm 17$  km.

424 The diameters of the flux ropes are also estimated in a similar fashion but without  
 425 the angle criteria mentioned earlier. Both of these criteria can be measured by the mag-  
 426 netic field magnitude along  $B_{min}$  of a flux rope crossing. For example, for a spacecraft to  
 427 cross the exact center of a flux rope, the magnetic field magnitude along  $B_{min}$  should be  
 428 zero. And for the case where the flux rope is not crossed through its center, there should  
 429 be a finite non zero magnetic field magnitude along  $B_{min}$ . To measure the significance of  
 430 the field magnitude along  $B_{min}$ , the  $|B_{min}|/|B|$  value of all the flux ropes are calculated.  
 431 In fact, the average value of  $|B_{min}|/|B|$  for all the 133 flux ropes is only  $0.12 \pm 0.01$ . This  
 432 indicates that all of the flux ropes observed were crossed at or very close to their center.

433 The estimated diameters of a total of 64 (out of 133) flux ropes which have  $\lambda_{int}/\lambda_{min} \geq 3$   
 434 and number of data points  $\geq 6$  are presented in a histogram in Figure 5(b) with a bin  
 435 size of 25 km. The distribution of the flux rope diameters is also a single peak positively  
 436 skewed distribution with a median value of 83 km and a mode class of 50-75 km. It ranges  
 437 from 48 km to 295 km and has an average diameter of  $90 \pm 6$  km. The lower 0.25 and  
 438 higher 0.75 quantiles are 59 km and 102 km respectively. Additional analysis conducted  
 439 with criterion  $\beta_{vex} < 45^\circ$  yields a total of 25 flux ropes and an average diameter of of  
 440  $79 \pm 6$  km. The low value of  $|B_{min}|/|B|$  and the consistency shown in the estimated di-  
 441 ameters regardless if the criterion on  $\beta_{vex}$  is applied, implies that the majority of the flux  
 442 ropes are crossed quasi-radially and they do not appear to be ideally circular as depicted  
 443 in Figure 4(e).

444 Note that if a boundary wave is configured similar to the three phases of the KHI  
 445 evolution [Amerstorfer *et al.*, 2010], there are many possible ways that VEX can traverse  
 446 through a boundary wave. Hence, with the limitations of the instruments on board of  
 447 VEX, which is also a single spacecraft mission, estimations of the exact shape and thus  
 448 the size of the observed boundary wave and flux ropes, are not possible.

#### 4.1.2 Velocity shear profile

In addition to the estimation of boundary wave widths, the difference of velocity across the ionopause when boundary waves are observed,  $|U_{iono} - U_{Mb}|$  is also calculated.  $U_{iono}$  and  $U_{Mb}$  are the average proton velocity in the ionosphere and magnetic barrier regions respectively. Due to the long IMA sampling time of 192s, to ensure there are at least two data points, only  $U_{iono}$  from orbits that VEX spent longer than 192s in the ionosphere are considered and  $U_{Mb}$  is estimated by taking an average proton velocity 5 minutes before crossing the inbound ionopause. A histogram of the measured velocity difference of 158 events with a bin size of 25 km/s is presented in Figure 5(c). The distribution of the velocity difference is a single peak positively skewed distribution with a median value of 87 km/s and a mode class of 25-75 km. The  $|U_{iono} - U_{Mb}|$  ranges from 5 km/s to 341 km/s and has an average velocity of  $104 \pm 6$  km/s.

Since the time spent by VEX in the magnetic barrier region is often short, much less than the long 192s sampling time of the IMA, the estimation of  $U_{Mb}$  by averaging the proton velocity 5 minutes before crossing the inbound ionopause, will often include the plasma populations in the sheath region. These have a much larger magnitude along the  $X_{VSO}$  axis due to the main solar wind bulk flow. Therefore, the  $U_{Mb}$  presented here is an overestimate and shows bias along the  $X_{VSO}$  axis. The magnitude of the ‘actual’  $U_{Mb}$  is expected to be lower. Hence, the velocity difference profile presented here should be examined with caution.

In general, the results of the estimated ionospheric boundary wave widths and the velocity difference flow across the ionospheric boundary are considerably comparable with the study of KHI wave on Venus. For instance, *Wolff et al.* [1980] shows that with a ‘gyroviscosity’ coefficient,  $\nu_L$  of  $250 \text{ km}^2/\text{s}$ , a velocity difference of 100 km/s results in a wavelength of  $\sim 31$  km while velocity difference of 10 km/s results in a wavelength of  $\sim 305$  km. For a typical 30 km thin ionopause, *Elphic and Ershkovich* [1984] shows that velocity difference of 100 km/s and 200 km/s results in wave growth times of 81s and 32s respectively. Considering a density jump (ionosphere to the sheath region) with a ratio of 10, the local MHD simulation by *Amerstorfer et al.* [2010] with the lower (30 km) and upper (80 km) limits of ionopause boundary thickness [*Elphic et al.*, 1981], gives a dominant KHI wavelength with a lower range limit of  $\sim 181$  km and a higher range limit of  $\sim 483$  km. Similarly in *Ong and Roderick* [1972], for the most dominant mode of KHI,

481 30 km and 80 km of ionopause boundary thickness gives a dominant KHI wavelength  
 482 with of  $\sim 224$  km and  $\sim 600$  km respectively. The comparable results shown between the  
 483 estimated values in this statistical analysis and the simulation results, suggests that KHI  
 484 may act as an excitation seed in inducing the ionospheric boundary wave that is observed  
 485 in the northern polar region of Venus. However, it is noteworthy to mention that the aver-  
 486 age estimated ionospheric boundary wave width of  $212 \pm 12$  km in this work lies close to  
 487 the lower limit of *Amerstorfer et al.* [2010] and is actually 10 km smaller than the lower  
 488 limit in *Ong and Roderick* [1972]. This slight inconsistency can be attributed to the differ-  
 489 ent parameters (e.g. gyroviscosity, density gradient, and velocity difference etc.) consid-  
 490 ered in these mentioned studies which would result in different KHI wavelength.

