A teardrop-shaped ionosphere at Venus in tenuous solar wind

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ABSTRACT

A very tenuous solar wind regime, following a series of large coronal mass ejections, impacted Venus during early August, 2010. STEREO-B downstream from Venus observed that the solar wind density at Earth orbit dropped to ~0.1 n/cm² and persisted at this value over 1 day. A similar low value was observed at Earth in 1999 and has attracted comprehensive attention (Lazarus, A.J., 2000. Solar physics: the day the solar wind almost disappeared. Science 287, 2172–2173.), especially its consequences on Earth’s ionosphere and magnetosphere (Lockwood, M., 2001. Astronomy: the day the solar wind nearly died. Nature 409, 677–679.). We now have an opportunity to examine the response of Venus’ ionosphere to such a tenuous solar wind. After Venus Express spacecraft entered the ionosphere near the terminator, it continuously sampled O⁺-dominated planetary plasma on the nightside till it left the optical shadow region when Venus Express was located at 2 R<s><sub>V</sub></sup> (Venus’ Radii) to the Venus center and 1.1 R<s><sub>V</sub></sup> to the Sun–Venus line. Moreover, the O⁺ speed was lower than the gravitational escape speed. We interpret this low-speed O⁺ as a constituent of the extended nightside ionosphere as a consequence of long-duration (18 h) tenuous solar wind, because the very low dynamic pressure enhances the source and reduces the sink of the nightside ionosphere. Though the full extent of the nightside ionosphere is not known due to the limitation of spacecraft’s trajectory, our results suggest that the global configuration of Venus’ ionosphere could resemble a teardrop-shaped cometary ionosphere.

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1. Introduction

Planetary ionospheres are created by ionization of their neutral atmosphere. In the inner solar system, the dayside part of any planetary ionosphere is mainly produced by the solar extreme ultraviolet and X-ray photon flux, but the nightside part is maintained by different processes relying on the strength of its intrinsic magnetic field (Witas et al., 2008). For Earth with a strong dipole, the closed magnetic flux tubes at tropical and midlatitudes act as a reservoir for plasma, called the plasmaosphere, which is created during the day by photoionization and carried upward by light ions. The plasma co-rotates with Earth and can flow back down on the night, tending to maintain the density in the ionosphere (Kelley, 2009). Venus has not only a negligible intrinsic magnetic field, but also a very low rotation rate (243 Earth day period) with a long night time (58 Earth days), thus the nightside ionosphere must be maintained through some processes different from the Earth case.

With in-situ measurements by Venera 9 and 10, and the later long-duration mission Pioneer Venus Orbiter (PVO), it has been established that the main source of the nightside ionospheric plasma is the dayside ionospheric plasma crossing the terminator driven by plasma pressure gradients (Knudsen et al., 1980a; Cravens et al., 1983; Brace and Kliore, 1991; Brace et al., 1995). A small and variable source of ionization is due to the precipitation of some portion of the energetic electrons that were detected at high altitudes in the planetary wake (Gringaus et al., 1977; Spenner et al., 1981, 1996). The nightside transferterminator flow, mainly consisting of O⁺, takes place about 150–300 km above the surface, and the flow speed can reach several kilometers per second at higher altitudes (see the review by Brace et al., 1995). Thus an ion inside the flow can move from SZA (solar zenith angle)=45° to
Since the motion of ionospheric plasma is also largely affected by the magnetic field, the strength of magnetic fields in the dayside and the terminator ionosphere crucially affects the transterminator flow. The transterminator flow varies with solar wind conditions because the induced magnetosphere, between the shocked solar wind plasma and the ionosphere, is created through the interaction of planetary plasma with variable solar wind. To keep the pressure balance between incident solar wind plasma and the sum of magnetic pressure and plasma pressure within the induced magnetosphere and ionosphere, the ionosphere will be magnetized under sufficiently high solar wind dynamic pressure (SWDP). Thus one effect of high SWDP is choking off much of the transport of ions from the dayside when the magnetic field pervades the entire ionosphere on both dayside and nightside (Cravens et al., 1982; Russell et al., 2006). Another effect is that high solar wind momentum flux causes high loss rate of planetary ions if the efficiency of momentum transfer from solar wind does not vary too much (see review by Dubinin et al., 2011). The former effect reduces the source as well as the latter enhances the sink of the ionospheric plasma on the nightside, thus the nightside ionosphere must shrink as a result. On the contrary, when the SWDP remains low for a long time, one may expect that a part of heavy ions in the transterminator flow accumulates on the nightside, at least within several days (i.e., time scale of the lifetime of O⁺), and thus enlarge the nightside ionosphere. But this hypothesis has not been examined in detail with PVO data because the periapsis passages only covered the near-tail region at altitudes of 150–3000 km (Brace and Kliore, 1991).

