Chapter

Particle Acceleration in the Venus Plasma Wake

H. Pérez-de-Tejada and R. Lundin

Abstract

Measurements conducted with the PVO and the VEX spacecraft have shown that the solar wind that streams around the Venus ionosphere produces plasma vortex-shaped structures across its wake. Those features are a varying property whose width gradually decreases with the downstream distance along the wake. Further studies suggest that as the width of the vortex structures becomes smaller with distance and since the total energy of the particles involved in the vortex motion should be maintained, the energy of particles that move in the central part of the wake should be enhanced. As a result, there should be a continuous energization of the planetary ions that are carried off by the solar wind from the Venus ionosphere; namely, accelerated planetary ions should be measured along the Venus wake. Different from measurements conducted in the Venus near wake where planetary O+ ions move with speeds smaller than those of the solar wind, the conditions far downstream along the wake imply that as a result of the gradual decrease of the vortex width with distance downstream from Venus, the planetary ions that stream in that direction acquire larger speed values and thus become accelerated.

Keywords: venus plasma wake, particle acceleration

1. Introduction

Measurements conducted with the Pioneer Venus Orbiter (PVO) and the Venus Express (VEX) spacecraft in orbit around Venus have provided evidence for the presence of vortex structures in the Venus wake and that reveal process similar to those that occur in similar fluid dynamic problems. An initial indication of the presence of vortex motion in the Venus wake was provided by changes in the direction of the velocity vectors of ions reported from the plasma measurements of the PVO [1, 2], and that was better described from the velocity vectors of the H+ and O+ ions obtained with the VEX data projected on a plane transverse to the wake direction reproduced in **Figure 1** [3]. Measurements made for both ion populations describe a counterclockwise rotation as seen from the wake and that extends across a large part of Venus cross section. The velocity distribution is oriented on a geometry different from what would be produced by magnetic tension forces along the field lines from the Venus polar regions. Instead, flow motion is dominant to produce the vortex shape in the particle displacement and that derives from effects related to the rotation of the Venus ionosphere. Further studies also showed a downward displacement of the

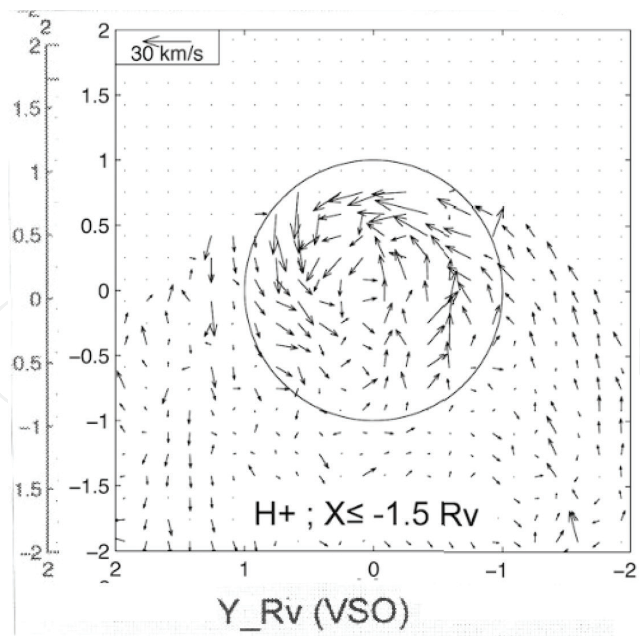

Figure 1.
(left panel) Velocity vectors of the H+ ions projected on the YZ-plane compiled from the VEX measurements (≈ 1–300 eV). Notice the formation of a tail ward moving vortex (helix) in the near wake at $X \le -1.5\ R_V$. (right panel) Velocity vectors of the O+ ions projected on the YZ-plane compiled from the VEX measurements. Notice the formation of a tail ward moving vortex (helix) in the near wake at $X \le -1.5\ R_V$ (from [3]).

trans-terminator flow in the Venus upper ionosphere [4, 5] and on the position of ionospheric holes [6] that were later interpreted as resulting from plasma channels that extend downstream from the Venus polar regions [7].

Particle acceleration of planetary O+ ions in the Venus wake has been a source of information regarding the fact that their measured speed values (20–30 km/s) are significantly smaller than the speed of the solar wind ions (200–300 km/s) in the near wake. Such smaller values are not expected from the acceleration of the planetary ions produced through the solar wind convective electric field where both plasma populations should rapidly acquire similar speeds. Instead, proton cyclotron waves produced through wave particle interactions [8] may lead the O+ ions to acquire larger speed values as they move along the Venus tail, thus becoming gradually accelerated. Information will be presented to stress that magnetic field forces are not sufficient to produce that response and thus that other mechanisms are required to produce the measured well-order displacement of the accelerated planetary ions. As a whole it will be suggested that through wave-particle interactions, the dynamics of vortex structures whose width decreases with distance downstream from Venus will produce a continuous enhancement of the particle speed for fluxes that remain moving along the wake direction.