491 Further analysis (not shown here) has been conducted to estimate the velocity differ-  
 492 ence of all orbits regardless of whether or not boundary waves are observed. The results  
 493 show that the ionospheric boundary does not always exhibit a wavelike appearance when  
 494 the velocity difference is large (i.e.  $|U_{iono} - U_{Mb}| > 150$  km/s). This can be due to: (1)  
 495 stabilizing terms (e.g. gravity [*Elphic and Ershkovich*, 1984]) which are more significant  
 496 and dominate; (2) resolution of VEX data is too low to observe the short boundary wave-  
 497 length resulting from the large velocity difference; and (3) the ionospheric boundary may  
 498 exist in a wave but it is not traversed by VEX.

#### 499 **4.1.3 Orientation of magnetic field**

500 Analysis reveals that the magnetic field orientation in the magnetic barrier region is  
 501 quasi-perpendicular to the Y-Z  $V_{SO}$  plane, which is a favorable condition for the excita-  
 502 tion of KHI along the along the  $Y_{VSO}$  direction. This orientation is evidenced from the bi-  
 503 modal shaped distribution of the magnetic field cone angles in the magnetic barrier region  
 504 presented in Figure 5(d), where the majority of the cone angles are  $< 45^\circ$  and  $> 135^\circ$ , i.e.  
 505 quasi-parallel to the  $X_{VSO}$  axis. The distributions of the histogram are very consistent for  
 506 all VEX passes regardless of whether boundary wave events are observed. This consistent  
 507 quasi-parallel orientation of magnetic field lines to the  $X_{VSO}$  axis is due to the draping  
 508 pattern of the magnetic field lines in the northern polar region of Venus. This is discussed  
 509 further in the next section.

#### 510 **4.1.4 Impacts and consequences**

511 When the KHI induced boundary wave becomes nonlinear, the broken wave can  
 512 detach and form flux ropes, which transfers the shocked solar wind plasma in the iono-  
 513 sphere. The reconnection of the consecutive two troughs or two crests (i.e.  $\lambda/2$ ) of a  
 514 turbulent boundary wave would ideally result in the production of flux ropes with diam-  
 515 eters comparable to the half-widths of the boundary wave. Therefore, the results of (1)  
 516 the similarity in the normal directions between the flux ropes and the boundary wave  
 517 (they mainly lie along the  $Y_{VSO}$  axis) and (2) the similarity between the estimated flux  
 518 rope diameters and the half-widths ( $\lambda/2$ ) of ionospheric boundary waves, suggest that the  
 519 flux ropes observed are likely to be formed as a result of detached ionospheric boundary  
 520 waves.

521 At the same time, atmospheric bubbles which contain plasma with ionospheric ori-  
 522 gin are also expected to form in a similar fashion to the production of flux ropes. Ide-  
 523 ally, atmospheric bubbles can be identified by the observation of ionospheric photoelectron  
 524 populations outside the ionosphere region. However, the convection of the atmospheric  
 525 bubbles out of the ionosphere and subsequently downstream with the main solar wind  
 526 bulk flow, can change the magnetization state as well as the characteristic energy signature  
 527 of the ionospheric photoelectron populations (at 21-24eV and at 27eV [*Coates et al.*, 2008;  
 528 *Cui et al.*, 2011]). In addition, the magnetic barrier region, where atmospheric bubbles  
 529 populate before they are convected downstream, is highly dynamic. These complications  
 530 may result in the atmospheric bubbles not being accurately identified in this work. On the  
 531 other hand, the high latitude elliptical polar orbit of VEX indicates little opportunity for  
 532 the spacecraft to encounter the atmospheric bubbles that often populate in the downstream  
 533 region ( $-X_{VSO}$ ) as a result of the convection of solar wind bulk flow.

#### 534 **4.2 Wave propagation along $Y_{VSO}$ : Draping pattern of magnetic field lines**

535 To assess if there is a preference in plasma velocity direction, the contribution of the  
 536 average plasma velocity components along the  $X_{VSO}$ ,  $Y_{VSO}$  and  $Z_{VSO}$  axes of the inbound  
 537 solar wind ( $U_{sw}$ ), magnetic barrier ( $U_{Mb}$ ) and ionosphere ( $U_{iono}$ ) are calculated. They  
 538 are (91.3, 6.7, 2.1) % for the inbound solar wind, (75.2, 11.7, 13.2) % for the magnetic  
 539 barrier and (15.1, 45.7, 39.2) % for the ionosphere. The values are normalized and are  
 540 measured by taking the ratio of the individual components with respect to their overall

541 magnitudes. They are expressed in percentage and the median values of their respective  
 542 distributions are utilized for this calculations. To eliminate the possible orbital dependence  
 543 of velocity, only quasi-terminator VEX trajectories are considered, i.e. when the orbital  
 544 plane is  $< 30^\circ$  to the terminator plane. The  $U_{sw}$ ,  $U_{Mb}$  and  $U_{iono}$  are averaged from a total  
 545 of 658, 341 and 465 plasma velocity vectors respectively.

546 Similar to Section 4.1.2, only  $U_{iono}$  from orbits for which VEX spent longer than  
 547 192s in the ionosphere are considered, while  $U_{sw}$  and  $U_{Mb}$  are estimated by taking an av-  
 548 erage of proton velocity 30 minutes before crossing the inbound bow shock and 5 minutes  
 549 before crossing the inbound ionopause respectively. The results show that the average so-  
 550 lar wind plasma velocity outside the bow shock is dominantly along the  $X_{VSO}$  axis, while  
 551 the components along the  $Y_{VSO}$  and  $Z_{VSO}$  axes are minimal, as expected from the main  
 552 solar wind bulk flow. However, through the bow shock and into the ionosphere, the con-  
 553 tributions of the velocity component along the  $X_{VSO}$  axis can be observed to decrease  
 554 drastically, while the contributions of the velocity components along the  $Y_{VSO}$  and  $Z_{VSO}$   
 555 axes becomes more significant. In the ionosphere, the plasma velocity is actually domi-  
 556 nated by the components along the  $Y_{VSO}$  axis (with a contribution of  $\approx 46\%$ ) followed by  
 557  $Z_{VSO}$  ( $\approx 39\%$ ) and  $X_{VSO}$  ( $\approx 15\%$ ) axes. These results are consistent with *Lundin et al.*  
 558 [2011, 2013, 2014] in which the authors attributed the persistent  $+Y_{VSO}$  directed ion flow  
 559 over the northern polar region to the solar wind aberration.

