



Venus Dayside and Nightside Ionosphere Variations During Corotating High-speed Streams: A Statistical Study using Pioneer Venus Orbiter Observations

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Abstract

We present a statistical study of Venus ionospheric variability using about two years of Pioneer Venus Orbiter measurements of the major ions O_2^+ , O^+ , and H^+ during quiet solar wind conditions, solar wind high-speed streams (HSSs), and preceding corotating interaction regions (CIRs). Under quiet solar wind conditions, the dayside ionosphere is characterized by a peak O_2^+ density ($\sim 41 \times 10^4 \text{ cm}^{-3}$) at an altitude of $\sim 164 \text{ km}$ (the V1 layer), an O^+ density peak ($\sim 71 \times 10^3 \text{ cm}^{-3}$) at $\sim 203 \text{ km}$ (the V2 layer), and an H^+ density peak ($\sim 8 \times 10^2 \text{ cm}^{-3}$) at $\sim 423 \text{ km}$, on average. The density of O_2^+ decreases sharply below the O^+ density at an altitude of $\sim 192 \text{ km}$ and below H^+ at $\sim 307 \text{ km}$. The ionosphere is characterized by prominent day–night asymmetries. The asymmetry in the peak ion densities (layer heights) is found to decrease (increase) systematically with altitude. CIRs and HSSs enhance the day–night asymmetries in the peak O_2^+ and O^+ densities compared to their quiet time values. Considering average ionospheric parameters during the CIRs (and preceding high-density heliospheric plasma sheets), significant decreases are recorded in the dayside peak O_2^+ density ($\sim 18\%$), the nightside peak O^+ density ($\sim 41\%$), the altitudes of the dayside O^+ ($\sim 3\%$) and H^+ ($\sim 19\%$) ion density peaks, and the dayside O_2^+/H^+ transition altitude ($\sim 7\%$) compared to their values for the quiet ionosphere. During the HSS impacts, dayside (nightside) ionospheric O_2^+ and O^+ peak densities exhibit decreases by $\sim 12\%$ ($\sim 64\%$) and $\sim 13\%$ ($\sim 44\%$), respectively, compared to their quiet ionospheric values. The results are discussed based on current understanding of the Venus ionospheric dynamics.

Unified Astronomy Thesaurus concepts: Venus (1763); Solar wind (1534); Fast solar wind (1872); Corotating streams (314); Solar coronal mass ejections (310); Planetary ionospheres (2185)

1. Introduction

The inner heliospheric planet Venus (located at a heliocentric distance of $\sim 0.72 \text{ au}$) is a nonmagnetized planet (S. S. Dolginov et al. 1968; C. T. Russell et al. 1980a; J. L. Phillips & C. T. Russell 1987) with a thick atmosphere (W. S. Adams & T. Dunham 1932; P. Connes et al. 1967) and a highly dynamic ionosphere (A. Kliore et al. 1967; K. L. Miller et al. 1980). The ionosphere extends from an altitude of $\sim 100 \text{ km}$ up to a few hundred km on the dayside and several thousand km on the nightside (W. C. Knudsen et al. 1982; J. L. Phillips et al. 1985, 1988; L. H. Brace et al. 1987). In the absence of an intrinsic planetary magnetic field, direct interaction of the electrically conductive ionospheric plasma with supersonic solar wind flow (E. N. Parker 1958) induces ionospheric currents leading to an “induced magnetosphere.” The magnetosphere is characterized by a “bow shock,” a “magnetosheath” of shocked, heated solar wind with interplanetary magnetic field (IMF) draping around the “ionopause” or the outer boundary of the ionosphere (J. Luhmann 1986; J. L. Phillips & D. J. McComas 1991).

Venus is known to have a well-structured ionosphere, dominated by the molecular oxygen ion O_2^+ below the altitude of $\sim 180 \text{ km}$, with dominant atomic oxygen ion O^+ at higher altitudes and a significant contribution of the proton/hydrogen

ion H^+ (H. A. Taylor et al. 1979, 1980a). While the nightside O_2^+ and O^+ ion concentrations are significantly lower than their dayside concentrations, H^+ is more abundant on the nightside than on the dayside (H. A. Taylor et al. 1979). Previous studies confirmed the lack of any seasonal dependence of the ionospheric variation (see L. Brace & A. Kliore 1991), while plasma density exhibits a strong solar cycle dependence where plasma density increases with increasing solar ionizing fluxes (W. C. Knudsen et al. 1986; A. J. Kliore & L. F. Mullen 1989; J. L. Fox & K. Y. Sung 2001; M. Mendillo et al. 2020; G. A. Collinson et al. 2021).

The upper boundary and vertical distributions of the ionosphere are shown to be strongly modulated by variations in the solar wind. L. H. Brace et al. (1980) reported that the dayside ionopause is compressed under high solar-wind dynamic pressure, whereas the nightside ionosphere exhibits extreme variability, developing ionospheric holes (e.g., T. E. Cravens et al. 1982, 1983; W. R. Hoegy & J. M. Grebowsky 2010), plasma clouds, and layered density structures. Enhanced dynamic pressure has been associated with magnetization of the ionosphere (J. G. Luhmann et al. 1983; J. L. Phillips et al. 1985; J. Kar & K. K. Mahajan 1987; A. Angsman et al. 2011). T. McNulty et al. (2010) reported that the energy of the pickup ions around Venus increases during interplanetary coronal mass ejection (ICME) impacts. Several works have reported a significant increase in the ionospheric O^+ escape rate during ICMEs (J. G. Luhmann et al. 2007, 2008; N. J. T. Edberg et al. 2011; A. P. Dimmock et al. 2018; D. Rout et al. 2024) and/or corotating interaction regions (CIRs; J. G. Luhmann et al. 2007; N. J. T. Edberg



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et al. 2011). It may be noted that J. G. Luhmann et al. (2007) studied only one CIR event, while N. J. T. Edberg et al. (2011) did not distinguish between CIRs and ICMEs.

The purpose of this work is to study the impacts of solar wind high-speed streams (HSSs) and CIRs on the Venus ionospheric variations in comparison to its variation under quiet solar wind conditions. HSSs emanating from solar coronal holes (A. S. Krieger et al. 1973) and carrying interplanetary Alfvén waves (P. J. Coleman 1966; J. W. Belcher & L. Davis 1971; M. Neugebauer et al. 1984) interact with the background slow streams to form CIRs, characterized by compressed plasma and magnetic fields (G. L. Siscoe 1972; E. J. Smith & J. H. Wolfe 1976; A. Balogh et al. 1999). While near-Earth HSSs and CIRs and their impacts on the Earth’s magnetosphere–ionosphere system are well studied (see B. T. Tsurutani & W. D. Gonzalez 1987; B. T. Tsurutani et al. 2006, 2024; R. Hajra et al. 2013, 2014a, c, 2014b, 2015a, 2015b, 2017, 2022; A. M. Souza et al. 2016, 2018; O. Mendes et al. 2017; F. L. Guarnieri et al. 2018; R. Hajra & J. V. Sunny 2022; J. V. Sunny et al. 2023, and references therein), inner heliospheric events and their impacts on nonmagnetized solar system bodies are less explored (see R. Hajra et al. 2018, and references therein). In this work, long-term measurements of Venus ionospheric parameters and the upstream solar wind will be utilized to conduct a systematic, statistical study of the ionospheric structure and composition under quiet solar wind conditions, CIRs, and HSSs. Such a study has never been done for Venus, to our knowledge.

2. Database and Methods

2.1. Database

This study is based on measurements of the Venus ionospheric ions and the upstream solar wind plasma and the IMF by the NASA Pioneer Venus Orbiter (PVO; L. Colin & C. F. Hall 1977). The measurements are obtained from the NASA Planetary Data System (PDS; <https://pds-ppi.igpp.ucla.edu/mission/PioneerVenus>). We consider the period from 1978 December through 1980 October, when suitable inner ionospheric measurements are available (note that solar wind plasma and IMF measurements are available from 1978 December through 1988 July). The ionospheric ions were measured by the PVO ion mass spectrometer (OIMS; H. A. Taylor et al. 1980b), and the data are collected from P. Cloutier (2024). The solar wind plasma data measured by the PVO plasma analyzer (OPA; D. S. Intriligator et al. 1980) are obtained from A. Seiff et al. (2024), and IMFs measured by the PVO fluxgate magnetometer (OMAG; C. T. Russell et al. 1980b) are obtained from C. T. Russell & M. Kniffin (2024). The IMF vector components are in the Venus solar orbital (VSO) coordinate system. This system has the x -axis directed from Venus toward the Sun and the y -axis points opposite to Venus’ orbital motion about the Sun. The z -axis completes a right-handed orthogonal coordinate system. The ionopause and the bow shock altitude measurements are obtained from L. H. Brace & R. F. Theis (2024a, 2024b).

2.2. Methods

The upstream solar wind/interplanetary conditions are studied by solar wind plasma and IMF parameters. The solar wind proton speed V_p and density N_p during 1978 December through 1980 October exhibit periodic variations, with

prominent periodicities of ~ 27 and ~ 13 days (see Appendix A Figure 8). These periodicities may be due to multiple HSSs impinging on Venus. Near-Venus solar wind plasma and IMF variations are analyzed to identify solar-wind HSSs and interplanetary CIRs. A typical HSS, emanated from a solar coronal hole (A. S. Krieger et al. 1973), is characterized by a fast rise in V_p to a peak of ~ 500 – 850 km s $^{-1}$, followed by a slower decay (B. T. Tsurutani et al. 1995, 2006). Proton temperature T_p more or less follows the HSS V_p temporal profile. In addition, the HSS is characterized by large-amplitude fluctuations in the IMF components, which are well correlated to the velocity components, indicative of interplanetary Alfvén waves (P. J. Coleman 1966; J. W. Belcher & L. Davis 1971; M. Neugebauer et al. 1984). In the interaction region between the HSS and background slow ($V_p \sim 300$ – 400 km s $^{-1}$) stream, a gradual increase in V_p is accompanied by enhancements in N_p , ram pressure P_{sw} , and IMF magnitude B_0 . This compressed plasma and IMF region is identified as a CIR (E. J. Smith & J. H. Wolfe 1976). It is composed of a compressed, accelerated slow solar wind and a compressed, decelerated HSS, separated by a tangential discontinuity known as a stream interface (SI; J. W. Belcher & L. Davis 1971; L. F. Burlaga 1974; A. J. Hundhausen & L. F. Burlaga 1975; J. T. Gosling et al. 1978). An SI is identified by (1) an abrupt decrease in N_p simultaneously with (2) an increase in T_p , (3) a small increase in V_p , and (4) an increase in alpha-to-proton density ratio. A CIR is preceded by a heliospheric current sheet (HCS; E. J. Smith et al. 1978) and a heliospheric plasma sheet (HPS; D. Winterhalter et al. 1994). An HCS crossing is identified by a simultaneous polarity reversal of the IMF components B_x and B_y (N. F. Ness & J. M. Wilcox 1964; E. J. Smith et al. 1978). The high-density, slow, and cold plasma adjacent to an HCS is called the HPS. See B. T. Tsurutani et al. (2016) for a schematic of a slow stream–HSS interaction and associated structures. We were not able to separate possible ionospheric impacts of HCS/HPS from the CIR impacts.

Following the above methods, we identified 21 HSSs preceded by CIRs. Details of the CIRs and HSSs are listed in Appendix B Table 3. The HSSs are characterized by a maximum solar wind V_p varying between ~ 500 and ~ 799 km s $^{-1}$, with an average (median) V_p of 627 ± 99 (~ 595) km s $^{-1}$ for all HSSs (the number following the $\pm$ symbol is 1σ deviation from the mean V_p). The CIRs continue for a minimum duration of ~ 22 hr to a maximum duration of ~ 3.73 days, with an average (median) duration of 1.81 ± 0.78 (~ 1.56) days for all events. The radial extent varies between ~ 0.21 and ~ 0.82 au, with an average (median) extent of 0.43 ± 0.17 (~ 0.44) au for all CIRs. Inside the compressed CIRs, the N_p peak varies between ~ 37 and ~ 100 cm $^{-3}$, with an average (median) N_p peak of 81 ± 21 (~ 88) cm $^{-3}$, the P_{sw} peak varies between ~ 8 and ~ 44 nPa, with an average (median) P_{sw} peak of 22 ± 9 (~ 21) nPa, the T_p peak varies between $\sim 2.23 \times 10^5$ and $\sim 9.48 \times 10^5$ K, with an average (median) T_p peak of $(5.77 \pm 2.07) \times 10^5$ ($\sim 5.96 \times 10^5$) K, and the B_0 peak varies between ~ 14 and ~ 43 nT, with an average (median) B_0 peak of 27 ± 8 (~ 26) nT for all CIRs.