2. Vortex data from the VEX measurements

Data from 8 VEX orbits obtained during 2006 and 2009 as the spacecraft moved into and left a vortex structure are summarized in **Table 1** and that were selected to produce the segments placed in **Figure 2**. As a whole there is a general difference in the position of the segments, which occurred closer to Venus (which is situated at the right side) in those corresponding to the 2009 orbits (thick underline) and that

Date	Inbound					Inbound							
	UT	X	Y	Z	v	UT	X	Y	Z	v	δ	Δ	ΔT
Aug 22/06	01.45	−2.83	−0.15	−0.83	25	01:55	−2.58	−0.15	−0.40	25	0.25	0.43	10
Aug 23/06	01:57	−2.75	−0.07	−0.60	15	02:05	−2.40	−0.07	−0.28	16	0.35	0.32	8
Aug 24/06	02.10	−2.45	−0.01	−0.26	30	02:18	−2.03	−0.01	0.20	30	0.42	0.46	8
Aug 28/06	02:22	−2.49	−0.28	−0.38	20	02:28	−2.20	0.24	0.07	20	0.29	0.31	6
Sep 19/09	01:54	−2.51	−0.04	−1.04	15	02:03	−2.20	−0.05	−0.55	15	0.31	0.49	9
Sep 21/09	02:03	−2.30	0.08	−0.65	15	02:13	−1.95	0.06	−0.12	15	0.35	0.53	10
Sep 25/09	02:15	−2.15	0.33	−0.45	20	02:27	−1.60	0.23	0.21	28	0.55	0.66	12
Sep 26/09	02:05	−2.47	0.46	−1.06	20	02:20	−1.83	0.32	−0.01	20	0.64	1.05	15

Table 1.
Corrected VEX coordinates (in R_V) together with the speed v of the planetary O+ ions (in km/s) measured during the inbound (left columns) and the outbound (right columns) crossings of vortex structures in four orbits of 2006 and four orbits of 2009. The columns in the far right indicate the width of the vortex structure in the X and in the Z directions and ΔT the time difference between both crossings.

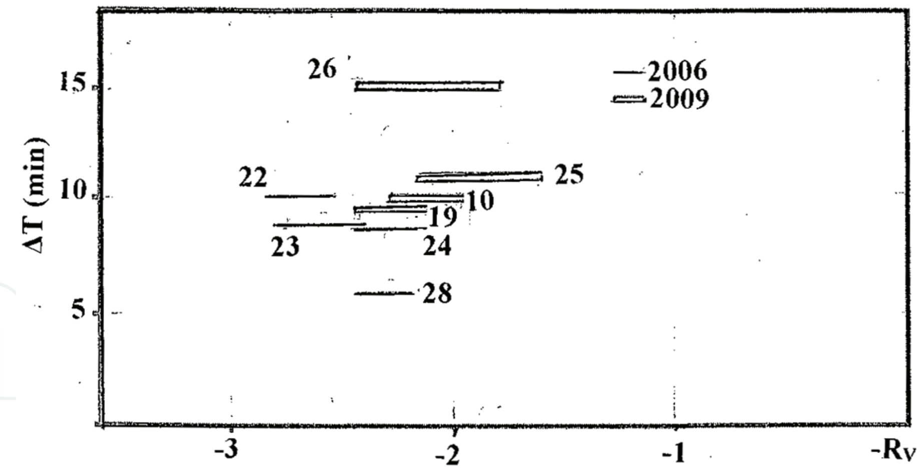

Figure 2.
Segments measured between the inbound and the outbound crossings of vortex structures by VEX in the eight orbits included in **Table 1** *(they are identified by changes in the particle flux intensity measured in the energy spectra of the O+ ions). Their corrected position along the X-axis shows that the 2009 orbits (marked with a double underline) are located closer to Venus, and also that the width value in the 2006 orbits (marked with a single underline) are mostly smaller since they have lower ΔT values and are encountered further downstream along the wake The numbers by the side of each segment state the day of their crossing date in* **Table 1** *(improved from [9]).*

represent conditions suitable to a minimum in the solar cycle. The segments derived from the 2006 orbits (single underline) are located further downstream along the wake [9]. Also, there is an indication that the time width ΔT between the inbound and the outbound crossings marked at the vertical coordinate in **Figure 2** is smaller in the 2006 orbits which trace the wake farther away from Venus (that transition is derived from the δ and the Δ values annotated in **Table 1** together width their time width ΔT obtained from their measurements). The numbers at the side of each segment indicate the day in the date of the orbits in **Table 1**.