In fact, the morphology of Venus’ nightside ionosphere resembles a cometary tail in many aspects, though Venus is a large solid object with a thin exosphere while an active comet near the Sun is a small object with a thick escaping atmosphere. Due to the absence of intrinsic magnetic fields on both, comets have some similarities processes of interaction between solar wind and ionosphere to those on Venus (Russell et al., 1982; Luhmann, 1991) and Mars (Lundin et al., 2008). It has been found that the nightside ionosphere generally becomes fringed above 1000 km (Brace et al., 1987). In analogy to comets, the fringes were called “tail rays” and the entire region was called “ionotail” to denote its difference from a typical ionosphere (Brace and Kliore, 1991). Nevertheless, the global configurations of the ionosphere at Venus and comets are quite different. The altitudes of Venus’ ionopause are usually comparable on both dayside and nightside, i.e., several hundred km (Brace and Kliore, 1991); while a cometary ionopause on the nightside is usually much more distant than on the dayside, thus it looks like a teardrop-shaped region (Gombosi et al., 1996).

Here we focus on the response of Venus’ nightside ionosphere to tenuous solar wind. The current mission Venus Express (VEX) is more suitable for this purpose because it is able to sample the mid-magnetotail (1−3 R_v (Venus’ radii)), a region never crossed by PVO (Zhang et al., 2006). An opportunity appeared on August 3–4, 2010, when the solar wind density gradually decreased from 50 /cm³ to an extremely low value as 0.2 /cm³ at Venus orbit and remained at this value over 1 day. The height of terminator ionopause is particularly of interest, which is determined by the balance between the sum of thermal pressure and magnetic pressure in the sheath and the thermal pressure in the ionosphere. It has been found that the total pressure in the sheath is linearly correlated to the incident SWDP (Phillips et al., 1988), thus in this paper we will directly consider the effect of tenuous solar wind as that of very low SWDP.

2. Instrumentations and observations

2.1. Instrumentations

VEX has an elliptical polar orbit with a 24-h period. The magnetometer (MAG) onboard VEX continuously operates. The Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) (Barabash et al., 2006) onboard VEX, including an Ion Mass Analyzer (IMA) and an Electron Spectrometer (ELS), only operates for several hours near each periapsis. IMA performs ion measurements in the energy range of 0.01–36 keV/charge with an energy resolution of 7%, and it covers the masses of H⁺, He⁺, He²⁺, O⁺ and heavier ions in the range of 20–80 amu/q. The total IMA field of view is 90° × 360° but is partially blocked by the spacecraft body (~25%). In maximum resolution mode, IMA measures the distribution function over the full energy and elevation ranges during 192 s. ELS is an axially symmetric quadrupole analyzer. It has a field of view of 360° × 4°, with the 360° measurement plane divided into 16 sectors, each 22.5° wide; the energy resolution (ΔE/E) is 7%.

2.2. Solar wind conditions at venus orbit

During early August, 2010, STEREO-B (STB) stayed around the Earth’s orbit (1.06 AU), and the separation angle with Venus (0.72 AU) was about 18° (Fig. 1). Therefore, the solar wind bulk properties at Venus orbit can be inferred from STB PLASTIC (Galvin et al., 2008) measurements by assuming a spherical expansion of the solar wind, i.e., the velocity does not change while the magnetic field strength and density are estimated by multiplying it by 1/R², where R is 0.72 (AU).