560 The domination of the plasma velocity along the  $Y_{VSO}$  axis in the ionosphere re-  
 561 gion further suggests that a velocity shear profile across the ionospheric boundary could  
 562 be set up and consequently exciting the boundary wave by means of KHI. However, the  
 563 follow up question is: what is the possible driving mechanism of the plasma along the  
 564  $Y_{VSO}$  axis?

#### 565 **4.2.1 Dependence of the boundary normals with respect to their locations**

566 Next the dependence of the normal directions of the boundary crossings with re-  
 567 spect to their locations is studied. The  $MV_x$ ,  $MV_y$ , and  $MV_z$ , which are the components  
 568 of the normalized boundary normal directions along the  $X_{VSO}$ ,  $Y_{VSO}$  and  $Z_{VSO}$  axes rel-  
 569 ative to the observation location of their associated boundary crossings in the X- $Y_{VSO}$   
 570 plane are shown in Figure 6(a)-(c). The measurement for each normal direction is binned



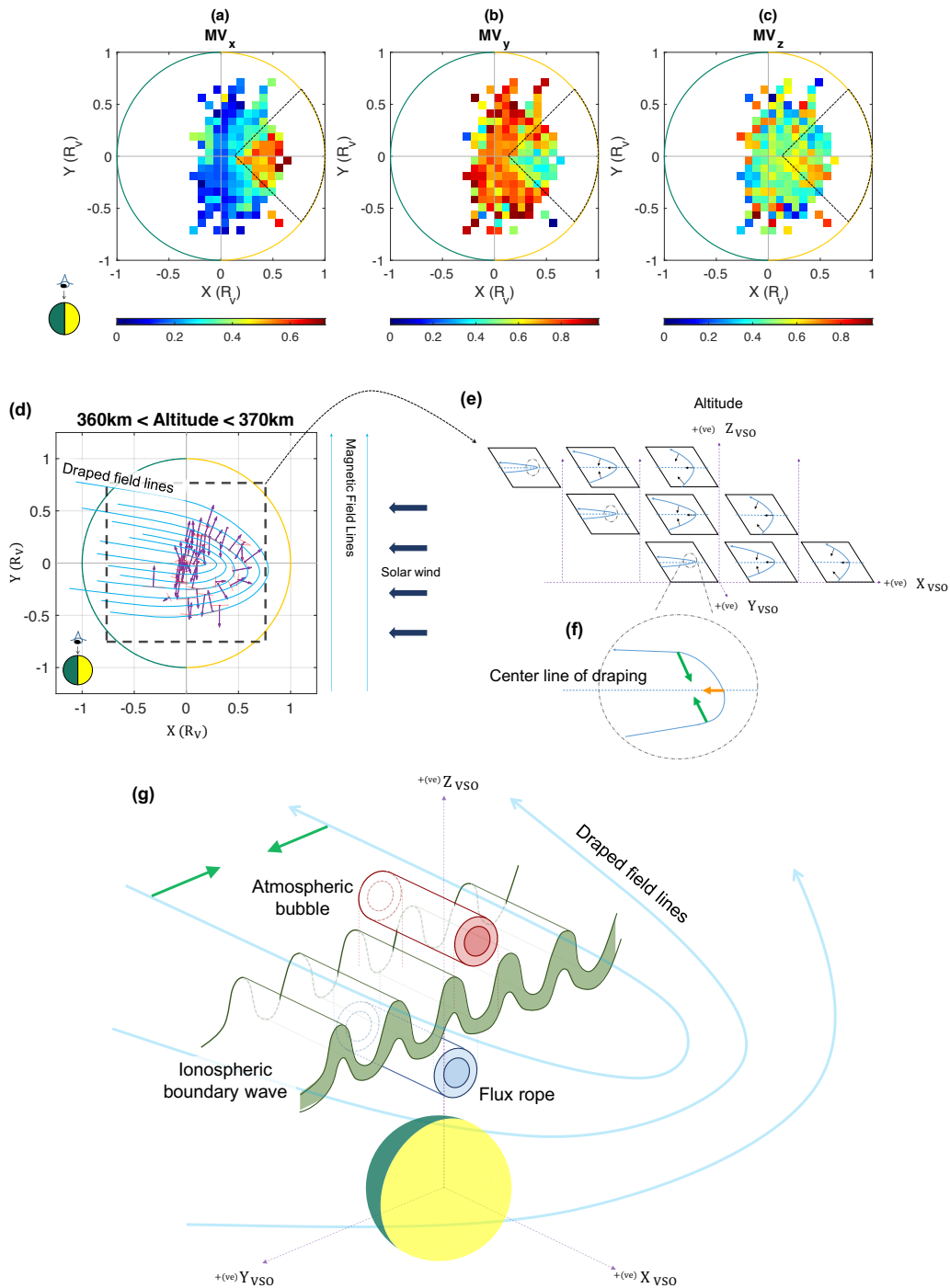
571 in  $0.075 \times 0.075 R_V$  bins ranging from  $-1 R_V$  to  $1 R_V$ . Only bins with two or more mea-  
 572 surements are shown.

573 The results presented in Figure 6(a)-(c) shows a clear dependence of the boundary  
 574 normal directions on their respective locations, especially when the azimuthal angle of the  
 575 locations,  $\phi_{Location} < |45^\circ|$ . These regions are outlined with the black-colored dashed  
 576 line which is just in front of  $X = 0$ . For instance, observable from Figure 6(a), the  $MV_x$   
 577 components in the region  $\phi_{Location} < |45^\circ|$  are much larger compared to the region  
 578  $\phi_{Location} > |45^\circ|$ . This is visible by the stronger red-colored patches in the region out-  
 579 lined with the black-colored dashed line. In contrast, from Figure 6(b), the  $MV_y$  compo-  
 580 nents in the same region are much smaller, visible from the weaker blue-colored patches.  
 581 While  $MV_z$  components are rather randomly distributed. Even though the majority of the  
 582 boundary normal directions are dominantly along the  $Y_{VSO}$  axis, the above results suggest  
 583 that, at the location  $\phi_{Location} < |45^\circ|$ , the boundary normal directions have slightly larger  
 584 components along the  $X_{VSO}$  axis.