In this work, “quiet” or “solar wind quiet” conditions refer to the absence of CIRs, HSSs, and ICMEs. A description of an ICME is given in Appendix C Figure 9. During the interval of this study, we identified 15 ICMEs impinging on Venus. The ICMEs are not included in the following analyses.

While the Venus ionosphere hosts a diversity of ion species, we have considered the O_2^+ ion (with a mass of 32 amu), dominant in the inner ionosphere, the O^+ ion (16 amu), dominant in the middle ionosphere, and the H^+ ion (1 amu), a significant contributor in the upper ionosphere particularly at night (see references in Section 1). We analyzed altitude profiles of the ions, as well as their variations with the solar zenith angle (SZA). See Appendix D Figure 10 for a detail description of SZA. SZAs are used to separate the ionospheric observations in dayside ($SZA < 90^\circ$) and nightside ($SZA > 90^\circ$).

In this work, we have verified statistical differences (if any) in ionospheric parameters between day and night, between CIR and quiet intervals, and between HSS and quiet intervals. Given that the ionospheric parameters typically follow an irregular distribution rather than a normal distribution, we applied the Mann–Whitney U -test (H. B. Mann & D. R. Whitney 1947; M. P. Fay & M. A. Proschan 2010; J. D. Gibbons & S. Chakraborti 2011) to determine whether the distributions significantly differ between two groups, and computed two-tailed p -values (P. H. Reiff 1990). A p -value less than 0.05 suggests a statistically significant difference (W. H. Press 2007).

3. Results

3.1. Characterizing the Venus Ionosphere: Case Studies during Quiet Solar Wind Conditions

Figure 1 shows measurements of three major ions O_2^+ , O^+ , and H^+ in the Venus ionosphere. During the outbound orbit # 0151 on 1979 May 4 and the inbound orbit # 0065 on 1979 February 7, SZA varied from $\sim 50^\circ$ to $\sim 57^\circ$ (Figures 1(a)–(c)) and from $\sim 106^\circ$ to $\sim 159^\circ$ (Figures 1(e)–(g)), respectively. Thus, measurements on May 4 and February 7 correspond to the dayside and the nightside ionosphere of the planet, respectively. During both of these orbits, the upstream solar wind (not shown) was quiet, i.e., the ionosphere was not impacted by any space weather events such as CIRs, HSSs, or ICMEs.

For both day and night, the inner ionosphere, below ~ 200 km altitude, is dominated by O_2^+ ions. We define the O_2^+ peak as the V1 layer. Above the V1 peak, O_2^+ density decreases sharply, while densities of O^+ and H^+ increase gradually and then decrease more slowly. The O^+ peak is defined as the V2 layer. The O^+ and H^+ densities are significantly larger than the O_2^+ density in the outer ionosphere. The altitude profiles also indicate two transition layers: an inner transition layer between O_2^+ and O^+ , and an outer transition layer between O^+ and H^+ . While these basic ionospheric structures are the same between day and night, the overall dayside ionosphere size (up to the ionopause) is significantly smaller than the extended nightside ionosphere forming an “ionotail.”

Based on the altitude profiles of the ions, we define eight characteristic parameters of the Venus ionosphere (Figure 1(d)). These are as follows: (1) the V1 layer peak O_2^+ ion density: $[O_2^+]_m$; (2) the altitude of the peak O_2^+ density: $h_m O_2^+$; (3) the inner transition altitude, where $[O_2^+] = [O^+]$: $h_{O_2^+/O^+}$; (4) the V2 layer peak O^+ density: $[O^+]_m$; (5) the altitude of the peak O^+ density: $h_m O^+$; (6) the outer transition altitude, where $[O_2^+] = [H^+]$: $h_{O_2^+/H^+}$; (7) the peak H^+ density: $[H^+]_m$; and (8) the altitude of the peak H^+ density: $h_m H^+$. We also considered (9) the ionopause altitude: IP; and (10) the bow shock altitude: BS, measured by the spacecraft. These 10 parameters are used in the following analyses to quantify dynamics of the Venus ionosphere. From Figure 1, the

estimated dayside (nightside) ionospheric parameters are as follows: $[O_2^+]_m \sim 34 \times 10^4$ ($\sim 7.5 \times 10^4$) cm^{-3} , $h_m O_2^+ \sim 165$ (~ 145) km, $h_{O_2^+/O^+} \sim 193$ (~ 155) km, $[O^+]_m \sim 66 \times 10^3$ ($\sim 16 \times 10^3$) cm^{-3} , $h_m O^+ \sim 213$ (~ 158) km, $h_{O_2^+/H^+} \sim 289$ (~ 185) km, $[H^+]_m \sim 3.6 \times 10^2$ ($\sim 6.7 \times 10^2$) cm^{-3} , and $h_m H^+ \sim 344$ (~ 185) km. Higher peak densities and altitudes of O_2^+ and O^+ during the day than at night indicate that the inner ionosphere dynamics is dominated by photoionization. On the other hand, exospheric H^+ layer seems to be enhanced in density and to penetrate closer to the planet at night. Ionopause and bow shock are identified at the altitudes of ~ 510 (~ 1642) km and ~ 6146 (~ 5333) km, respectively, on the dayside (nightside) of the planet.

3.2. CIR/HSS Impacts on the Dayside Ionosphere

Figure 2 shows the solar wind plasma and IMF measurements upstream of Venus during 1979 December 22–30. From the solar wind V_p temporal variation (Figure 2(a)), we identified a slow solar wind stream with $V_p \sim 310$ – 410 km s^{-1} during December 22–24, and an HSS with $V_p \sim 500$ – 720 km s^{-1} during December 25–27 (the HSS is marked by a light-gray shading). The HSS is characterized by a fast rise (at a rate of ~ 3.3 m s^{-2}) to a peak V_p of ~ 720 km s^{-1} followed by a gradual decrease (rate ~ 1.6 m s^{-2}) in V_p , typical of an HSS emanated from a solar coronal hole (see Section 2.2). T_p more or less follows the V_p temporal profile, while the plasma- β (β being the ratio of the plasma pressure to the magnetic pressure) seems to decrease from the slow stream to the HSS (Figure 2(c)). The IMF components indicate large-amplitude interplanetary Alfvén waves during the HSS (Figure 2(d)). Positive B_x and negative B_y polarities during the HSS indicate a sunward IMF, characteristic of an HSS emanated from a negative polarity coronal hole (coronal hole observation is not available).

In the interaction region between the slow stream and the HSS, the plasma and IMF are compressed, identified as a CIR from $\sim 12:20$ UT on December 23 to $\sim 12:20$ UT on December 25 (marked by a gray shading). The CIR is characterized by a peak $N_p \gtrsim 97$ cm^{-3} (Figure 2(b)), a peak $P_{sw} \gtrsim 21$ nPa (Figure 2(b)), and an IMF B_0 peak $\gtrsim 23$ nT (Figure 2(d)). The compression effect is much more prominent in the plasma than in the IMF. The parameters have significantly lower values before and after the CIR: N_p of ~ 15 – 30 cm^{-3} , P_{sw} of ~ 1 – 8 nPa, and B_0 of ~ 5 – 12 nT. It may be noted that the CIR has no sharp boundaries, but it is characterized by gradual increases and decreases in the plasma and IMF parameters at the leading and trailing edges, respectively. This is typical for inner heliospheric CIRs (A. J. Hundhausen 1973; R. Schwenn & E. Marsch 1990; J. T. Gosling & V. J. Pizzo 1999; I. G. Richardson 2018) and indicates that the CIRs are not yet well developed. Is it possible to identify the interplanetary structures prior to and inside the CIR as mentioned in Section 2.2? Inside the marked CIR interval, two distinct N_p and IMF B_0 peaks can be noted. However, the IMF measurements (gaps) are not suitable to confirm if the first peak is possibly an HPS or to identify HCS and SI. Thus, it is assumed that the CIR impacts discussed below (and in rest of this paper) represent a combined impact of the CIRs and preceding HPSs.

As observed from Figure 2(e), the spacecraft, during each orbit, entered the Venus ionosphere for a short time interval around 07:10–08:20 UT, when the spacecraft distance from the Venus center was $< 1.1 R_V$ (R_V is the Venus radius,

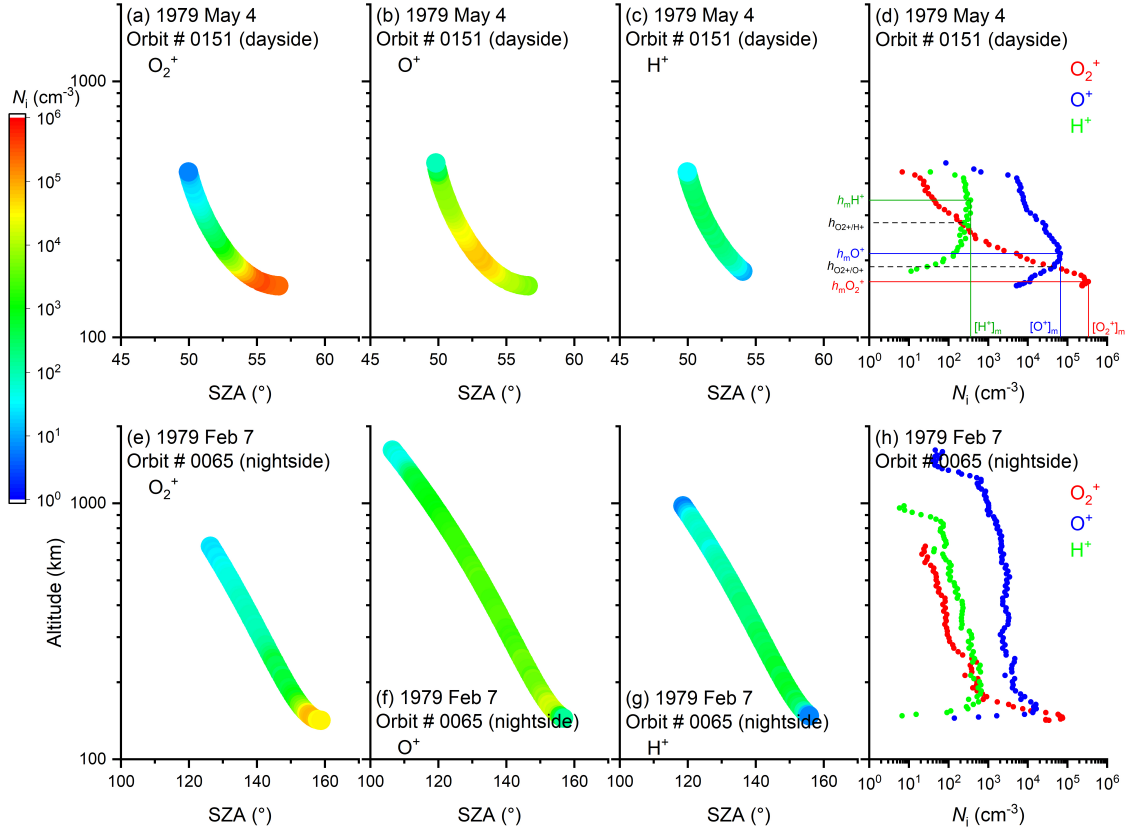


Figure 1. Major ions O_2^+ , O^+ , and H^+ in the quiet Venus ionosphere. (a)–(c), (e)–(g) Variations of the ion densities with SZA (x-axis) and altitude (y-axis); color bar on the left showing the ion density N_i . (d), (h) Altitude profiles of N_i . Top and bottom panels correspond to the dayside outbound orbit # 0151 on 1979 May 4, and the nightside inbound orbit # 0065 on 1979 February 7, respectively. Computations of ionospheric parameters from the altitude profiles of N_i are shown in panel (d). Details are given in the text.

~ 6000 km). During these ionospheric explorations, the spacecraft SZA varied between $\sim 45^\circ$ and $\sim 72^\circ$, indicating that the spacecraft was in the dayside ionosphere. Figure 3 shows the (dayside) ionospheric measurements during the CIR and HSS events. From the altitude profiles of the major ions O_2^+ , O^+ , and H^+ (Figures 3(a)–(f)), an overall ionospheric compression during the CIR (Figures 3(b)–(d)) is followed by an expansion during the HSS (Figures 3(e) and (f)) compared to the pre-CIR (Figure 3(a)) ionospheric variation. This is also confirmed by the estimated ionopause location (Figure 3(l)), moving inward from a pre-CIR altitude of ~ 300 – 466 km to a minimum altitude of ~ 217 km during the CIR, and then gradually moving outward to ~ 557 km at the HSS tail (bow shock estimation is not available for this event).