The magnetic field data show that a series of Interplanetary Coronal Mass Ejections (ICMEs) successively impacted VEX and STB during August 1–3, and thus we can determine a 17.5 h time delay through matching the first jumps in the magnetic field observations. As shown in the top panel of Fig. 2, the scaled (×2) and time-shifted (−17.5 h) STB magnetic field (Acuna et al., 2008) is overall consistent with VEX/MAG data. The periodic peaks (with a 24-h period) in VEX magnetic field data denote the magnetosheath region, where the magnitudes of magnetic field reached 30–60 nT due to compression (Zhang et al., 2008a). IMA generally starts to sample solar wind several hours before it crossed into the magnetosheath region. For this event, IMA was also shortly switched on to sample solar wind at apoapsis on August 2 and 4. Though IMA’s detector is roughly looking at the Sun, it may significantly underestimate the solar wind density if the velocity has a large angle with the Sun–Venus line, because of Field-Of-View limitation. The circles in second and third
panel show estimated density and velocity using linear fitting (Fraenz et al., 2006), which are roughly consistent with the scaled STB data during August 3–6. Yet IMA significantly underestimated the density during August 1–2 comparing to scaled STB data, probably due to the large and variable $V_Y$ (not shown).

This paper focuses on the effect of the tenuous solar wind regime. From 1400 UT on August 3 to 0100 UT on August 5, the solar wind density at Venus orbit was estimated at 0.2 #/cm$^3$. The corresponding value 0.1 #/cm$^3$ at Earth orbit was the same as the lowest value ever observed before (Lazarus, 2000; Lockwood, 2001). The SWDP at Venus orbit during this time was about 0.1 nPa, which is one order lower than the averaged value ranges from 4.5 nPa (at solar max) to 6.6 nPa (at solar min) (Russell et al., 2006). In fact, this value is the minimum throughout the whole STEREO database during 2007–2010. Note that the SWDP remained at this value for 18 h before the VEX periapsis crossing at 0730 UT on August 4.

2.3. Overview of the response of Venus’ ionosphere

Fig. 3 shows the VEX trajectory on August 4 in Venus Solar Orbital (VSO) coordinate system. The x-axis points from Venus

Fig. 2. An overview of solar wind conditions at Venus orbit during August 1–6, 2010. From top to bottom: magnetic field (B), proton density (N), solar wind speed (V) and solar wind dynamic pressure ($P_{SW}$). The black lines are time-shifted (+17.5 h) and scaled ($\times 2$) STB data to Venus orbit. The red line and circles are VEX data. The peaks in VEX magnetic field data repeatedly appearing each orbit correspond to the magnetosheath field, which can be an indicator of periapsis crossing. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Fig. 3. VEX trajectory in the cylindrical coordinate system during 0658–0858 UT on August 4, 2010. $R_{VY} = \sqrt{Y^2 + Z^2}$, where X, Y, and Z are in the Venus Solar Orbital (VSO) coordinate system.
towards the Sun. The z-axis points to the north and is perpendicular to the orbital plane of Venus. The y-axis completes the right-handed coordinate system. Here we also plot the averaged position of the bowshock and ion composition boundary (ICB) during the solar minimum 2006 (Martinecz et al., 2008). The ICB is an inner boundary of the magnetosheath defined by a decrease in energetic protons and energetic electrons. Though the position of ICB is expected to vary with solar activity level, we may directly use the results by Martinecz et al. (2008), because 2010 is still not subject to the orbital plane of Venus. The y-axis completes the right-handed coordinate system. Here we also plot the averaged position of the bowshock and ion composition boundary (ICB) during the solar minimum 2006 (Martinecz et al., 2008). The ICB is an inner boundary of the magnetosheath defined by a decrease in energetic protons and energetic electrons. Though the position of ICB is expected to vary with solar activity level, we may directly use the results by Martinecz et al. (2008), because 2010 is still not subject to the solar maximum. Therefore, the trajectory predicts that VEX sampled the terminator ionosphere and the wake region. Fig. 4 shows the observations of six periaxis crossings by IMA and ELS during August 1–6. On each day VEX successively sampled solar wind, magnetosheath, terminator ionosphere, wake region, and finally re-entered the solar wind via the magnetosheath. One may note that the outbound bowshock was outside of the observation intervals plotted for August 2–3. This is because the bowshock moves outward when the solar wind density and Mach number is low (Lockwood, 2001; Zhang et al., 2008b). Here the Mach numbers (scaled from STB data) lowered to 2.6 and 1.5 for the two periaxis crossings, respectively. The terminator ionosphere can be recognized from the absence of the sheath-like electrons (> 50 eV) and the appearance of a photoelectron peak shifted by the spacecraft potential to ~18 eV (Coates et al., 2008, 2011). The plasma sheet (PS), which is a thin layer of dense accelerated planetary plasma spatially coinciding with the current sheet of the magnetotail, can be discerned by the reversal of By and energization of ions (Fedorov et al., 2008).