#### 585 **4.2.2 Draping of magnetic field lines**

586 In Figure 6(d), taking the normal directions of the boundary crossings (represented  
 587 as purple arrows) across an altitude range from 360 km to 370 km as an example, the  
 588 boundaries (represented as red-dotted lines which are perpendicular to the normal direc-  
 589 tions) show an alignment that is comparable to a typical pattern of draped magnetic field  
 590 lines (represented as blue lines) around Venus. These curved patterns are also valid at  
 591 other altitude ranges (illustrations not shown here). The results from Figure 6(d) are con-  
 592 sistent with Figure 6(a)-(c). The expected overall draping configuration of magnetic field  
 593 lines across the cross section of altitude is illustrated in Figure 6(e).

603 Upstream of the bow shock, the IMF may appear in a range of orientations. The  
 604 IMF moves towards Venus in the direction of the main solar wind bulk flow ( $-X_{VSO}$ ). If  
 605 the magnetic field lines are represented as an ellipse, as the field lines drape around the  
 606 planet, the eccentricity tends from infinity (upstream of bow shock) towards zero (out-  
 607 side of the ionopause in the polar regions of Venus). This is illustrated in Figure 6(e) and  
 608 (f). Typically, upstream of the bow shock, the solar wind has a higher plasma  $\beta$  (defined  
 609 as the ratio of thermal to magnetic pressure). In this case, the thermal pressure domi-  
 610 nates and the magnetic field lines are not “frozen into” the plasma. The plasma still gy-



594 **Figure 6.** (a)-(c) The distribution of  $MV_x$ ,  $MV_y$ , and  $MV_z$ , which are the components of the normalized  
 595 boundary normal directions along the  $X_{VSO}$ ,  $Y_{VSO}$  and  $Z_{VSO}$  projected from their locations in the  $X$ - $Y$   $V_{SO}$   
 596 plane. (d) An illustration of how all the perpendicular directions of boundary normal directions (from the  
 597 altitude band  $360 \text{ km} < \text{altitude} < 370 \text{ km}$ ) could be related to field draping. Note the intended slight solar  
 598 wind direction aberration is due to the orbital motion of Venus. (e)-(f) Illustrates how the draping patterns of  
 599 magnetic field lines may change as a function of altitude and along  $X_{VSO}$  direction for the area in the black  
 600 square box in (d) (adapted from [Chong *et al.*, 2017]). (g) Illustration of how field draping might lead to iono-  
 601 spheric boundary wave and the production of flux rope and atmospheric bubble. Illustration is not drawn to  
 602 scale.

611 rates around the field lines but has an overall velocity component mainly in the direction  
 612 of solar wind bulk velocity in the  $-X_{VSO}$  direction (represented by the orange arrow in  
 613 Figure 6(f)). In contrast, through the magnetosheath the IMF lines start to pile up and  
 614 drape around Venus more ‘orderly and regularly’, with the field lines eventually extend-  
 615 ing mainly in the direction of the solar wind bulk flow regardless of the IMF orientation  
 616 [McComas *et al.*, 1986; Masunaga *et al.*, 2011; Tanaka, 1993]). At the same time, the  
 617 plasma is slowly cooled down and slows towards the ionopause, where the thermal pres-  
 618 sure is gradually converted into magnetic pressure. This consequently results in a lower  
 619  $\beta$  where the magnetic pressure dominates and the plasma is now “frozen into” the mag-  
 620 netic field lines. As a result, just outside of the Venusian ionopause around the polar re-  
 621 gions, as illustrated by the green arrows in Figure 6(f), the now much lower  $\beta$  plasma is  
 622 ‘forced’ to move towards the center line of draping (which is along the  $Y_{VSO}$  axis) due to  
 623 the movement of magnetic field lines (which is along the  $Y_{VSO}$  axis). This could subse-  
 624 quently set up a velocity shear along the  $Y_{VSO}$  axis. In addition, as the density jump is  
 625 along the  $Z_{VSO}$  axis in the northern polar region, the combination together with the ve-  
 626 locity shear along the  $Y_{VSO}$  axis and the quasi-parallel orientation of magnetic field lines  
 627 to the  $X_{VSO}$  axis, should favor the growth of KHI induced ionospheric boundary waves  
 628 along the Y-Z  $VSO$  plane and with a propagation direction along the  $Y_{VSO}$  axis. This pro-  
 629 posed mechanism is consistent with the results presented in this work and is illustrated in  
 630 Figure 6(g). Note that the flux rope and the atmospheric bubble are only depicted simply  
 631 to illustrate their possible presence. Their actual shapes are not known and the depicted  
 632 circular shapes are for illustration purposes only.

633 The dependence of the boundary wave events on the orientations of the IMF has  
 634 also been assessed. To eliminate the effects when the IMF might have changed between  
 635 the inbound and outbound bow shock, IMF data is only considered when the angle be-  
 636 tween the inbound and outbound IMF orientations are  $< 15^\circ$ . Results (not shown here)  
 637 indicate that the IMF orientations for the orbits when ionospheric boundary wave events  
 638 are observed and the orbits where they are not observed, are similar. This implies that the  
 639 occurrence of boundary wave does not show any dependence on the orientations of the  
 640 IMF.

## 5 Summary and conclusions

By utilizing the MAG, ELS and IMA data onboard of VEX, we have conducted the first statistical analysis of the perturbations of the ionospheric boundary at Venus over the period 2006 to 2014. Results from the minimum variance analysis reveals that the Venusian ionospheric boundary does not always appear to be smooth, but a rippled boundary that fluctuates mainly along the Y-Z  $V_{SO}$  plane and predominantly with boundary normals along the  $Y_{VSO}$  axis. Further analysis shows that the estimated widths of the ionospheric boundary wave and the estimated velocity difference flow across the boundaries are consistent to the results from previous simulation studies of the Kelvin-Helmholtz Instability. This leads to the suggestion that the ionospheric boundary wave develops due to the Kelvin-Helmholtz Instability. Furthermore, our analysis suggests that the draping pattern of magnetic field lines play a principal role in enhancing the plasma flow along the  $Y_{VSO}$  axis and subsequently sets up a velocity shear that favors the excitation of ionospheric boundary waves.