The peak ionospheric densities and layer altitudes (Figures 3(g)–(k)) estimated during daily ionospheric explorations of the spacecraft exhibit large variations during the CIR and HSS events. The V1/ O_2^+ layer density (altitude) gradually decreases (increases) from $\sim 48 \times 10^4 \text{ cm}^{-3}$ (~ 164 km) during the pre-CIR period to $\sim 43 \times 10^4 \text{ cm}^{-3}$ (~ 174 km) during the CIR and to $\sim 38 \times 10^4 \text{ cm}^{-3}$ (~ 178 km) during the HSS, and then increases (decreases) to $\sim 56 \times 10^4 \text{ cm}^{-3}$ (~ 170 km) at the HSS tail (Figure 3(i)). The variation of the V2/ O^+ layer (Figure 3(h)) is almost opposite to that of the V1/ O_2^+ layer. The O^+ peak density (altitude) increases (decreases) significantly from a pre-CIR value of $\sim 63 \times 10^3 \text{ cm}^{-3}$ (~ 204 km) to $\sim 103 \times 10^3 \text{ cm}^{-3}$ (~ 197 km) during the CIR period and

further to $\sim 122 \times 10^3 \text{ cm}^{-3}$ (~ 194 km) during the HSS phase. The H^+ density (altitude) decreases from a pre-CIR value of $\sim 12.0 \times 10^2 \text{ cm}^{-3}$ (~ 484 km) to $\sim 3 \times 10^2 \text{ cm}^{-3}$ (~ 275 km) during the CIR, and increases up to $\sim 8 \times 10^2 \text{ cm}^{-3}$ (~ 621 km) during the HSS (Figure 3(g)). The O_2^+/O^+ transition altitude (Figure 3(j)) and the O_2^+/H^+ transition altitude (Figure 3(k)) exhibit only small variations from their pre-CIR values (~ 194 and ~ 309 km, respectively) to the CIR (~ 192 and ~ 311 km, respectively) and HSS (~ 193 and ~ 309 km, respectively) intervals. Thus, different ionospheric layers seem to respond differently to the CIR/HSS impacts.

How about the ionospheric losses? We estimated the column density or the column abundance of the ions by integrating the ion densities in altitude (between the minimum PVO altitude and the ionopause altitude). The average pre-CIR abundances of the O_2^+ , O^+ , and H^+ ions are $\sim 90 \times 10^{10}$, $\sim 126 \times 10^{10}$, and $\sim 3 \times 10^{10} \text{ cm}^{-2}$, respectively. The minimum abundances during the CIR interval are estimated to be $\sim 51 \times 10^{10}$, $\sim 69 \times 10^{10}$, and $\sim 0.2 \times 10^{10} \text{ cm}^{-2}$, indicating $\sim 44\%$, $\sim 45\%$, and $\sim 93\%$ “column-losses” of the O_2^+ , O^+ , and H^+ ions, respectively. However, we note that this parameter (the column-loss) is not suitable to represent the actual erosion of the Venus ionosphere during disturbed solar wind conditions, for which suitable measurements of ion flux distributions are required. In addition, due to a large variation in the PVO altitudes from one case to the other, the column abundance

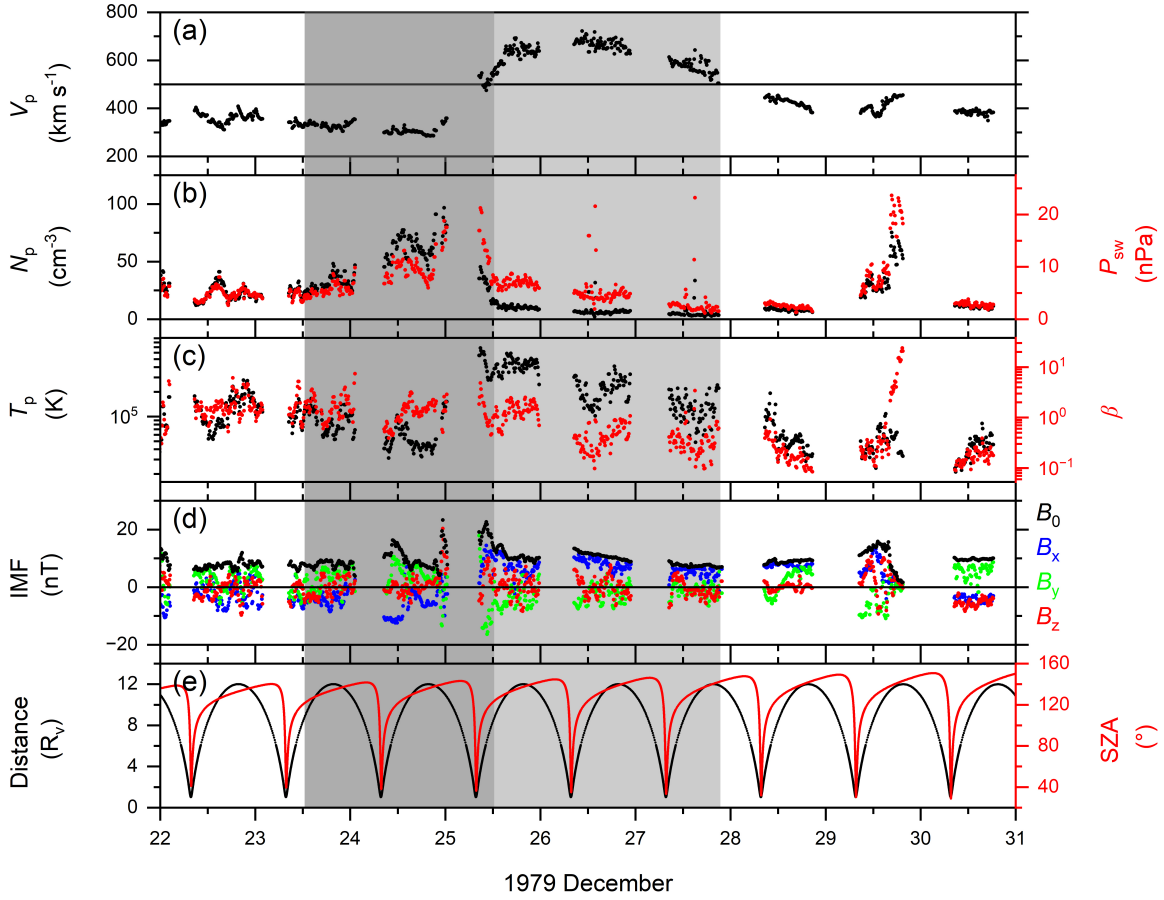


Figure 2. Upstream solar/interplanetary conditions during 1979 December 22–30. From top to bottom, panels are: (a) the solar wind proton speed V_p , black horizontal line indicating $V_p = 500 \text{ km s}^{-1}$, (b) the proton density N_p (black, legend on the left) and the ram pressure P_{sw} (red, legend on the right), (c) the proton temperature T_p (black, legend on the left) and the plasma- β (red, legend on the right), (d) the IMF magnitude B_0 (black), and the B_x (blue), B_y (green), and B_z (red) components, and (e) the spacecraft distance from the center of Venus (black, legend on the left) and the SZA of the spacecraft (red, legend on the right). Vertical shaded regions indicate a CIR (gray) and an HSS (light-gray).

estimations (which are highly dependent on the altitude range) may be misleading, and thus are not included in this work.

Figure 4 shows the Venus ionospheric variations and upstream solar wind plasma and IMF variations during 1979 April 26 through May 4. A slow solar wind stream with $V_p \sim 260\text{--}380 \text{ km s}^{-1}$ on April 26–27 is followed by a $V_p > 500 \text{ km s}^{-1}$ HSS during April 29 through May 1 (marked by a vertical light-gray shading; Figure 4(g)). The HSS peak V_p is $\sim 595 \text{ km s}^{-1}$ at $\sim 15:40 \text{ UT}$ on April 29. The HSS is characterized by a sunward IMF, as is evident from the positive B_x and negative B_y polarities (Figure 4(j)). The CIR between the streams, characterized by compressed plasma and IMF, extends from $\sim 13:20 \text{ UT}$ on April 27 to $\sim 11:50 \text{ UT}$ on April 29 (marked by a gray shading). This is characterized by a peak N_p of $\gtrsim 98 \text{ cm}^{-3}$ (Figure 4(h)), a P_{sw} peak of $\gtrsim 12 \text{ nPa}$ (Figure 4(h)), and an IMF B_0 peak of $\sim 24 \text{ nT}$ (Figure 4(j)). These are significantly higher values compared to their pre-CIR values: $N_p \sim 8\text{--}20 \text{ cm}^{-3}$, $P_{sw} \sim 4\text{--}7 \text{ nPa}$, and $B_0 \sim 8\text{--}14 \text{ nT}$.

The spacecraft briefly entered the ionosphere each day between $\sim 21:10$ and $\sim 22:20 \text{ UT}$, when the spacecraft SZA varied between $\sim 50^\circ$ and $\sim 90^\circ$, indicating the dayside ionosphere (Figure 4(k)). Figures 4(a)–(f) show the altitude profiles of the dayside ionospheric O_2^+ , O^+ , and H^+ during April 26 through May 1. The ionospheric V1 and V2 layers, and O_2^+/O^+ and O_2^+/H^+ transition layers exhibit significant

variations, with an overall compression during the CIR followed by an expansion during the HSS. The inner ionospheric variations are consistent with those shown in Figure 3.

3.3. CIR/HSS Impacts on the Nightside Ionosphere

Figure 5(g) shows an HSS ($V_p > 500 \text{ km s}^{-1}$) impacting on Venus for more than 4 days, during 1979 March 20–25. V_p increases gradually to a peak value of $\sim 660 \text{ km s}^{-1}$ on March 23. The IMF $B_x < 0$ and $B_y > 0$ (antisunward IMF; Figure 5(j)) during the HSS indicate its emanation from a positive polarity coronal hole. Interaction of the HSS with preceding/background slow $V_p \sim 286\text{--}392 \text{ km s}^{-1}$ stream (March 18–19) compressed the plasma and IMF, forming a CIR between $\sim 12:10 \text{ UT}$ on March 19 and $\sim 13:00 \text{ UT}$ on March 20. Within the CIR, the average V_p is $\sim 436 \text{ km s}^{-1}$, N_p (P_{sw}) increases from $\sim 21 \text{ cm}^{-3}$ ($\sim 7 \text{ nPa}$) to $\sim 63 \text{ cm}^{-3}$ ($\sim 21 \text{ nPa}$) (Figure 5(h)), and the IMF B_0 reaches a peak of $\sim 39 \text{ nT}$ (Figure 5(j)).

During each orbit, the spacecraft entered the Venus ionosphere (spacecraft distance $< 1.1 R_V$ from the center of the planet) around $21:10\text{--}22:20 \text{ UT}$, when the spacecraft SZA varied between 105° and 128° (Figure 5(k)), indicating the nightside of the ionosphere. The ionospheric measurements are available from above the altitude of $\sim 162 \text{ km}$; thus,