A similar conclusion can also be reached by plotting the inbound and the outbound crossings of vortex structures in those orbits and that is projected on the XZ plane as shown in **Figure 3**. The position of the data points is displaced to lower −Z values with increasing distance downstream from Venus. The two sets of data with four orbits each indicate a different displacement of the vortex structure along the −Z direction. In all the data points, there is a similar displacement in the position of the vortex structure toward the southern hemisphere with increasing distance downstream from Venus. However, there is a general preference in those features to occur closer to Venus in the 2009 measurements since the VEX passage across the Z = 0 axis is by X = −1.8 R_V in that set while it reaches X = − 2.2 R_V in the 2006 measurements. This difference implies that the vortex structures are located closer to Venus during solar cycle minimum conditions by 2009, and that their position along the wake varies along that cycle. The persistent location of the vortex crossings following a similar trend for both the inbound and the outbound passes, which is suitable for 2006 and 2009, supports the view that it is a common phenomenon. It is also to be noted that the close crossing position in orbits labeled 22, 23, 24, and 28 in **Figure 3** (which correspond to the day of the date where they were made during 2006) gives the rate of change of the vortex size with distance in the X and the Z coordinates. In fact, since ΔZ ~ 0.2 R_V and ΔX ~ 0.3 R_V across those orbits, it is possible to suggest that the vortex width changed at a rate with a significant (~ 30°) angle in that part of the wake.

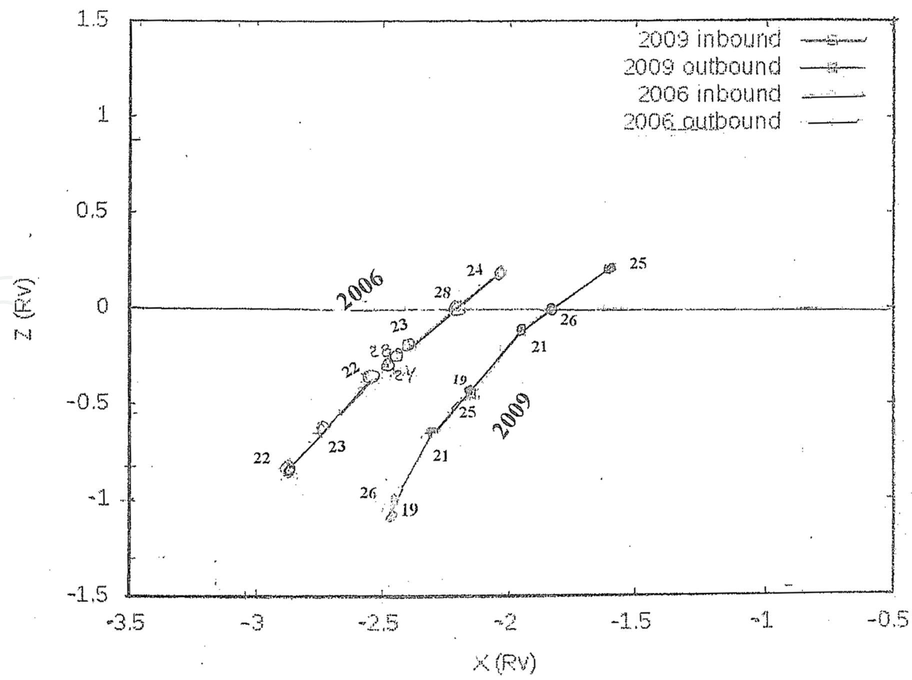

Figure 3.
Corrected position of the VEX spacecraft projected on the XZ plane during its entry (inbound) and exit (outbound) through a corkscrew plasma structure in several orbits. The two traces correspond to the four orbits in 2006 and the four orbits in 2009 listed in **Table 1**. *The numbers at the site of each crossing state the day of their crossing date in that* **Table 1**.