The gradual energization of ions from tens of eV to several keV with increasing altitude in the wake region, as seen during ICME passage August 1–2 and during quiet time August 5–6, characterizes the magnetotails of Venus and Mars (Fedorov et al., 2008). However, the ions above 50 eV disappeared in the tail region during the low SWDP period August 3–4. During the periaxis crossing on August 4 when the SWDP remained at the minimum level 0.1 nPa, the magnetic field inside the terminator ionosphere exhibited some small-scale magnetic structures instead of large-scale field. This is the typical feature of the unmagnetized states observed at both terminator ionosphere (Zhang et al., 2008a) and dayside ionosphere (Luhmann and Cravens, 1991). The tail field became fairly weak, and sometimes lowered to less than 1 nT. Yet the terminator ionosphere and the tail region were still strongly magnetized on August 3, and this can be treated as a transition status between the ionosphere on August 2 (high SWDP) and the ionosphere on August 4 (very low SWDP). In order to show the unusual features of the ionosphere after the long-duration low SWDP, we can compare the VEX observations on August 4 to that on August 6. Here the ionosphere on August 6 is chosen as a “normal” ionosphere for two reasons: (1) the solar wind condition was at a normal level, i.e., density 1–2#/cm³ and speed 360–400 km/s; (2) the orientation and magnitude of IMF were quite similar to that on August 4. As shown by the top panels of Fig. 5a, for both days the total field strength is ~5 nT and the direction is Y-dominated orientation in the solar wind regimes (before 0715 UT). This similarity is crucially important for the comparison because the shape and size of the induced magnetosphere depend on the strength and orientation of the IMF.

2.4. Behavior of Venus’ ionosphere in the tenuous solar wind

The measurements of the “normal” ionosphere are depicted in the left of Fig. 5a. The electron and ion energy spectrums show different plasma regimes: solar wind (0700–0718 UT),
magnetosheath (0718–0730 UT), terminator ionosphere (0732–0737 UT), wake region (0737–0811 UT), and then the magnetosheath (0811–0900 UT). The terminator ionosphere is discerned from the absence of sheath-like electrons and the appearance of photoelectrons. The large drop in magnetic field strength during 0734–0736 UT suggests that the lower ionosphere was not magnetized. VEX crossed the plasma sheet during 0755–0800 UT when the polarity of $B_X$ was reversed and the ions were energized to 1 keV. The gradual acceleration of ions with increasing altitude in the wake region (0737–0811 UT) is a common feature for various tail-crossing orbits of VEX and also Mars Express on Mars (Fedorov et al., 2008). The 10–50 eV heavy ion (mainly $O^+$) velocity (fourth panel) was observed to be above 10 km/s when VEX went outside the terminator ionosphere, which indicated that those ionospheric ions were escaping (at VEX altitude the escaping velocity is less than 10 km/s). Note that the heavy ion velocity is calculated after subtracting VEX velocity and considering the spacecraft potential.

Comparing to the observations on August 6, one can find some well-known consequences of low SWDP on August 4 (right panels of Fig. 5a). The terminator ionosphere (0728–0739 UT) expanded and became “unmagnetized”, of which the typical feature is no large-scale magnetic field but with small-scale magnetic structures (Luhmann and Cravens, 1991); The tail field decreased (sometimes

Fig. 5. Comparison of ionospheres under normal and very low SWDP. The left half is for August 6 as a normal situation, while the right half is for August 4. (a) From top to bottom: magnetic field, electron energy spectrum, ion energy spectrum, 10–50 eV heavy ion velocity. (b) Upper panel: the 10–50 eV heavy ion counts along VEX trajectory in the cylindrical coordinate system. Lower panel: the velocity vector of 10–50 eV heavy ion projected on $X–Z$ and $X–Y$ plane in VSO coordinate system.
lowered to less than 1 nT), implying that little IMF penetrated into the wake region. The most striking difference in right panels from left panels is the absence of the gradual acceleration of ions with increasing altitude in the wake region, instead, 10–50 eV ions were recorded during 0742–0804 UT until VEX moved to X = −2.0 R\(_V\). These ions were all O\(^{+}\) as seen from the example of Energy-Mass matrix (the inserted panel), thus they must come from the dayside ionosphere. It is worth noting that the speed of O\(^{+}\) was less than the gravitational escape speed (7.2 km/s at 1 R\(_V\) high), thus this region probably did not disconnect from the ionosphere. The flow vectors shown in Fig. 5b suggest that the terminator flow still existed but with lower speed compared to that under normal SWDP. The O\(^{+}\) regime during 0742–0804 UT was not consistent with a small-scale tail ray, which is generally highly structured and bounded by current sheets (Brace and Kliore, 1991).