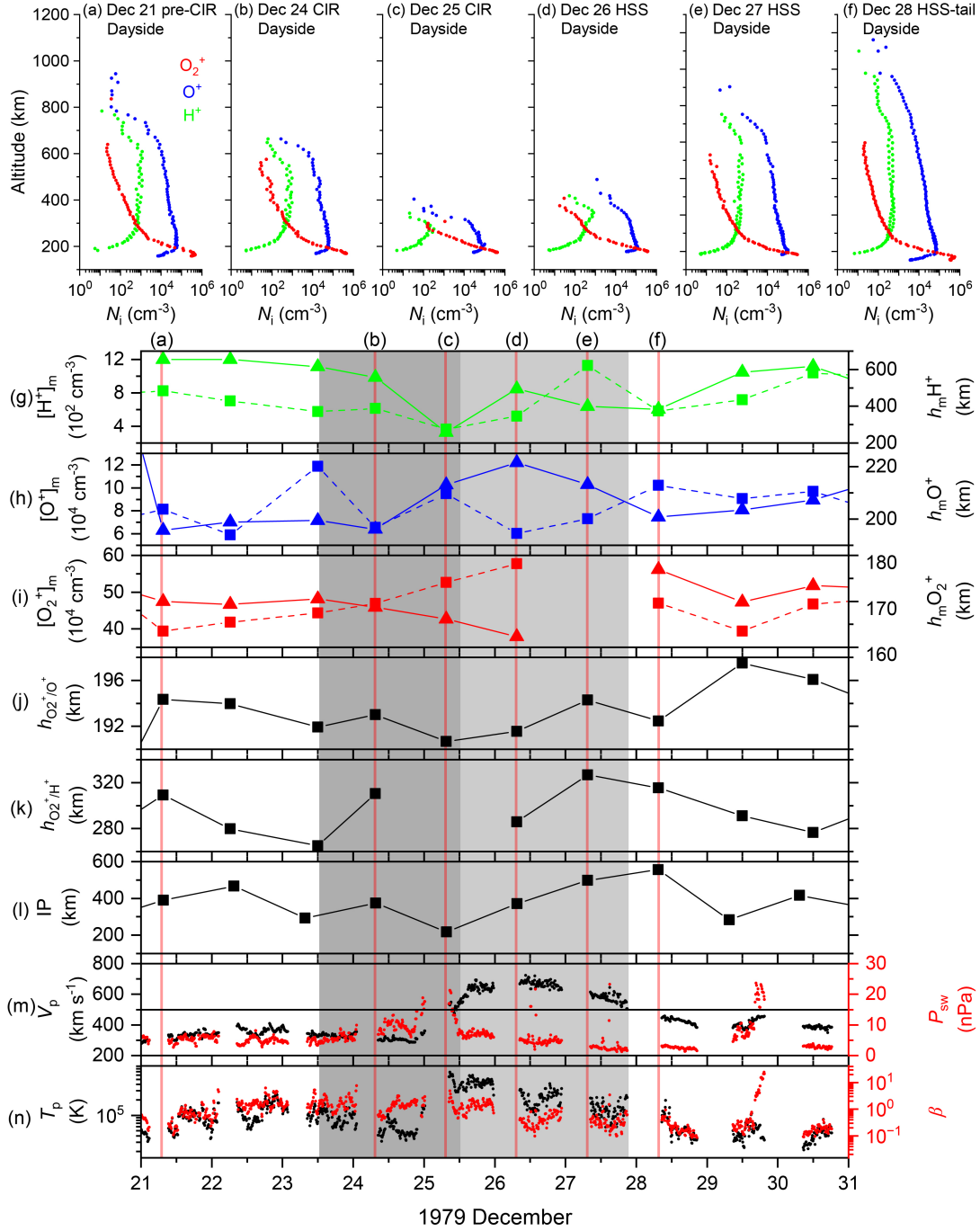


Figure 3. Response of the dayside Venus ionosphere to the 1979 December 23–27 CIR/HSS event. (a)–(f) Altitude profiles of O_2^+ (red), O^+ (blue), and H^+ (green) ions. Variations of (g) $[H^+]_m$ (triangles, connected with solid lines, legend on the left) and $h_m H^+$ (squares, connected with dashed lines, legend on the right), (h) $[O^+]_m$ (triangles, connected with solid lines, legend on the left) and $h_m O^+$ (squares, connected with dashed lines, legend on the right), (i) $[O_2^+]_m$ (triangles, connected with solid lines, legend on the left) and $h_m O_2^+$ (squares, connected with dashed lines, legend on the right), (j) $h_{O_2^+/O^+}$, (k) $h_{O_2^+/H^+}$, (l) IP, (m) V_p (black, legend on the left, black horizontal line indicating $V_p = 500 \text{ km s}^{-1}$) and P_{sw} (red, legend on the right), (n) T_p (black, legend on the left) and β (red, legend on the right) during 1979 December 21–31. Note that in panels (g)–(l), the data resolution is 1 day due to measurements of ionospheric parameters during daily ionospheric orbits of the spacecraft. Vertical red shadings in panels (g)–(n) indicate intervals of the altitude profiles in the panels (a)–(f), marked accordingly. Vertical gray and light-gray shadings indicate the CIR and the HSS intervals, respectively, as in Figure 2.

estimations of the inner ionospheric parameters, particularly, O_2^+ and O^+ peak densities and altitudes, are uncertain. However, compared to the dayside ionosphere under the CIR/HSS impacts (as shown in Figures 3 and 4), the size of the nightside ionosphere (under the CIR/HSS impacts) depicted in Figures 5(a)–(f) is significantly larger. The ionopause and bow shock altitudes vary in the ranges of

$\sim 1081\text{--}2409 \text{ km}$ and $\sim 6052\text{--}8242 \text{ km}$, respectively, during the interval shown in Figure 5. Another interesting result is that the high-altitude ionosphere (above the V2 peak) is dominated by H^+ ions: the H^+ density is comparable to or higher than the O^+ density. The peak density of H^+ ions remains nearly unchanged during the CIR interval ($\sim 57 \times 10^2 \text{ cm}^{-3}$) but drops to $\sim 30 \times 10^2\text{--}53 \times 10^2 \text{ cm}^{-3}$

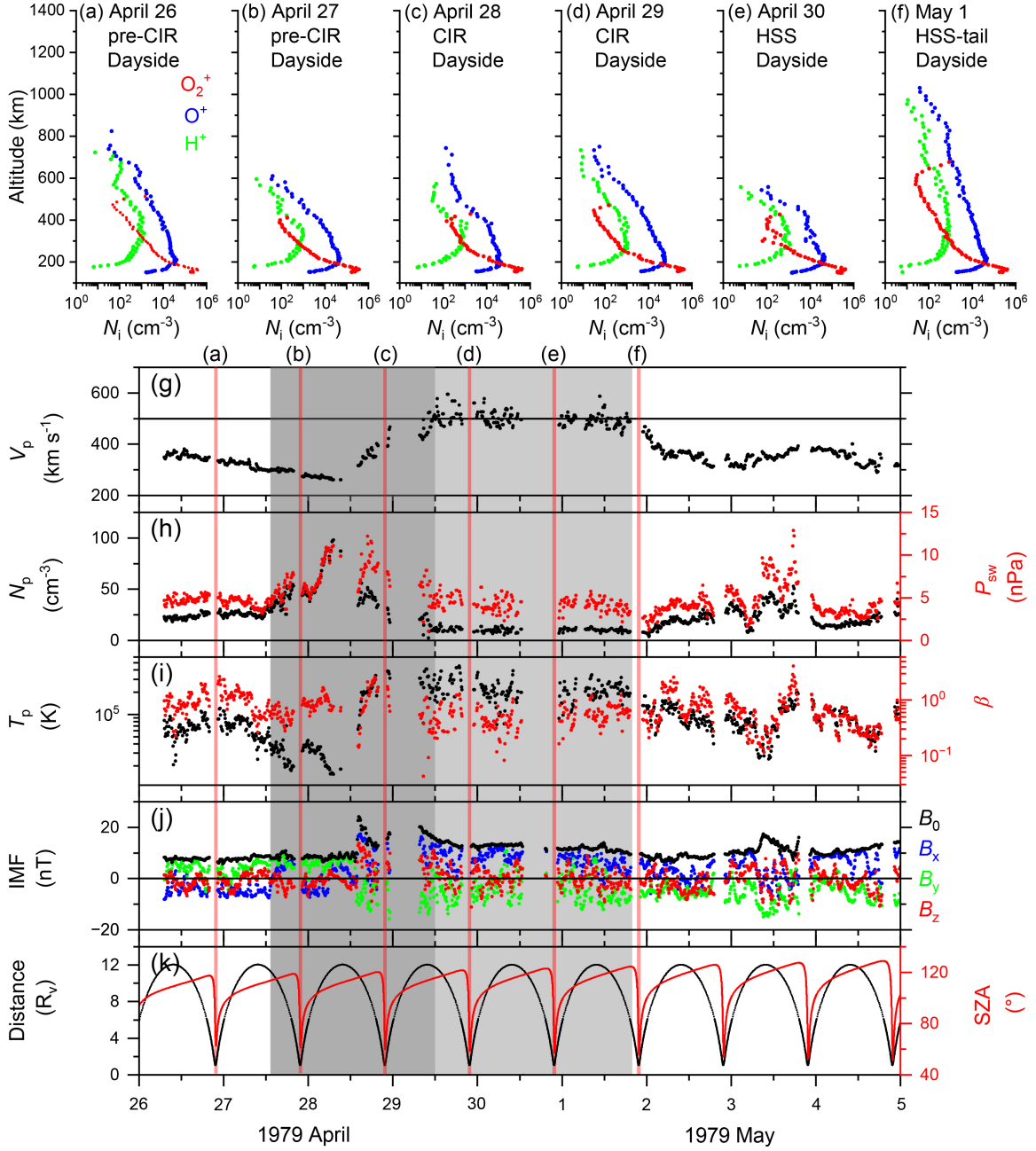


Figure 4. The dayside Venus ionospheric variations and upstream solar/interplanetary conditions during 1979 April 26 through May 4. (a)–(f) Altitude profiles of O_2^+ (red), O^+ (blue), and H^+ (green) ions. Variations of (g) V_p , black horizontal line indicating $V_p = 500 \text{ km s}^{-1}$, (h) N_p (black, legend on the left) and P_{sw} (red, legend on the right), (i) T_p (black, legend on the left) and β (red, legend on the right), (j) IMF B_0 (black), and the B_x (blue), B_y (green), and B_z (red) components, and (k) the spacecraft distance from the center of Venus (black, legend on the left) and the SZA of the spacecraft (red, legend on the right). Vertical red shadings in panels (g)–(k) indicate intervals of the altitude profiles in the panels (a)–(f), marked accordingly. A CIR is marked by a vertical gray shading, and an HSS by a vertical light-gray shading.

upon entering the HSS interval. The H^+ peak altitude decreases from $\sim 242 \text{ km}$ in the pre-CIR period to $\sim 178 \text{ km}$ during the CIR interval, recovers to $\sim 205 \text{ km}$ in the HSS proper, and then gradually declines to $\sim 174 \text{ km}$. The O_2^+/H^+ transition altitude increases from $\sim 167 \text{ km}$ during the CIR interval to $\sim 188 \text{ km}$, before decreasing to $\sim 177 \text{ km}$ in the HSS tail.

3.4. Statistical Results

From 1978 December through 1980 October, we identified 30 dayside ($\text{SZA} < 90^\circ$) and 40 nightside ($\text{SZA} > 90^\circ$) orbits

under quiet upstream solar wind/interplanetary conditions. Considering 21 CIR/HSS events during this period, the numbers of dayside and nightside orbits during the CIR impacts are 22 and 26, respectively, and those during the HSS impacts are 38 and 36, respectively. For all these orbits, we computed the ionospheric characteristic parameters, as described in Figure 1(d) (Section 3.1). The distributions of the quiet time ionospheric parameters are shown in Figures 6 and 7. Similar statistical distributions are developed for the ionospheric parameters under the CIR and HSS impacts (not shown to conserve space). In both these figures, we marked the