When the Venusian ionospheric boundary is excited by the KHI and reaches a non-linear state, the wave can break off and detach, subsequently result in the formation of atmospheric bubbles and flux ropes. If ionopause waves [Luhmann, 1990] exist all along the terminator region, the draping pattern of magnetic field lines can act to enhance the production of both atmospheric bubbles and flux ropes, particularly in both the northern and southern polar regions of Venus where the magnetic field lines are more tightly draped. This can explain why the majority of the observed flux ropes from this statistical analysis, have similar widths and boundary normal directions to the ionospheric boundary wave. In addition, this scenario can also provide an explanation to the detection of atmospheric plasma outflows which are observed mainly in the polar regions; e.g. plasma clouds [Brace *et al.*, 1982] and high energy  $O^+$  fluxes [Masunaga *et al.*, 2011]. Both studies attributed their respective observations to the limitations of the PVO orbits and the upstream IMF orientations. In addition, rippling ionopause could also potentially lead to the flapping of Venusian magnetotail [Rong *et al.*, 2015] and subsequently the productions of magnetic plasmoids in the magnetotail region [Zhang *et al.*, 2012]. However, since the ionosphere region is only sampled in locations limited to the northern polar region due to the polar orbit of VEX, it is not possible to assess and compare the nature of the ionospheric boundary in different regions, i.e. subsolar, southern polar and equatorial flank regions.

674 Continuous scattering and the subsequent convection of atmospheric bubbles down-  
675 stream and away from Venus over a prolonged period of time plays an important role in  
676 atmospheric loss from Venus. The statistical analysis presented here, provides observa-  
677 tional evidence of the ionospheric boundary existing in a wavelike appearance. This could  
678 have had a significant impact for the planetary evolution of Venus. However, the location  
679 of the boundary, which is a standoff boundary between the planetary atmosphere and the  
680 incoming solar wind, varies significantly depending on if the planetary body is magne-  
681 tized. Hence, it is of interest for future work to measure the distributions of the boundary  
682 surface wave and assess the role of field draping on the stability of planetary boundaries,  
683 particularly for unmagnetized bodies where the boundaries are much closer to the planets.

### 684 **Acknowledgments**

685 Participants from Sheffield received financial assistance from STFC Consolidated Grant  
686 ST/R000697/1. Particle and low resolution magnetic field data are available from AMDA  
687 (<http://amda.cdpp.eu/>) and from the ESA Planetary System Archive (PSA) at [https://www.cosmos.esa.int/web/psa/venus-](https://www.cosmos.esa.int/web/psa/venus-express)  
688 [express](https://www.cosmos.esa.int/web/psa/venus-express). High resolution MAG data is available on request from the VEX - MAG PI, Tie-  
689 Long Zhang. The authors would like to thank all the MAG and ASPERA-4 team mem-  
690 bers for the big effort which led to the successful operation of the instrument and the cal-  
691 ibration of the data. R. Frahm acknowledges contributions from NASA (contract NASW-  
692 00003). The authors are very grateful for the insightful discussions with Glyn Collinson.

### 693 **References**

- 694 Amerstorfer, U. V., N. V. Erkaev, D. Langmayr, and H. K. Biernat (2007), On Kelvin-  
695 Helmholtz instability due to the solar wind interaction with unmagnetized planets, *Plan-*  
696 *etary and Space Science*, *55*(12), 1811–1816, doi:10.1016/j.pss.2007.01.015.
- 697 Amerstorfer, U. V., N. V. Erkaev, U. Taubenschuss, and H. K. Biernat (2010), Influence  
698 of a density increase on the evolution of the Kelvin-Helmholtz instability and vortices,  
699 *Physics of Plasmas*, *17*(7), 072901, doi:10.1063/1.3453705.
- 700 Arshukova, I., N. Erkaev, H. Biernat, and D. Vogl (2004), Interchange instabil-  
701 ity of the venusian ionopause, *Advances in Space Research*, *33*(2), 182–186, doi:  
702 10.1016/j.asr.2003.04.015.
- 703 Barabash, S., J.-A. Sauvaud, H. Gunell, H. Andersson, A. Grigoriev, K. Brinkfeldt,  
704 M. Holmström, R. Lundin, M. Yamauchi, K. Asamura, et al. (2007), The analyser of

- 705 space plasmas and energetic atoms (ASPERA-4) for the Venus Express mission, *Planetary and Space Science*, 55(12), 1772–1792, doi:10.1016/j.pss.2007.01.014.
- 706
- 707 Biernat, H. K., N. V. Erkaev, U. V. Amerstorfer, T. Penz, and H. I. M. Lichtenegger  
708 (2007), Solar wind flow past Venus and its implications for the occurrence of the  
709 Kelvin-Helmholtz instability, *Planetary and Space Science*, 55(12), 1793–1803, doi:  
710 10.1016/j.pss.2007.01.006.
- 711 Brace, L. H., R. F. Theis, W. R. Hoegy, J. H. Wolfe, J. D. Mihalov, C. T. Russell,  
712 R. C. Elphic, and A. F. Nagy (1980), The dynamic behavior of the Venus ionosphere  
713 in response to solar wind interactions, *J. Geophys. Res.*, 85(A13), 7663–7678, doi:  
714 10.1029/JA085iA13p07663.
- 715 Brace, L. H., R. F. Theis, and W. R. Hoegy (1982), Plasma clouds above the ionopause  
716 of Venus and their implications, *Planetary and Space Science*, 30(1), 29–37, doi:  
717 10.1016/0032-0633(82)90069-1.
- 718 Brace, L. H., R. C. Elphic, S. A. Curtis, and C. T. Russell (1983), Wave structure in the  
719 Venus ionosphere downstream of the terminator, *Geophysical Research Letters*, 10,  
720 1116–1119, doi:10.1029/GL010i011p01116.
- 721 Chamberlain, J. W. (1963), Planetary coronae and atmospheric evaporation, *Planetary and*  
722 *Space Science*, 11, 901–960, doi:10.1016/0032-0633(63)90122-3.
- 723 Chandrasekhar, S. (1961), *Hydrodynamic and Hydrodynamic stability*, OUP.
- 724 Chong, G. S., S. A. Pope, T. L. Zhang, G. A. Collinson, S. N. Walker, and M. A. Ba-  
725 likhin (2017), A study of ionopause perturbation and associated boundary wave for-  
726 mation at Venus, *Journal of Geophysical Research (Space Physics)*, 122, 4284–4298,  
727 doi:10.1002/2016JA023769.
- 728 Coates, A. J., R. A. Frahm, D. R. Linder, D. O. Kataria, Y. Soobiah, G. Collinson, J. R.  
729 Sharber, J. D. Winningham, S. J. Jeffers, S. Barabash, J.-A. Sauvaud, R. Lundin,  
730 M. Holmström, Y. Futaana, M. Yamauchi, A. Grigoriev, H. Andersson, H. Gunell,  
731 A. Fedorov, J.-J. Thocaven, T. L. Zhang, W. Baumjohann, E. Kallio, H. Koskinen, J. U.  
732 Kozyra, M. W. Liemohn, Y. Ma, A. Galli, P. Wurz, P. Bochsler, D. Brain, E. C. Roelof,  
733 P. Brandt, N. Krupp, J. Woch, M. Fraenz, E. Dubinin, S. McKenna-Lawlor, S. Orsini,  
734 R. Cerulli-Irelli, A. Mura, A. Milillo, M. Maggi, C. C. Curtis, B. R. Sandel, K. C.  
735 Hsieh, K. Szego, A. Asamura, and M. Grande (2008), Ionospheric photoelectrons at  
736 Venus: Initial observations by ASPERA-4 ELS, *Planetary and Space Science*, 56, 802–  
737 806, doi:10.1016/j.pss.2007.12.008.