The upper panels of Fig. 5b illustrate the distribution of 10–50 eV heavy ion counts along the VEX trajectories. For the normal condition (left panel), ionospheric heavy ions disappeared at X = −1.4 R\(_V\), but it persisted until X = −2.0 R\(_V\) with lower count rate on August 4 (right panel). Moreover, one should note that R\(_{cp}^\) (distance to the Sun-Venus line) was 1.1 R\(_V\) when X = −2.0 R\(_V\), and this phenomenon is contrary to the statistical results demonstrated by Fedorov et al. (2008), who showed that there is generally no low-energy ions beyond R\(_{cp}^\) = 0.8 R\(_V\) (see their Fig. 4). Since O\(^{+}\) is the dominant ion species of terminator flow responsible for the maintenance of the nightside ionosphere (Miller and Whitten, 1991), we interpret this unusual phenomenon as that VEX sampled the nightside ionosphere. In other words, the nightside ionosphere was significantly extended tailward. Since LMA only scans a polar angle range of 90° and is partly obscured by the spacecraft (Barabash et al., 2006), it may significantly underestimate the particle flux and density. But we may estimate the O\(^{+}\) density from the magnetic pressure by assuming that the total pressure (sum of magnetic pressure and plasma pressure) is equivalent in adjacent regions. The magnetic pressure around 0800 UT is about 0.02 nPa, and if the total pressure around 0750 UT is the same value, the O\(^{+}\) density at 0750 UT (altitude 3000 km, SZA = 143°) would be \(\sim 750 \text{}/\text{cm}^3\), assuming \(T_\text{i} = 0.2 \text{eV}\) according to PVO measurement at this region (Knudsen et al., 1980b). This value approaches to the O\(^{+}\) density observed by PVO under 1000 km on the nightside ionosphere during solar maximum (Miller and Whitten, 1991).

The dayside ionopause also expanded on August 4 due to the very low SWDP. The SZA/altitudes at the inbound crossings of the ionopause on August 4 and 6 were 60°/650 km and 65°/400 km, respectively. The ionopause at the subsolar point (SZA = 0°) must be under 650 km on August 4 according to numerous PVO observations (Brace and Kliore, 1991).

3. Discussion

We have compared the VEX observations in Venus’ ionosphere and wake under normal solar wind conditions and after a long-duration tenuous solar wind. The observations confirm some phenomena in response of the plasma environment at Venus to the very low dynamic pressure already revealed by the PVO mission, e.g., the terminator ionosphere expands and becomes “unmagnetized”, but the new observations widen our knowledge of this extreme condition, namely that the nightside ionosphere is significantly extended tailward. The long-duration (18 h) tenuous solar wind is the main cause of this phenomenon, but the VEX orbit, which is able to sample the mid-magnetotail (up to 2 R\(_V\) for our event), is also of advantage for discovering it, because PVO never crossed the mid-magnetotail (1–3 R\(_V\)) (Zhang et al., 2006). However, the VEX orbit still cannot fully determine the global morphology and length of the nightside ionosphere for our event because it was far from the central tail (R\(_{cp}^\text{X}\) was always larger than 0.85 R\(_V\)) and left the wake region at 2.0 R\(_V\), tailward of Venus.