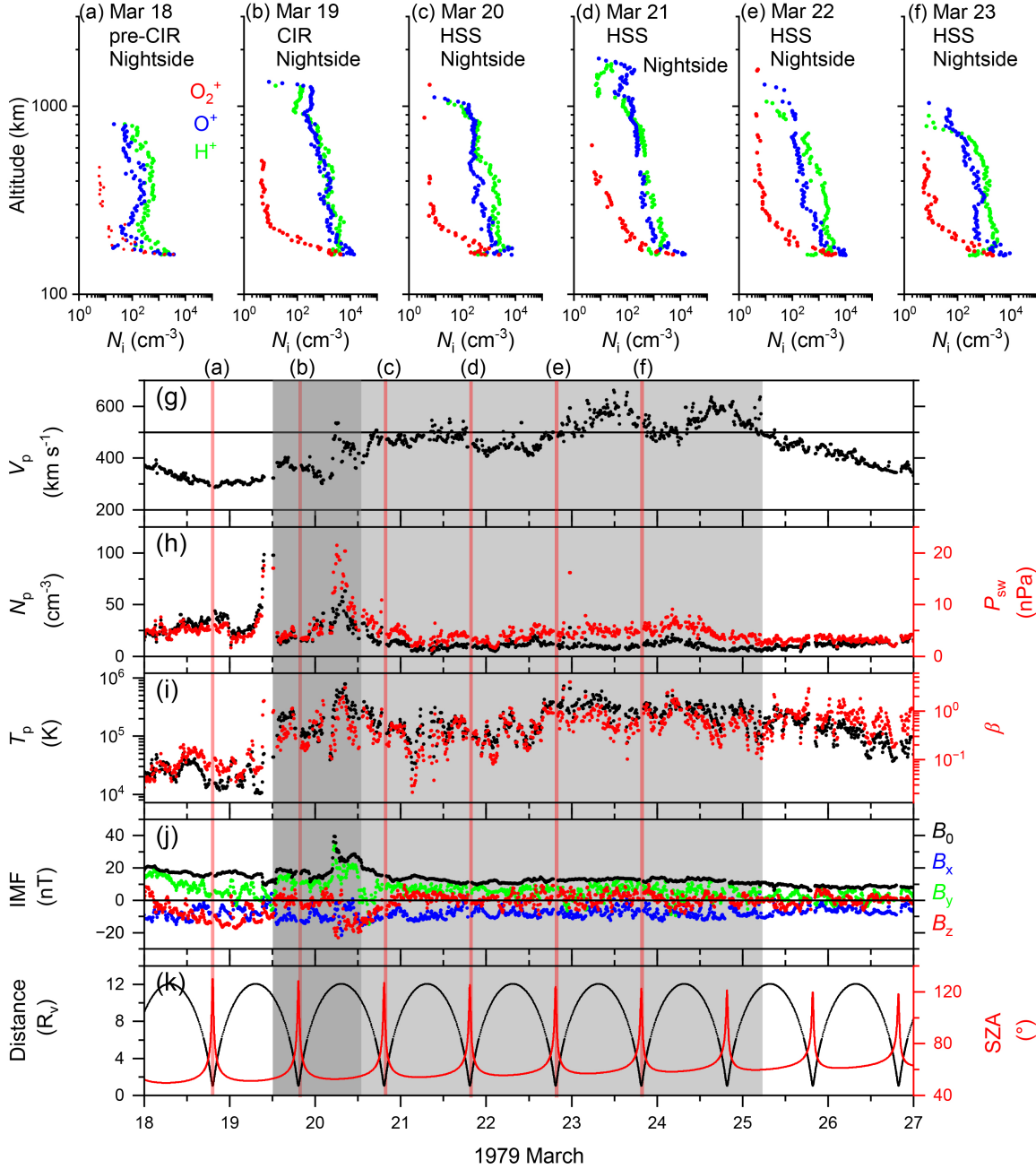


Figure 5. Response of the nightside Venus ionosphere to the 1979 March 19–25 CIR/HSS event. The panels are in the same format as in Figure 4.

mean (vertical or horizontal solid lines) $\pm 1\sigma$ deviations (horizontal or vertical bars) for the quiet time distributions as well as the mean values under the CIRs and HSSs (downward pointing or leftward pointing arrows) for comparison. The statistical features of the parameters (distributions) are summarized in Table 1. The statistical significance of these results has been verified by computations of the statistical p -values.

Statistical differences between the dayside and nightside ionospheric parameters for the quiet, CIR, and HSS conditions have been confirmed by estimated p -values < 0.05 (not shown), indicating that the day–night asymmetry of the ionospheric parameters is statistically significant under all solar wind conditions. The asymmetries, quantified as the percentage differences of the dayside ionospheric values from

the nightside values, are listed in Table 2. Interestingly, asymmetry in $[\text{O}_2^+]_m$ ($\sim 294\%$, $\sim 505\%$, and $\sim 863\%$ during the quiet solar wind condition and the CIR and HSS impacts, respectively) is greater than that in $[\text{O}^+]_m$ ($\sim 181\%$, $\sim 345\%$, and $\sim 334\%$, respectively), and that in $[\text{O}^+]_m$ is greater than that in $[\text{H}^+]_m$ ($\sim -51\%$, $\sim -59\%$, and $\sim -56\%$, respectively), that is, the day–night asymmetry in the peak ion density decreases with increasing altitude. On the other hand, asymmetry in the layer altitude increases with increasing altitude: $h_m\text{O}_2^+$ exhibiting the smallest day–night asymmetry ($\sim 8\%$, $\sim 5\%$, and $\sim 7\%$, respectively) and $h_m\text{H}^+$ exhibiting the highest asymmetry ($\sim 54\%$, $\sim 51\%$, and $\sim 71\%$, respectively).

On average, the quiet dayside O_2^+ (Figure 6(f)) and O^+ (Figure 6(d)) ion peak densities are ~ 4 and ~ 3 times those for the nightside ionosphere. On the contrary, the nightside H^+

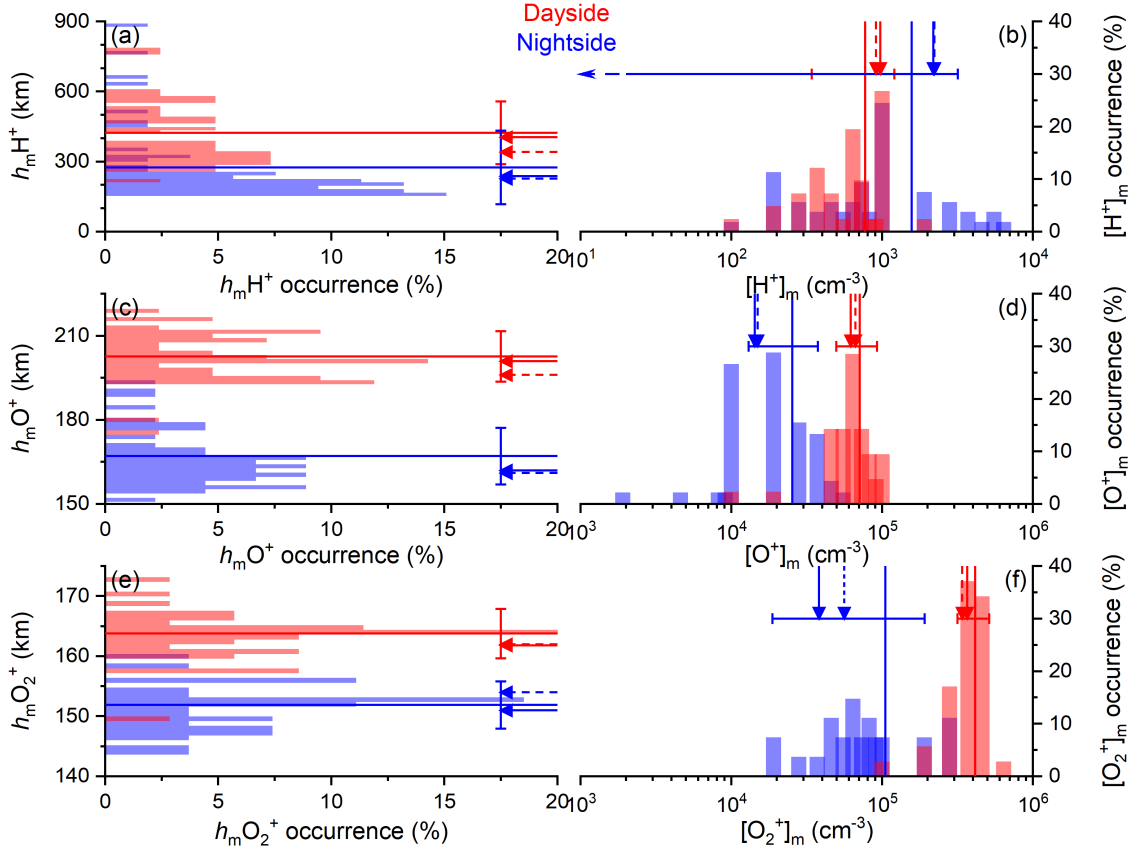


Figure 6. Statistical distributions of the Venus ionospheric parameters: (a) $h_m H^+$, (b) $[H^+]_m$, (c) $h_m O^+$, (d) $[O^+]_m$, (e) $h_m O_2^+$, and (f) $[O_2^+]_m$ under quiet solar wind conditions. In the peak altitude/left (peak density/right) panels, horizontal (vertical) lines and vertical (horizontal) bars indicate the mean values and 1σ deviations of the distributions, respectively, for the dayside (red) and nightside (blue) ionosphere. Red and blue arrows indicate the mean values for the dayside and nightside ionospheric parameters, respectively, under the CIR (arrows with dashed lines) and HSS (arrows with solid lines) impacts.

peak density is approximately twice that during the day (Figure 6(b)). The variability of the peak densities, as measured by 1σ deviations from the mean values, is higher in the nightside ($\sim 82\%$ – 102%) than in the dayside ($\sim 24\%$ – 56%), and the strongest variability is noted for the H^+ ions ($\sim 56\%$, $\sim 102\%$ in the dayside and nightside ionospheres, respectively).

Compared to the ion densities, the quiet ionospheric V1 (Figure 6(e)) and V2 (Figure 6(c)) peak altitudes and the O_2^+/O^+ transition altitude (Figure 7(d)) are well defined, as confirmed by low 1σ deviations of only $\sim 2\%$ – 6% of their mean values (Table 1). On average, the dayside ionospheric altitudes are $\sim 8\%$ – 54% higher than the nightside ionospheric altitudes, with the day–night asymmetry increasing with altitude (Table 2). However, as expected, the nightside ionopause (“ionotail”) (Figure 7(b)) and the bow shock (Figure 7(a)) altitudes are $\sim 56\%$ and $\sim 75\%$ higher than their dayside locations, respectively.

In general, higher values of the quiet time ionospheric $[O_2^+]_m$, $[O^+]_m$, $h_m O_2^+$, $h_{O_2^+/O^+}$, $h_m O^+$, and $h_{O_2^+/H^+}$ during the daytime compared to their nighttime values represent a significantly well-developed and dense dayside ionosphere, dominated by photoionization. On the other hand, larger $[H^+]_m$ and lower $h_m H^+$ at night are indicative of intensification/penetration of the exosphere closer to the planet.

How does the ionospheric variability change under the CIR and HSS impacts? As observed from Table 2, the day–night asymmetries in the ionospheric peak O_2^+ and O^+ densities increase significantly during the CIRs ($\sim 505\%$ and $\sim 345\%$, respectively) and HSSs ($\sim 863\%$ and $\sim 334\%$, respectively) compared to their values during quiet periods ($\sim 294\%$ and $\sim 181\%$, respectively). Note that the increases during the CIRs are in fact attributed to combined impacts of the CIRs and preceding HPS. The day–night asymmetries of the ionospheric layer altitudes, the ionopause, and the bow shock altitudes during the CIRs/HSSs are broadly similar to those during quiet periods. In other words, the most prominent variability of the Venus ionosphere is the variations between day and night, which persists or is enhanced by CIR and HSS impacts.

Comparing the statistical mean values of the ionospheric parameters (Figures 6 and 7), the O_2^+ and O^+ peak densities and altitudes slightly decrease and the H^+ peak density slightly increases during CIRs and HSSs compared to their mean values during quiet periods. Based on the statistical significance test, most of these differences are statistically insignificant ($p > 0.05$; Table 1). Here, we list the statistically significant results for the $p < 0.05$ cases. Considering average ionospheric parameters during the CIRs, significant decreases are recorded in the dayside peak O_2^+ density ($\sim 18\%$), the nightside peak O^+ density ($\sim 41\%$), the dayside peak altitudes of O^+ ($\sim 3\%$) and H^+ ($\sim 19\%$) ions, and the O_2^+/H^+ transition

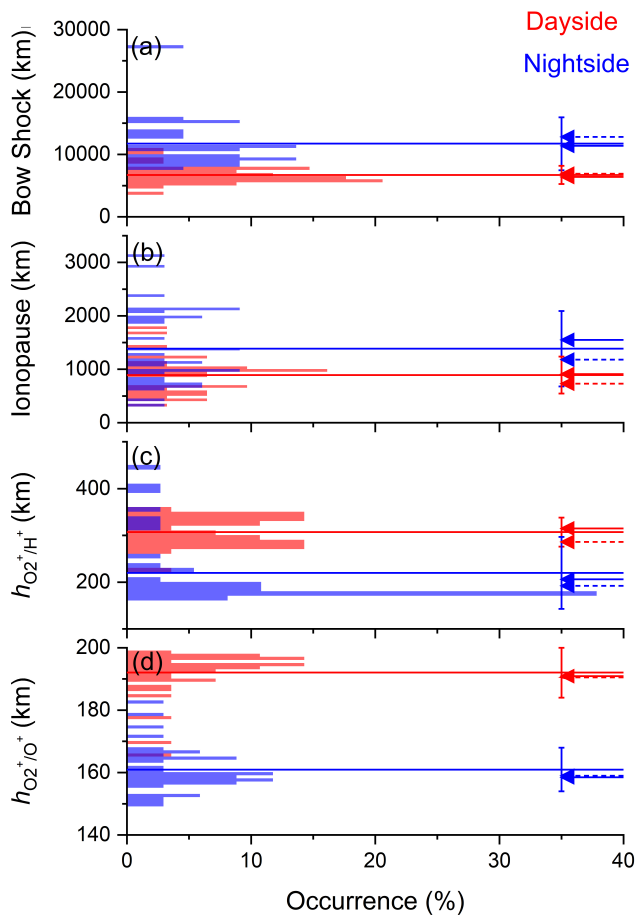


Figure 7. Statistical distributions of: (a) the bow shock altitude, (b) the ionopause altitude, and the ionospheric transition altitudes (c) $h_{O_2^+/H^+}$, and (d) $h_{O_2^+/O^+}$ under quiet solar wind conditions. Horizontal lines and vertical bars indicate the mean values and 1σ deviations of the distributions, respectively, for the dayside (red) and nightside (blue) ionosphere. Red and blue arrows indicate the mean values for the dayside and nightside ionospheric parameters, respectively, under the CIR (arrows with dashed lines) and HSS (arrows with solid lines) impacts.

altitude ($\sim 7\%$) compared to their values for the quiet ionosphere. During the HSS impacts, dayside (nightside) ionospheric O_2^+ and O^+ peak densities exhibit decreases by $\sim 12\%$ ($\sim 64\%$) and $\sim 13\%$ ($\sim 44\%$), respectively, while the dayside O_2^+ peak altitude decreases slightly ($\sim 1\%$) compared to their quiet ionospheric values.