- 738 Cui, J., M. Galand, A. J. Coates, T. L. Zhang, and I. C. F. Müller-Wodarg (2011),  
739 Suprathermal electron spectra in the Venus ionosphere, *Journal of Geophysical Research*  
740 (*Space Physics*), *116*, A04321, doi:10.1029/2010JA016153.
- 741 Elphic, R. C., and A. I. Ershkovich (1984), On the stability of the ionopause of Venus, *J.*  
742 *Geophys. Res.*, *89*(A2), 997–1002, doi:10.1029/JA089iA02p00997.
- 743 Elphic, R. C., C. T. Russell, J. A. Slavin, and L. H. Brace (1980), Observations of the  
744 dayside ionopause and ionosphere of Venus, *J. Geophys. Res.*, *85*(A13), 7679–7696, doi:  
745 10.1029/JA085iA13p07679.
- 746 Elphic, R. C., C. T. Russell, J. G. Luhmann, F. L. Scarf, and L. H. Brace (1981),  
747 The Venus ionopause current sheet - Thickness length scale and controlling fac-  
748 tors, *Journal of Geophysical Research: Space Physics*, *86*, 11,430–11,438, doi:  
749 10.1029/JA086iA13p11430.
- 750 Ferrari, A., S. Massaglia, and E. Trussoni (1982), Magnetohydrodynamic Kelvin-  
751 Helmholtz instabilities in astrophysics. III - Hydrodynamic flows with shear layers,  
752 *Monthly Notices of the Royal Astronomical Society*, *198*, 1065–1079.
- 753 Futaana, Y., G. Stenberg Wieser, S. Barabash, and J. G. Luhmann (2017), Solar Wind  
754 Interaction and Impact on the Venus Atmosphere, *Space Science Reviews*, *212*, 1453–  
755 1509, doi:10.1007/s11214-017-0362-8.
- 756 Hartle, R., and J. Grebowsky (1993), Light ion flow in the nightside ionosphere of venus,  
757 *Journal of Geophysical Research: Planets (1991–2012)*, *98*(E4), 7437–7445, doi:  
758 10.1029/93JE00399.
- 759 Huba, J. D. (1981), The Kelvin-Helmholtz Instability in inhomogeneous plasmas, *J. Geo-*  
760 *phys. Res.*, *86*(A5), 3653–3656, doi:10.1029/JA086iA05p03653.
- 761 Jeans, J. H. (1955), *The dynamical theory of gases*, University Press.
- 762 Knetter, T., F. M. Neubauer, T. Horbury, and A. Balogh (2004), Four-point discontinuity  
763 observations using Cluster magnetic field data: A statistical survey, *Journal of Geophys-*  
764 *ical Research (Space Physics)*, *109*, A06102, doi:10.1029/2003JA010099.
- 765 Lammer, H., H. I. M. Lichtenegger, H. K. Biernat, N. V. Erkaev, I. L. Arshukova,  
766 C. Kolb, H. Gunell, A. Lukyanov, M. Holmstrom, S. Barabash, T. L. Zhang,  
767 and W. Baumjohann (2006), Loss of hydrogen and oxygen from the upper at-  
768 mosphere of Venus, *Planetary and Space Science*, *54*(13-14), 1445–1456, doi:  
769 10.1016/j.pss.2006.04.022.

- 770 Leinweber, H. K., C. T. Russell, K. Torkar, T. L. Zhang, and V. Angelopoulos (2008),  
771 An advanced approach to finding magnetometer zero levels in the interplanetary mag-  
772 netic field, *Measurement Science and Technology*, *19*(5), 055104, doi:10.1088/0957-  
773 0233/19/5/055104.
- 774 Luhmann, J. G. (1990), 'Wave' analysis of Venus ionospheric flux ropes, *Washington*  
775 *DC American Geophysical Union Geophysical Monograph Series*, *58*, 425–432, doi:  
776 10.1029/GM058p0425.
- 777 Luhmann, J. G., and J. U. Kozyra (1991), Dayside pickup oxygen ion precipitation at  
778 Venus and Mars - Spatial distributions, energy deposition and consequences, *Journal*  
779 *of Geophysical Research: Space Physics*, *96*, 5457–5467, doi:10.1029/90JA01753.
- 780 Luhmann, J. G., and C. T. Russell (1997), Venus: Magnetic field and magnetosphere,  
781 in *Encyclopedia of Planetary Science*, Encyclopedia of Earth Science, pp. 905–907,  
782 Springer Netherlands.
- 783 Luhmann, J. G., C. T. Russell, and R. C. Elphic (1984), Time scales for the decay of in-  
784 duced large-scale magnetic fields in the Venus ionosphere, *Journal of Geophysical Re-*  
785 *search: Space Physics*, *89*, 362–368, doi:10.1029/JA089iA01p00362.
- 786 Lundin, R., S. Barabash, Y. Futaana, J.-A. Sauvaud, A. Fedorov, and H. Perez-de-Tejada  
787 (2011), Ion flow and momentum transfer in the Venus plasma environment, *Icarus*, *215*,  
788 751–758, doi:10.1016/j.icarus.2011.06.034.
- 789 Lundin, R., S. Barabash, Y. Futaana, M. Holmström, H. Perez-De-Tejada, and J.-  
790 A. Sauvaud (2013), A large-scale flow vortex in the Venus plasma tail and its  
791 fluid dynamic interpretation, *Geophysical Research Letters*, *40*, 1273–1278, doi:  
792 10.1002/grl.50309.
- 793 Lundin, R., S. Barabash, Y. Futaana, M. Holmström, J.-A. Sauvaud, and A. Fedorov  
794 (2014), Solar wind-driven thermospheric winds over the Venus North Polar region, *Geo-*  
795 *physical Research Letters*, *41*, 4413–4419, doi:10.1002/2014GL060605.
- 796 Masters, A., N. Achilleos, C. Bertucci, M. K. Dougherty, S. J. Kanani, C. S. Arridge,  
797 H. J. McAndrews, and A. J. Coates (2009), Surface waves on Saturn's dawn flank mag-  
798 netopause driven by the Kelvin-Helmholtz instability, *Planetary and Space Science*, *57*,  
799 1769–1778, doi:10.1016/j.pss.2009.02.010.
- 800 Masunaga, K., Y. Futaana, M. Yamauchi, S. Barabash, T. L. Zhang, A. O. Fedorov,  
801 N. Terada, and S. Okano (2011), O<sup>+</sup> outflow channels around Venus controlled by di-  
802 rections of the interplanetary magnetic field: Observations of high energy O<sup>+</sup> ions