The plasma composing the tailward expanded ionosphere is mainly supplied by the dayside ionosphere through terminator flow. The low SWDP results in an enhanced flow rate because the flow channel becomes wider and less IMF penetrates into the terminator ionosphere to block the flow (e.g., Russel et al., 2006). However, the terminator flow does not always increase when SWDP keeps decreasing. Brace et al. (1995) pointed out that terminator flow will be diverted upward to populate the newly formed ionosphere above when SWDP is at some low level, thus may reduce the nightward flow at lower altitudes. This “saturation effect” can also be seen in our case: the speed of nightward flow is significantly smaller under lower SWDP (Fig. 5b). But there is another consequence of low SWDP important to maintain the nightside ionosphere, i.e., reduction of the ion loss due to gaining momentum from solar wind, because the SWDP itself stands for the available solar wind momentum (Dubinin et al., 2011; Wei et al., 2012). Here the VEX observations under the extremely low SWDP condition should be explained by the combined effect of enhanced source (terminator flow) and reduced sink (ion loss into the interplanetary space). Because the lifetime of O\(^{+}\) is several days while the time scale of O\(^{+}\) transport across the terminator is an hour (mentioned in Section 1.), the tailward extended ionosphere was perhaps formed by the accumulation of the plasma transported from the dayside within the 18-hour duration of low SWDP. Knudsen (1998) have also suggested a tailward extension of Venus’ ionosphere from solar minimum to solar maximum. He interpreted the extension as being only a consequence of an enhanced source: a high solar EUV level results in a higher ionopause at the terminator, and then an enhanced source forms. In our case not only the source is enhanced but also the sink is reduced.

The tailward expanded ionosphere in the tenuous solar wind may resemble a “teardrop-shaped” cometary ionosphere as illustrated by the upper panel of Fig. 6. For comparison, we also depict a magnetized ionosphere under normal SWDP during solar minimum in the lower panel. According to VEX observations during solar minimum (Angsmann et al., 2011), it is known that Venus’ ionosphere is frequently magnetized. While PVO observations during solar maximum also suggest that Venus’ ionosphere is also frequently magnetized under high SWDP. Luhmann and Cravens (1991). Therefore, here the illustration of “normal SWDP” case during solar minimum is modified from Fig. 1 in the review paper by Luhmann and Cravens (1991). For comet Halley, Gombosi et al. (1996) suggested that distance of the dayside (nightside) ionopause to the center of the nucleus could be 3300 (17,000) km. For our event, if we apply this ratio 1:5 (3300:17,000) to the Venus ionosphere, along the Sun–Venus line, the dayside ionopause at X = 1.1 R\(_V\) (650 km above the surface) corresponds to a nightside ionopause at X = −5.5 R\(_V\). Though Venus is a large body with a thin ionosphere compared to a near-Sun comet, 5.5 R\(_V\) is not impossible if we consider its larger gravity and the long duration (18 h) low SWDP period, during which there could be enough plasma transported from the dayside to the nightside.

To our knowledge, the SWDP 0.1 nPa is not the extrema ever happened to Venus. The PVO mission has observed the response of the plasma environment at Venus to even more tenuous solar wind. In the whole life of the PVO mission, the minimum of recorded solar wind density is 0.1 \#/\text{cm}^3 (Jarvinen et al., 2008), which is even lower than 0.2 \#/\text{cm}^3 on August 4. The normal range of SWDP at Venus orbit is estimated at between 4.5 nPa (at solar max) and 6.6 nPa (at solar min) as revealed by PVO mission (Russell et al., 2006). For our event (solar minimum), VEX crossed the ionopause at 650 km at SZA = 60° on August 4 when
The SWDP lowered to ~0.1 nPa, while at 400 km at SZA=65° on August 4 when the SWDP was in the normal range ~6 nPa. On January 31, 1980 (solar maximum), PVO recorded an ionopause crossing at 2700 km at SZA=60°, when the SWDP was 0.04 nPa (Russell et al., 1993). For such a case, one can at least expect that the ion loss rate is even smaller than that in our case, thus Venus’ ionosphere at that time may have been larger than in our case.

4. Summary

On August 4, 2010 the solar wind density at Venus orbit decreased to 0.2 #/cm³, while the dynamic pressure dropped to 0.1 nPa. The typical features of the tail region, i.e., the gradual acceleration of ions and a compressed magnetotail, did not appear when Venus Express crossed the wake region. Instead, Venus Express sampled O⁺ dominant ionospheric plasma, and the O⁺ speed was lower than gravitational escape speed. These observations suggest that the nightside ionosphere extended at least 2 Rv from Venus’ center, but the full length is still not known due to the limited coverage of the VEX orbit. However, our results suggest that the global configuration of Venus’ ionosphere could resemble a teardrop-shaped comet-like ionosphere.

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