4. Summary

We have presented, for the first time, a statistical study of the Venus ionosphere under varying solar wind conditions. The ionospheric dynamics are quantified by the estimations of the peak densities and altitudes of O_2^+ , O^+ , H^+ ions, and the O_2^+/O^+ , O_2^+/H^+ transition altitudes, along with the ionopause and bow shock locations. Variations in these parameters serve as quantitative descriptors of the Venus ionosphere. We list below the major findings of the present work.

1. From 1978 December through 1980 October, the Venus ionosphere was impacted by 21 corotating HSSs emanated from solar coronal holes. On average, the

HSSs are characterized by a peak V_p of $\sim 627 \pm 99 \text{ km s}^{-1}$. The preceding CIR compressions, with an average radial extent of $\sim 0.43 \pm 0.17 \text{ au}$ and duration of $\sim 1.81 \pm 0.78 \text{ days}$, are characterized by the peak $N_p \sim 81 \pm 21 \text{ cm}^{-3}$, $P_{sw} \sim 22 \pm 9 \text{ nPa}$, $T_p \sim (5.77 \pm 2.07) \times 10^5 \text{ K}$, and IMF $B_0 \sim 27 \pm 8 \text{ nT}$ for all events (Appendix B Table 3).

2. Under quiet solar wind conditions, the average dayside peak density of ionospheric O_2^+ (the V1 layer) ($\sim 41 \times 10^4 \text{ cm}^{-3}$) is ~ 4 times the nightside density (Figure 6(f), Table 1). The dayside V1 peak altitude ($\sim 164 \text{ km}$) is $\sim 8\%$ higher than its nightside altitude (Figure 6(e), Table 1).
3. The dayside (nightside) O^+ density increases above the O_2^+ density at an altitude of $\sim 192 \text{ km}$ ($\sim 161 \text{ km}$), and attains a peak density of $\sim 71 \times 10^3 \text{ cm}^{-3}$ ($\sim 25 \times 10^3 \text{ cm}^{-3}$) at an altitude of $\sim 203 \text{ km}$ ($\sim 167 \text{ km}$), forming the V2 layer peak under quiet solar wind conditions (Figures 6(c), (d), 7(d), Table 1).
4. Quiet time exospheric H^+ density peak ($\sim 16 \times 10^2 \text{ cm}^{-3}$) at night is about twice the dayside peak density, and is located at an altitude ($\sim 275 \text{ km}$) $\sim 35\%$ closer to the planet surface than the dayside peak altitude (Figures 6(a), (b), Table 1). The H^+ density decreases with decreasing altitude and falls below the O_2^+ density at altitudes of $\sim 307 \text{ km}$ and $\sim 220 \text{ km}$ on the dayside and nightside, respectively (Figure 7(c), Table 1).
5. In terms of day–night asymmetry: $[O_2^+]_m > [O^+]_m > [H^+]_m$, and $h_m O_2^+ < h_{O_2^+/O^+} < h_m O^+ < h_{O_2^+/H^+} < h_m H^+$. In other words, the day–night asymmetry in ionospheric peak ion densities decreases with increasing altitude, while that in the layer altitudes increases with increasing altitude (Table 2). This feature is observed during the quiet, CIR, and HSS conditions.
6. The dayside ionospheric peak density of O_2^+ (O^+) is ~ 4 (~ 3) times the nightside value during quiet intervals, ~ 6 (~ 4) times during CIR intervals, and ~ 10 (~ 4) times during HSS intervals, indicating significant increases in the day–night asymmetries of O_2^+ and O^+ densities under disturbed conditions. However, the asymmetries of other ionospheric parameters remain approximately the same under all conditions (Table 2).
7. Considering average ionospheric parameters during the CIRs (and preceding HPSs), significant decreases are recorded in the dayside peak O_2^+ density ($\sim 18\%$), the nightside peak O^+ density ($\sim 41\%$), the dayside peak altitudes of O^+ ($\sim 3\%$) and H^+ ($\sim 19\%$) ions, and the dayside O_2^+/H^+ transition altitude ($\sim 7\%$) compared to their values for the quiet ionosphere (Table 1).
8. During the HSS impacts, the dayside (the nightside) ionospheric O_2^+ and O^+ peak densities exhibit decreases by $\sim 12\%$ ($\sim 64\%$) and $\sim 13\%$ ($\sim 44\%$), respectively, compared to the quiet ionospheric values (Table 1).

5. Discussion

Statistical features of the CIRs. Typical/statistical solar wind plasma and IMF features of near-Venus CIRs are estimated based on all CIRs identified in this work. While our study is limited to near-Venus CIRs during 1978–1980 (when suitable ionospheric measurements are available), L. K. Jian et al. (2008)

Table 1
Statistical Properties of the Venus Ionosphere During Quiet Solar Wind Conditions and the CIR and HSS Impacts

Parameters	Quiet		CIR		HSS		<i>p</i> -value (versus Quiet)	
	Day (30)	Night (40)	Day (22)	Night (26)	Day (38)	Night (36)	CIR	HSS
$[\text{O}_2^+]_{\text{m}}$ (10^4 cm^{-3})	41.4 $\pm$ 9.9 (41.5)	10.5 $\pm$ 8.6 (7.5)	33.9 $\pm$ 9.3 (32.0)	5.6 $\pm$ 5.6 (4.5)	36.6 $\pm$ 7.7 (35.2)	3.8 $\pm$ 2.8 (2.8)	0.0331 (0.3817)	0.0109 (0.0193)
$h_{\text{mO}_2^+}$ (km)	164 $\pm$ 4 (164)	152 $\pm$ 4 (153)	162 $\pm$ 6 (163)	154 $\pm$ 9 (154)	162 $\pm$ 4 (162)	151 $\pm$ 3 (150)	0.2109 (0.8784)	0.0434 (0.1982)
$h_{\text{O}_2^+/\text{O}^+}$ (km)	192 $\pm$ 8 (194)	161 $\pm$ 7 (159)	191 $\pm$ 7 (193)	159 $\pm$ 4 (160)	191 $\pm$ 5 (192)	159 $\pm$ 3 (159)	0.3149 (0.7366)	0.1301 (0.5744)
$[\text{O}^+]_{\text{m}}$ (10^3 cm^{-3})	71.0 $\pm$ 21.4 (68.3)	25.3 $\pm$ 12.2 (23.0)	66.3 $\pm$ 23.0 (63.3)	14.9 $\pm$ 5.7 (12.9)	62.0 $\pm$ 24.4 (56.3)	14.3 $\pm$ 8.5 (11.9)	0.2158 (0.0427)	0.0126 (0.0084)
h_{mO^+} (km)	203 $\pm$ 9 (202)	167 $\pm$ 10 (165)	196 $\pm$ 10 (196)	161 $\pm$ 6 (161)	201 $\pm$ 8 (200)	162 $\pm$ 5 (162)	0.0039 (0.2294)	0.2989 (0.1455)
$h_{\text{O}_2^+/\text{H}^+}$ (km)	307 $\pm$ 31 (305)	220 $\pm$ 77 (183)	286 $\pm$ 30 (282)	192 $\pm$ 51 (176)	315 $\pm$ 58 (308)	206 $\pm$ 65 (176)	0.0381 (0.0739)	0.5743 (0.1609)
$[\text{H}^+]_{\text{m}}$ (10^2 cm^{-3})	7.7 $\pm$ 4.3 (7.0)	15.7 $\pm$ 16.0 (8.8)	9.1 $\pm$ 5.2 (8.1)	22.2 $\pm$ 21.8 (13.9)	9.7 $\pm$ 5.1 (9.1)	22.2 $\pm$ 19.3 (13.4)	0.4664 (0.2504)	0.2651 (0.0993)
h_{mH^+} (km)	423 $\pm$ 135 (381)	275 $\pm$ 158 (218)	341 $\pm$ 102 (300)	226 $\pm$ 62 (201)	404 $\pm$ 130 (354)	237 $\pm$ 170 (204)	0.0108 (0.5292)	0.4546 (0.2005)
IP (10^2 km)	8.9 $\pm$ 3.5 (9.2)	13.9 $\pm$ 7.1 (11.5)	7.3 $\pm$ 2.6 (7.1)	11.8 $\pm$ 5.1 (11.1)	9.1 $\pm$ 3.4 (8.0)	15.5 $\pm$ 7.5 (13.7)	0.0745 (0.3864)	0.8682 (0.3466)
BS (10^3 km)	6.7 $\pm$ 1.5 (6.4)	11.7 $\pm$ 4.2 (10.8)	6.9 $\pm$ 2.1 (6.8)	12.8 $\pm$ 6.0 (10.0)	6.4 $\pm$ 1.2 (6.1)	11.4 $\pm$ 2.5 (11.4)	0.7259 (0.9176)	0.3332 (0.5642)

Note. Numbers in parentheses in the column headers indicate the number of orbits used for the statistics. Values in columns (2)–(7) present the statistical mean $\pm 1\sigma$ deviation (median). In column (8), the *p*-values correspond to the statistical comparison between dayside (nightside) ionospheric parameters under the CIR impacts and the quiet conditions. In column (9), the *p*-values correspond to the statistical comparison between dayside (nightside) ionospheric parameters under the HSS impacts and the quiet conditions. The *p*-values less than 0.05 and corresponding mean parameters are marked by bold font. These mean values are statistically different between the CIR and quiet conditions and between the HSS and quiet conditions. During the quiet, CIR, and HSS periods, the *p*-values estimated for the statistical comparison between the dayside and nightside ionospheric parameters are less than 0.05 (not shown), implying that the day–night asymmetry is statistically significant under all conditions.

conducted a survey of all CIRs³ identified by PVO between 1979 and 1988. Our results (CIR characteristic features) are largely consistent with their results and any inconsistency may be related to solar cycle variations of the events given that they cover a longer period of observation (a detailed comparison is beyond the scope of the present work). It may be interesting to compare the near-Venus CIR features with those near Earth. R. Hajra & J. V. Sunny (2022) presented a statistical study of all CIRs impinging on the Earth’s magnetosphere during solar cycle 24 (2008–2019) (see also R. Hajra et al. 2022; J. V. Sunny et al. 2023, and references therein for other statistical studies of CIRs). Compared to the near-Earth CIRs (R. Hajra & J. V. Sunny 2022), near-Venus CIRs (the present study) are ~ 1.4 times longer in average radial extent, with peak $N_p \sim 2.8$ times, $P_{\text{sw}} \sim 2$ times, $T_p \sim 1.2$ times, and $B_0 \sim 1.8$ times their values near Earth. The variations in the CIR plasma and IMF features between Venus and Earth may

³ It may be noted that these authors used the term “stream interaction regions”/“SIRs,” and mentioned that “SIRs that recur with a rough period of one solar rotation cycle are commonly called corotating interaction regions (CIRs).” We consider this a misleading and vague description in scientific studies. We refer the readership to the original defining papers by J. W. Belcher & L. Davis (1971) and E. J. Smith & J. H. Wolfe (1976), where the term “corotating” was given to indicate the shape of the structure and not whether it recurred or not. In particular, E. J. Smith & J. H. Wolfe (1976) called these regions “corotating interaction regions”/CIRs due to their shape in space. The shape is like water coming from a rotating water sprinkler. The water comes radially outward (with a small aberrational effect), but because of the rotation of the sprinkler head, the shape of the water has a “corotational shape.” There is no reason to introduce a new term to represent the same interplanetary phenomenon. We recommend B. T. Tsurutani et al. (2026) for a historical background of the term CIR.