- 803 around the terminator, *Journal of Geophysical Research (Space Physics)*, *116*, A09326,  
804 doi:10.1029/2011JA016705.
- 805 McComas, D. J., H. E. Spence, C. T. Russell, and M. A. Saunders (1986), The av-  
806 erage magnetic field draping and consistent plasma properties of the Venus mag-  
807 netotail, *Journal of Geophysical Research: Space Physics*, *91*, 7939–7953, doi:  
808 10.1029/JA091iA07p07939.
- 809 McElroy, M. B., M. J. Prather, and J. M. Rodriguez (1982), Loss of  
810 oxygen from Venus, *Geophysical Research Letters*, *9*, 649–651, doi:  
811 10.1029/0GPRLA000009000006000649000001.
- 812 Möstl, U. V., N. V. Erkaev, M. Zellinger, H. Lammer, H. Gröller, H. K. Biernat, and  
813 D. Korovinskiy (2011), The Kelvin-Helmholtz instability at Venus: What is the unsta-  
814 ble boundary?, *Icarus*, *216*, 476–484, doi:10.1016/j.icarus.2011.09.012.
- 815 Nykyri, K., and A. Otto (2001), Plasma transport at the magnetospheric boundary due to  
816 reconnection in Kelvin-Helmholtz vortices, *Geophysical research letters*, *28*, 3565–3568,  
817 doi:10.1029/2001GL013239.
- 818 Ong, R. S. B., and N. Roderick (1972), On the kelvin-Helmholtz instability of the  
819 Earth's magnetopause, *Planetary and Space Science*, *20*(1), 1–10, doi:10.1016/0032-  
820 0633(72)90135-3.
- 821 Penz, T., N. Erkaev, H. Biernat, H. Lammer, U. Amerstorfer, H. Gunell, E. Kallio,  
822 S. Barabash, S. Orsini, A. Milillo, et al. (2004), Ion loss on mars caused by the  
823 kelvin-helmholtz instability, *Planetary and Space Science*, *52*(13), 1157–1167, doi:  
824 10.1016/j.pss.2004.06.001.
- 825 Pope, S. A., M. A. Balikhin, T. L. Zhang, A. O. Fedorov, M. Gedalin, and S. Barabash  
826 (2009), Giant vortices lead to ion escape from Venus and re-distribution of plasma in  
827 the ionosphere, *Geophys. Res. Lett.*, *36*(7), L07,202, doi:10.1029/2008GL036977.
- 828 Pope, S. A., T. L. Zhang, M. A. Balikhin, M. Delva, L. Hvizdos, K. Kudela, and A. P.  
829 Dimmock (2011), Exploring planetary magnetic environments using magnetically un-  
830 clean spacecraft: a systems approach to VEX MAG data analysis, *Ann. Geophys.*, *29*(4),  
831 639–647, doi:10.5194/angeo-29-639-2011.
- 832 Price, D. J. (2008), Modelling discontinuities and Kelvin-Helmholtz instabili-  
833 ties in SPH, *Journal of Computational Physics*, *227*(24), 10,040–10,057, doi:  
834 10.1016/j.jcp.2008.08.011.

- 835 Rodriguez, J. M., M. J. Prather, and M. B. McElroy (1984), Hydrogen on Venus - Ex-  
 836 ospheric distribution and escape, *Planetary and space science*, *32*, 1235–1255, doi:  
 837 10.1016/0032-0633(84)90067-9.
- 838 Rong, Z. J., S. Barabash, G. Stenberg, Y. Futaana, T. L. Zhang, W. X. Wan, Y. Wei, X. D.  
 839 Wang, L. H. Chai, and J. Zhong (2015), The flapping motion of the Venusian magneto-  
 840 tail: Venus Express observations, *Journal of Geophysical Research (Space Physics)*, *120*,  
 841 5593–5602, doi:10.1002/2015JA021317.
- 842 Russell, C. T. (1986), The Venus magnetotail, *Advances in Space Research*, *6*, 291–300,  
 843 doi:10.1016/0273-1177(86)90045-1.
- 844 Russell, C. T. (1990), Magnetic flux ropes in the ionosphere of Venus, *Washington*  
 845 *DC American Geophysical Union Geophysical Monograph Series*, *58*, 413–423, doi:  
 846 10.1029/GM058p0413.
- 847 Russell, C. T., and R. C. Elphic (1979), Observation of magnetic flux ropes in the Venus  
 848 ionosphere, *Nature*, *279*(5714), 616–618, doi:10.1038/279616a0.
- 849 Russell, C. T., R. C. Elphic, and J. A. Slavin (1980), Limits on the possible in-  
 850 trinsic magnetic field of Venus, *J. Geophys. Res.*, *85*(A13), 8319–8332, doi:  
 851 10.1029/JA085iA13p08319.
- 852 Sonnerup, B. U. Ö., and M. Scheible (1998), Minimum and Maximum Variance Analysis,  
 853 *ISSI Scientific Reports Series*, *1*, 185–220.
- 854 Spreiter, J. R., A. L. Summers, and A. W. Rizzi (1970), Solar wind flow past nonmag-  
 855 netic planets-Venus and Mars, *Planetary and Space Science*, *18*(9), 1281–1299, doi:  
 856 10.1016/0032-0633(70)90139-X.
- 857 Sundberg, T., S. A. Boardsen, J. A. Slavin, L. G. Blomberg, and H. Korth (2010), The  
 858 Kelvin-Helmholtz instability at Mercury: An assessment, *Planetary and Space Science*,  
 859 *58*, 1434–1441, doi:10.1016/j.pss.2010.06.008.
- 860 Svedhem, H., D. V. Titov, F. W. Taylor, and O. Witasse (2007a), Venus as a more Earth-  
 861 like planet, *Nature*, *450*(7170), 629–632, doi:10.1038/nature06432.
- 862 Svedhem, H., D. V. Titov, D. McCoy, J. P. Lebreton, S. Barabash, J. L. Bertaux,  
 863 P. Drossart, V. Formisano, B. Häusler, O. Korablev, W. J. Markiewicz, D. Neve-  
 864 jans, M. Pätzold, G. Piccioni, T. L. Zhang, F. W. Taylor, E. Lellouch, D. Koschny,  
 865 O. Witasse, H. Eggel, M. Warhaut, A. Accomazzo, J. Rodriguez-Canabal, J. Fab-  
 866 rega, T. Schirmann, A. Clochet, and M. Coradini (2007b), Venus Express-The first  
 867 European mission to Venus, *Planetary and Space Science*, *55*(12), 1636–1652, doi:

868 10.1016/j.pss.2007.01.013.

869 Tanaka, T. (1993), Configurations of the solar wind flow and magnetic field around the  
870 planets with no magnetic field: Calculation by a new MHD simulation scheme, *Journal*  
871 *of Geophysical Research: Space Physics*, *98*, 17,251–17,262, doi:10.1029/93JA01516.

872 Terada, N., S. Machida, and H. Shinagawa (2002), Global hybrid simulation of the Kelvin-  
873 Helmholtz instability at the Venus ionopause, *J. Geophys. Res.*, *107*(A12), 1471, doi:  
874 10.1029/2001JA009224.

875 Thomas, V. A., and D. Winske (1991), Kinetic simulation of the Kelvin-Helmholtz in-  
876 stability at the Venus ionopause, *Geophysical research letters*, *18*, 1943–1946, doi:  
877 10.1029/91GL02552.

878 Titov, D. V., H. Svedhem, D. Koschny, R. Hoofs, S. Barabash, J. L. Bertaux, P. Drossart,  
879 V. Formisano, B. Häusler, O. Korabely, W. J. Markiewicz, D. Nevejans, M. Pät-  
880 zold, G. Piccioni, T. L. Zhang, D. Merritt, O. Witasse, J. Zender, A. Acco-  
881 mazzo, M. Sweeney, D. Trillard, M. Janvier, and A. Clochet (2006), Venus Ex-  
882 press science planning, *Planetary and Space Science*, *54*(13-14), 1279–1297, doi:  
883 10.1016/j.pss.2006.04.017.

884 Walker, S. N., M. A. Balikhin, T. L. Zhang, M. E. Gedalin, S. A. Pope, A. P. Dimmock,  
885 and A. O. Fedorov (2011), Unusual nonlinear waves in the Venusian magnetosheath, *J.*  
886 *Geophys. Res.*, *116*(A1), A01,215, doi:10.1029/2010JA015916.

887 Wolff, R., B. Goldstein, and S. Kumar (1979), A model of the variability of the  
888 venus ionopause altitude, *Geophysical Research Letters*, *6*(5), 353–356, doi:  
889 10.1029/GL006i005p00353.

890 Wolff, R. S., B. E. Goldstein, and C. M. Yeates (1980), The onset and development of  
891 Kelvin-Helmholtz instability at the Venus ionopause, *J. Geophys. Res.*, *85*(A13), 7697–  
892 7707, doi:10.1029/JA085iA13p07697.

893 Zhang, T. L., W. Baumjohann, M. Delva, H.-U. Auster, A. Balogh, C. T. Russell,  
894 S. Barabash, M. Balikhin, G. Berghofer, H. K. Biernat, H. Lammer, H. Lichtenegger,  
895 W. Magnes, R. Nakamura, T. Penz, K. Schwingenschuh, Z. Vörös, W. Zambelli, K.-  
896 H. Fornacon, K.-H. Glassmeier, I. Richter, C. Carr, K. Kudela, J. K. Shi, H. Zhao,  
897 U. Motschmann, and J.-P. Lebreton (2006), Magnetic field investigation of the Venus  
898 plasma environment: Expected new results from Venus Express, *Planetary and Space*  
899 *Science*, *54*, 1336–1343, doi:10.1016/j.pss.2006.04.018.

- 900 Zhang, T. L., M. Delva, W. Baumjohann, M. Volwerk, C. T. Russell, S. Barabash, M. Ba-  
901 likhin, S. Pope, K. H. Glassmeier, K. Kudela, C. Wang, Z. Vörös, and W. Zam-  
902 belli (2008a), Initial Venus Express magnetic field observations of the Venus bow  
903 shock location at solar minimum, *Planetary and Space Science*, *56*(6), 785–789, doi:  
904 10.1016/j.pss.2007.09.012.
- 905 Zhang, T. L., M. Delva, W. Baumjohann, M. Volwerk, C. T. Russell, S. Barabash, M. Ba-  
906 likhin, S. Pope, K. H. Glassmeier, C. Wang, and K. Kudela (2008b), Initial Venus Ex-  
907 press magnetic field observations of the magnetic barrier at solar minimum, *Planetary*  
908 *and Space Science*, *56*(6), 790–795, doi:10.1016/j.pss.2007.10.013.
- 909 Zhang, T. L., Q. M. Lu, W. Baumjohann, C. T. Russell, A. Fedorov, S. Barabash, A. J.  
910 Coates, A. M. Du, J. B. Cao, R. Nakamura, W. L. Teh, R. S. Wang, X. K. Dou,  
911 S. Wang, K. H. Glassmeier, H. U. Auster, and M. Balikhin (2012), Magnetic Reconnec-  
912 tion in the Near Venusian Magnetotail, *Science*, *336*, 567, doi:10.1126/science.1217013.