Table 2
Day–Night Asymmetry of the Venus Ionosphere During the Quiet Solar Wind Conditions and the CIR and HSS Impacts

Parameters	Quiet (70)	CIR (48)	HSS (74)
$[\text{O}_2^+]_{\text{m}}$ (%)	294	505	863
$h_{\text{mO}_2^+}$ (%)	8	5	7
$h_{\text{O}_2^+/\text{O}^+}$ (%)	19	20	20
$[\text{O}^+]_{\text{m}}$ (%)	181	345	334
h_{mO^+} (%)	22	22	24
$h_{\text{O}_2^+/\text{H}^+}$ (%)	40	49	53
$[\text{H}^+]_{\text{m}}$ (%)	−51	−59	−56
h_{mH^+} (%)	54	51	71
IP (%)	−36	−38	−41
BS (%)	−43	−46	−44

Note. Asymmetry is defined as $[(\text{Dayside} - \text{Nightside})/\text{Nightside}] \times 100\%$, estimated using the mean values. Numbers in parentheses in the column headers indicate the number of orbits used for the statistics. The asymmetries are statistically significant, as confirmed by estimated *p*-values less than 0.05 (not shown).

be related to overall radial variation of the solar wind and/or radial evolution of CIRs. This can be verified in a future study.

The ionospheric compositions and their day–night variations are already well explored (see references in Section 1). However, here we have presented, for the first time, statistical variations of the ion densities in different layers, altitudes of the maximum densities, and the O_2^+/O^+ and O_2^+/H^+ transition layer heights. Such a characterization is important for quantifying the ionospheric dynamics under varying solar

wind conditions. The statistical values provided in Table 1 can be used as typical/reference ionospheric conditions under solar wind quiet, CIR, and HSS impacts.

Explanations of the ionospheric day–night asymmetry. A systematic variation of the ionospheric day–night asymmetry (in layer heights and ion densities) with altitude, identified in this work, has never been reported before. What causes the largest day–night difference in the inner ionospheric O_2^+ peak density, comparatively lower difference in the middle ionospheric O^+ density, and the least difference in the higher-altitude H^+ density peak? In the dayside ionosphere, O_2^+ is mainly produced through local ionization by solar EUV radiation (A. Kliore et al. 1967; A. F. Nagy et al. 1980; T. E. Cravens et al. 1981). The nightside O_2^+ variation is contributed almost equally by nightward transport of O_2^+ ions produced in the dayside and local O_2^+ production by suprathermal electron impact (A. J. Kliore et al. 1979; W. C. Knudsen et al. 1980; K. Spennner et al. 1981; H. Taylor et al. 1982; T. E. Cravens et al. 1983; K. L. Miller & R. C. Whitten 1991; J. Fox 1992; A. Wood et al. 2012). Since transport of heavy O_2^+ ion may be less efficient (D. M. Butler & J. W. Chamberlain 1976), a large day–night difference in O_2^+ may result if the nightside electron-impact ionization is significantly less efficient than the dayside photoionization. In addition, for this lower-altitude ion, a large loss rate on the nightside can contribute to a lower net O_2^+ compared to its dayside density, resulting in a large day–night asymmetry. Variation of the dayside O^+ ions above the VI peak is contributed by the local photoionization as well as by the upward transport of the ions from the lower photochemical source region (e.g., A. F. Nagy et al. 1980). On the other hand, the nightside O^+ is mainly transported from the dayside (K. Spennner et al. 1981; H. Taylor et al. 1982; R. Whitten et al. 1982; W. C. Knudsen et al. 1986). Thus, relatively weaker day–night asymmetry in O^+ suggests efficient transport and a slower loss of the higher-altitude O^+ at night. The lowest day–night asymmetry in H^+ may be related to the fact that it is less dependent on direct photoionization, but it is produced mainly through charge exchange with the exospheric neutral hydrogen atoms (H. C. Brinton et al. 1980; R. Hodges & B. A. Tinsley 1982; H. Taylor et al. 1985). More studies involving observations and modeling are required for a better understanding of the day–night asymmetry of ionospheric compositions and vertical structures.

Explanations of the CIR impacts. We have presented the first quantitative, statistical study of the Venus ionospheric compositions and vertical structures during CIRs and HSSs. During CIRs (and preceding HPSs adjacent to the HCSs), the O_2^+ peak density is found to decrease significantly in the dayside, while the O^+ peak density decreases in the nightside ionosphere, compared to their quiet values. Since the dayside VI layer O_2^+ production is largely dependent on the EUV photoionization (that may not be altered by a CIR impact), a decrease in dayside O_2^+ may imply enhanced O_2^+ loss during the CIR impact. Here is an explanation for a plausible increase in the O_2^+ loss rate. Enhanced ram pressure during the CIR compresses the dayside ionosphere, leading to a magnetization of the ionosphere through increased magnetic pile-up around the Venus ionosphere (J. G. Luhmann et al. 1983; J. L. Phillips et al. 1985; J. Kar & K. K. Mahajan 1987; A. Angsman et al. 2011). The induced horizontal (ionospheric) magnetic fields may reduce the vertical mobility of photoelectrons, thereby

reducing the electron heating (T. E. Cravens et al. 1979). In fact, J. G. Luhmann et al. (1983), based on PVO electron temperature and magnetic field measurements of the Venus ionosphere, showed that the effective electron heating below ~ 200 km altitude (near the O_2^+ peak) reduces by orders of magnitude in the magnetized ionosphere. The dissociative recombination coefficient of O_2^+ ion $\alpha(O_2^+)$ is inversely proportional to the electron temperature T_e : $\alpha(O_2^+) \propto T_e^{-0.7}$ (e.g., F. J. Mehr & M. A. Biondi 1969; E. Alge et al. 1983). Thus, a reduction in the temperature accelerates the chemical loss of O_2^+ , leading to a significant decrease of the dayside O_2^+ concentration during CIRs.

On the other hand, the nightside O^+ variation is almost entirely dependent on day-to-nightward O^+ transport (K. Spennner et al. 1981; W. C. Knudsen et al. 1987; K. L. Miller & R. C. Whitten 1991). While the CIR ram pressure enhancement may not significantly impact the nightside ionospheric structure, it compresses the terminator. Thus, the nightward O^+ flow through the terminator may be dramatically reduced during a CIR (e.g., T. E. Cravens et al. 1983). This may explain the decrease in the nightside O^+ density during the CIRs. We also noted statistical reductions in the altitudes of the peak O^+ and H^+ densities and the O_2^+/H^+ transition altitude in the dayside ionosphere. These may be attributed to overall compression of the dayside ionosphere by enhanced ram pressure (H. A. Taylor et al. 1979; R. C. Elphic et al. 1980; H. Taylor et al. 1981; J. L. Phillips et al. 1985).

Explanations of the HSS impacts. During the HSS passages, ionospheric altitudes are not impacted significantly because the solar wind ram pressure (in the HSSs) is too low to compress the ionosphere as a whole. However, both O_2^+ and O^+ ion concentrations are found to decrease in both the dayside and nightside ionosphere during the HSSs. The decreases are comparatively larger in the nightside ionosphere. The decreases are plausibly related to the increases in the heavy ion escape rates. The HSSs may lead to increases in (1) the convective electric field $\vec{V}_p \times \vec{B}$ ($\vec{V}_p$ and $\vec{B}$ are the solar wind bulk velocity and IMF vector, respectively) (e.g., T. McEnulty et al. 2010), (2) the magnetic tension force $\vec{j} \times \vec{B}$ ($\vec{j}$ is the electric current) (e.g., L. Brace et al. 1982; M. Ong et al. 1991), and (3) plasma acceleration due to magnetic reconnection between oppositely directed magnetic fields (e.g., N. J. T. Edberg et al. 2011). All these processes may result in significant increases in the escape rates of the heavy ions from the Venus ionosphere (e.g., J. G. Luhmann et al. 2007, 2008; N. J. T. Edberg et al. 2011; A. P. Dimmock et al. 2018; D. Rout et al. 2024) leading to decreases in the measured ion concentrations. Observed heavy ion losses, larger in the nightside than in the dayside ionosphere, are consistent with the enhanced escape rates downstream from the planet.

6. Final Comments

The Venus ionosphere exhibits significant day–night asymmetries in layer height and ion concentrations, which systematically vary with ionospheric altitude. This is a new finding that requires further study. We found that the CIRs and HSSs lead to only $\sim 12\%$ – 18% decreases in the peak densities of the ionospheric heavy ions in the dayside, while the decreases on the nightside are significantly stronger, $\sim 41\%$ – 64% . We attribute these results to increased ionospheric heavy ion escape rates as well as enhanced local chemical losses during solar disturbances. It is interesting to compare these

results with the effects of CIRs on the plasma dynamics of a comet, which is also nonmagnetized. R. Hajra et al. (2018) reported that during the CIR impacts, the plasma density of the comet 67P/Churyumov–Gerasimenko (K. I. Churyumov & S. I. Gerasimenko 1972) increased by up to $\sim 500\%$ – 1000% compared to the quiet time plasma density. Note that contrary to the gravitationally bound Venus ionosphere, the plasma is not gravitationally bound to the comet. Extreme cometary plasma enhancements were attributed to the dominating electron-impact ionization process compared to photoionization and charge exchange with the solar wind. Future studies of Venus ionospheric variation during solar wind disturbances should aim to identify the underlying physical processes through theoretical modeling and suitable observations.

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Author Contributions

J.G. provided the formal analyses and validation, prepared the first draft of the manuscript, and revised the manuscript. R.H. came up with the original research concept, supervised the work, validated the results, and contributed in preparing the first draft and the final draft of the manuscript. Q.L. supervised the work and revised the manuscript. A.D. revised the manuscript. All authors read and approved the final draft of the manuscript.

Appendix A Lomb–Scargle Periodograms

Figure 8 shows variations of the upstream solar wind proton speed V_p (Figure 8(a)), and the density N_p (Figure 8(b)) during 1978 December through 1980 October, and their Lomb–Scargle periodograms (N. R. Lomb 1976; J. D. Scargle 1982) (Figure 8(c)). Both V_p and N_p exhibit periodic variations. The V_p periodogram shows two prominent peaks at ~ 31 and ~ 16 days, while the N_p periodogram exhibits peaks at ~ 29 and ~ 15 days. The periodicities are close to the solar rotation period (~ 27 days) and its first harmonic (~ 13 days), respectively (J. T. Gosling et al. 1976; J. B. Zirker 1977;

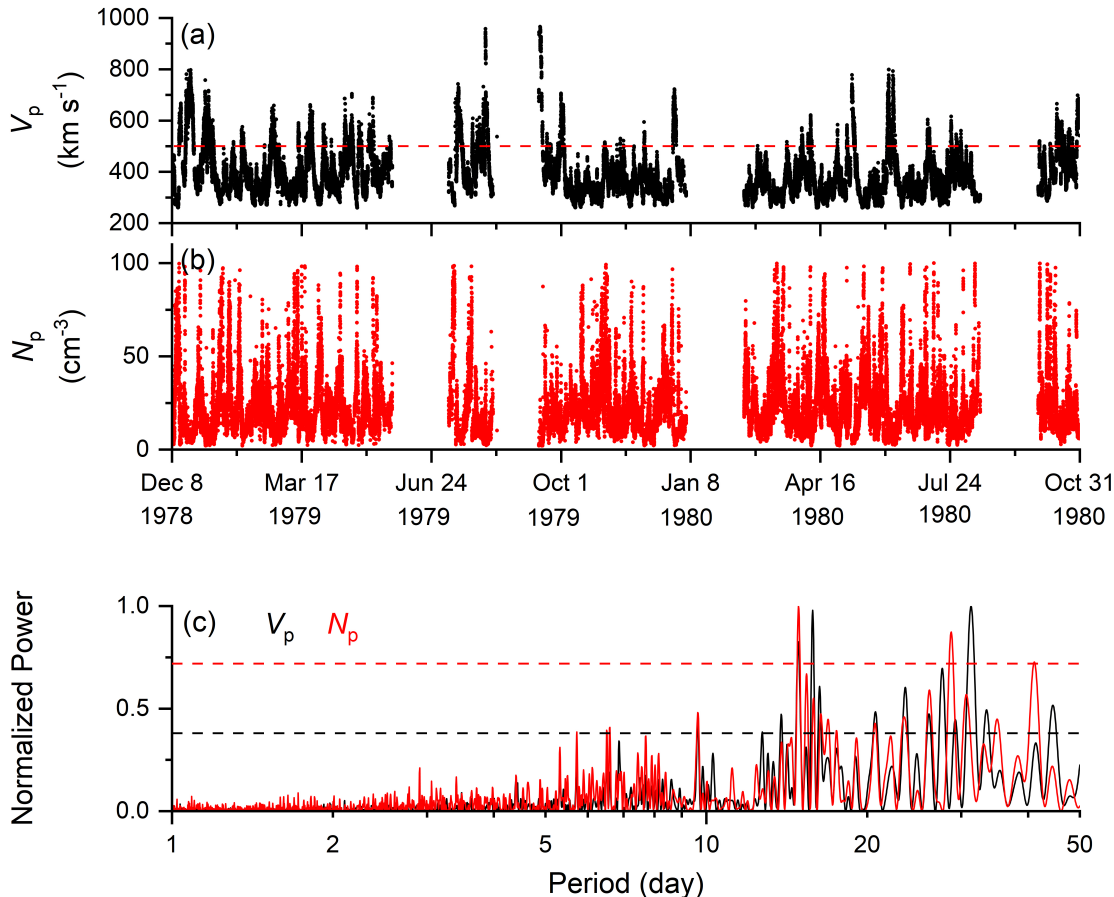


Figure 8. Lomb–Scargle periodograms of upstream solar-wind parameters. From top to bottom, panels are: (a) the solar wind proton speed V_p , the horizontal dashed line indicating $V_p = 500 \text{ km s}^{-1}$, (b) the proton density N_p , and (c) the Lomb–Scargle periodograms of V_p (black) and N_p (red), horizontal dashed lines indicating the 95% confidence levels of the periodograms (black and red correspond to V_p and N_p , respectively).

B. A. Lindblad & H. Lundstedt 1981). Thus, the periodicities may indicate modulation of the solar wind plasma by corotating HSSs emanated from solar coronal holes.

Appendix B List of the CIR and HSS Events

Table 3 lists 21 HSSs and preceding CIRs identified in this work. HSSs are characterized by a maximum solar wind

proton speed V_p . CIRs are characterized by their duration, radial extent, and peak proton density N_p , ram pressure P_{sw} , temperature T_p , and IMF B_0 . Since most CIRs have no clear/sharp boundaries, the start and end times of the CIRs are determined from the gradual increases and decreases, respectively, in N_p , P_{sw} , and B_0 . Considering the gradually increasing V_p during the CIR interval, we estimated the radial extent of the CIR as the “area under the V_p curve.”

Table 3
CIRs and HSSs Under this Study

CIR							HSS	
Start Time (UT)	End Time (UT)	Extent (au)	Peak N_p (cm^{-3})	Peak P_{sw} (nPa)	Peak T_p (10^5 K)	Peak B_0 (nT)	Peak V_p (km s^{-1})	V_p Peak Time (UT)
781217 03:10	781218 01:20	0.21	98	27	5.60	28	798	781222 06:20
790119 13:40	790122 14:00	0.61	90	17	2.80	21	517	790123 21:30
790127 01:20	790130 19:10	0.82	96	17	7.82	22	551	790131 13:50
790219 09:50	790221 04:30	0.44	75	21	4.43	33	659	790223 19:00
790319 12:10	790320 13:00	0.49	98	21	7.80	39	661	790323 11:50
790329 05:50	790403 06:10	0.63	88	14	5.31	25	532	790404 07:10
790427 13:20	790429 11:50	0.30	98	12	4.30	24	595	790429 15:40
790713 01:30	790714 06:30	0.45	37	14	6.37	26	730	790714 16:50
790928 18:30	790930 23:10	0.62	40	38	7.24	32	667	701002 12:40
791030 23:40	791102 08:00	0.46	87	14	5.04	26	515	791103 10:20
791202 03:30	791203 09:00	0.31	87	12	6.05	30	556	791203 17:00
791223 12:20	791225 12:20	0.40	97	21	6.87	23	722	791226 10:30
800317 19:10	800319 04:40	0.25	97	16	2.23	14	517	800321 07:10
800426 04:10	800427 08:40	0.24	37	8	3.97	16	584	800429 00:20
800504 23:00	800506 18:50	0.45	90	44	3.39	40	778	800509 22:50
800604 15:40	800606 15:00	0.61	66	19	9.48	30	799	800607 02:40
800727 16:00	800728 20:00	0.31	67	25	7.72	43	561	800801 05:30
800930 00:40	801001 05:20	0.24	100	34	8.82	35	500	801003 22:00
801010 20:50	801013 04:00	0.58	98	23	5.96	21	665	801013 09:20
801021 22:00	801022 18:40	0.25	72	35	2.70	15	559	801023 08:20
801027 12:00	801028 19:00	0.33	75	24	7.24	25	698	801029 05:30
Range		(0.21, 0.82)	(37, 100)	(8, 44)	(2.23, 9.48)	(14, 43)	(500, 799)	...
Median		0.44	88	21	5.96	26	595	...
Mean $\pm 1\sigma$		0.43 ± 0.17	81 ± 21	22 ± 9	5.77 ± 2.07	27 ± 8	627 ± 99	...

Note. Times are given in a format as follows: last two digits of a year (00–99), followed by two-digit month of a year (01–12), two-digit day of a month (01–31), and UT in hh:mm format, where hh and mm stand for two-digit hour (00–23) and two-digit minute (00–59), respectively. “Extent” refers to the radial extent of the CIR.

Appendix C

Example of an ICME

Figure 9 shows an ICME impacting on Venus during 1980 April 7–9. Sharp and simultaneous increases in the solar wind V_p (Figure 9(a)), N_p (Figure 9(b)), P_{sw} (Figure 9(b)), T_p (Figure 9(c)), and IMF B_0 (Figure 9(d)) at $\sim 01:20$ and $\sim 04:10$ UT on April 8 represent two interplanetary fast forward (FF) shocks (C. F. Kennel et al. 1985; B. T. Tsurutani et al. 1988) (marked by vertical dashed lines). The shocks compressed the plasma and IMF up to $\sim 10:20$ UT on April 8, resulting in an interplanetary sheath,

marked by a green horizontal bar at the top (C. F. Kennel et al. 1985; B. T. Tsurutani et al. 1988). The sheath is followed by a region up to $\sim 19:00$ UT on April 8 (marked by a gray shading, and a red horizontal bar at the top), where IMF components exhibit smooth rotations in polarities, and both T_p and plasma- β are low. This is called a magnetic cloud (MC; L. Burlaga et al. 1981; W. D. Gonzalez & B. T. Tsurutani 1987; K. Marubashi & R. P. Lepping 2007). Using similar criteria/method, we identified nine ICMEs impacting on Venus between 1978 December and 1980 October.

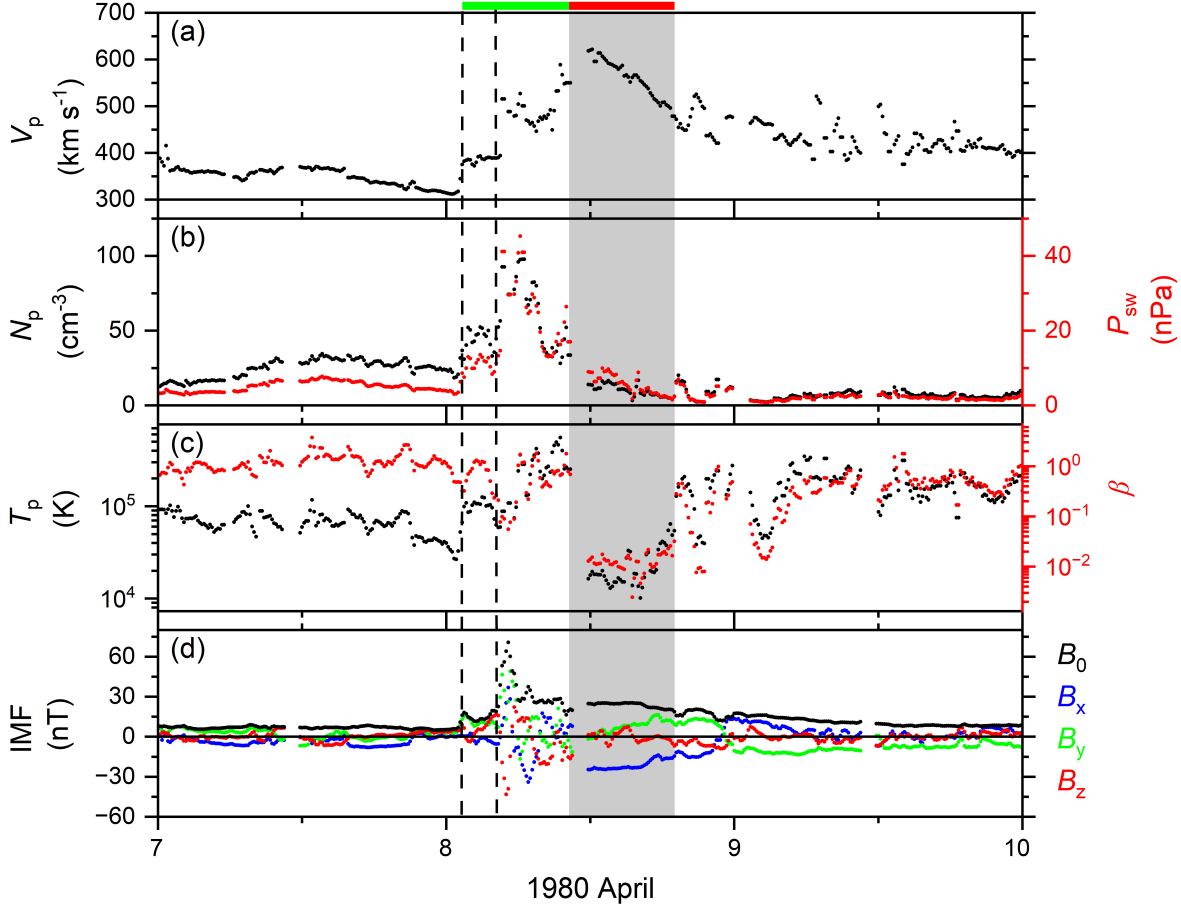


Figure 9. Upstream solar/interplanetary conditions during 1980 April 7–9. From top to bottom, panels are: (a) the solar wind proton speed V_p , (b) the proton density N_p (black, legend on the left) and the ram pressure P_{sw} (red, legend on the right), (c) the proton temperature T_p (black, legend on the left) and the plasma- β (red, legend on the right), and (d) the IMF magnitude B_0 (black), and the B_x (blue), B_y (green), and B_z (red) components. Vertical dashed lines show FF shocks, and the vertical shaded region indicates a MC (marked by a red horizontal bar at the top). The region between the first shock and the MC is an interplanetary sheath (marked by a green horizontal bar at the top).

Appendix D Solar Zenith Angle

Figure 10 shows estimation of the SZA. It is defined as the angle between the local zenith direction at the measurement point, approximated by the vector from the center of Venus to the spacecraft/ionospheric observation point, and the

direction from the center of Venus to the Sun. Thus, SZA ranges between 0° and 180° , $\text{SZA} = 0^\circ$ corresponds to the subsolar point, $\text{SZA} = 90^\circ$ corresponds to the terminator (sunrise and sunset), $\text{SZA} < 90^\circ$ corresponds to the dayside ionosphere, and $\text{SZA} > 90^\circ$ corresponds to the nightside ionosphere.

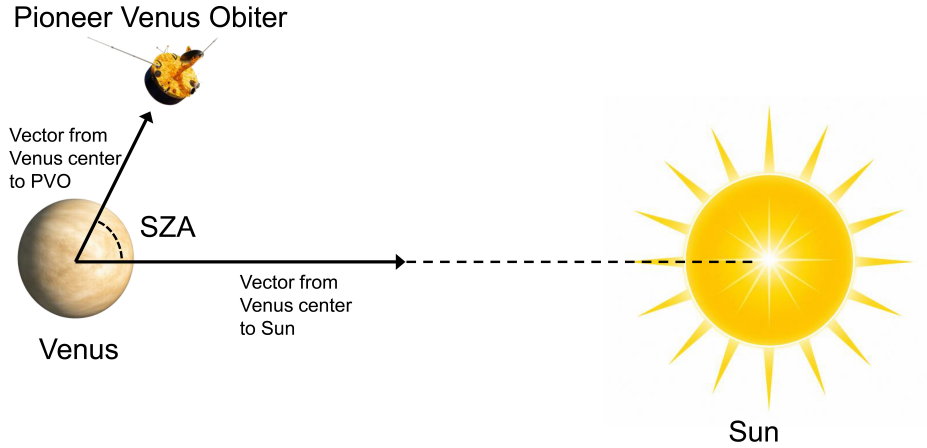


Figure 10. Schematic of the SZA. It is measured as the angle between the local zenith direction from the center of Venus to the spacecraft and the Venus center to the Sun direction.

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