An extended study of those results was conducted by considering VEX orbits that exhibit an indication of vortex structures throughout the operation time of that spacecraft (between 2006 and 2013). Even though the plasma conditions differed significantly among them, it was possible to collect a number of orbits for each year of operation and that led to their general distribution reproduced in **Figure 4** [10]. In particular, they describe variations in their width as follows: For each orbit there is a segment bounded by the entry and exit of the spacecraft through a vortex with a number that marks the two last digits of the year when measurements were made (they include the four orbits for 2006 and for 2009 that were discussed in **Figures 2** and **3**). The length of that segment corresponds to the time width of the vortex structure and is marked by its position placed on the vertical coordinate; that is, segments positioned at high values in that axis indicate wide vortices while those situated at low values correspond to thin vortices. M**ost** notable is that the segments identify two different regions; one corresponding to orbits before the minimum solar cycle conditions (between 2006 and 2009) and the other to orbits that occurred during and after those conditions (between 2009 and 2013). Two big circles select schematically different sets of orbits that are located either far away from Venus between 2006 and 2009 (left circle) and those that are placed closer to Venus (between 2009 and 2013 (right circle) during solar cycle minimum conditions. The implication here is that as in **Figures 2** and **3,** the vortex structures occur closer to Venus during minimum solar cycle conditions.

Equally important is that the time width ΔT (segment length) in the 2006: 2009 orbit range is clearly smaller (placed at lower values along the vertical coordinate within the left circle) than that in the 2009: 2913 orbit range (larger values in the right circle). In agreement with both traces in **Figure 3** the vortex structures identified between 2006 and 2009 (left circle in **Figure 4**) occur farther away from Venus than those detected between 2009 and 2013 (right circle). As a result, the thickness

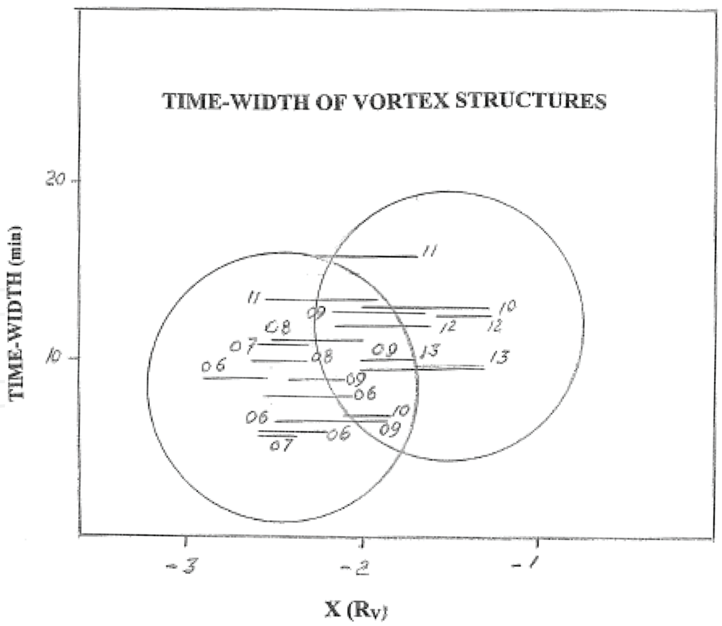

Figure 4.
Corrected values of the time-width (in minutes) between the VEX inbound and outbound crossings of vortex structures as a function of the X-distance (R_V) downstream from Venus that were measured in 20 orbits. The numbers at the side of each segment represent the two last digits of the year when measurements were made in different orbits between 2006 and 2013 (four orbits were examined during 2006 and also during 2009). The two circles confine orbits between 2006 and 2009 (left circle) prior to a solar cycle minimum and those between 2009 and 2013 (right circle) during and after that period [9].

Figure 5.
View of a corkscrew vortex flow in fluid dynamics. Its geometry is equivalent to that of a vortex flow in the Venus wake with its width and position varying during the solar cycle. Near minimum solar cycle conditions the vortex is located closer to Venus (right side) and there are indications that its width becomes smaller with increasing distance downstream from the planet. Such is the case for the 2006 orbits (marked with a single underline in **Figure 2***) and that were conducted before the solar cycle minimum at 2009–2010 thus implying that the vortex flow becomes thinner when it is detected further downstream along the wake [9].*

of the vortex structures located far away from Venus (left circle) becomes smaller with increasing distance along the wake, thus implying a corkscrew shape similar to that represented schematically in **Figure 5** for a flow configuration behind an object immersed in a fluid and where it thins out with the downstream distance [11].

3. Particle acceleration in the Venus wake

The tendency of the width of vortex structures to decrease with distance downstream from Venus indicated in **Figure 2** has implications regarding its effects on the motion of the planetary ions that stream within them. Most notable is that their kinetic energy around such features depends on the scale size of the vortices and if the latter become smaller with the downstream distance as produced by the expansion of the solar wind into the wake, the energy released should be assimilated by particles that remain moving in the smaller-size vortices. In addition, such particles have directed motion along the wake, and as a result, some of that energy should contribute to enhance their speed in that direction. It is thus possible that a fraction of planetary ions dragged along by the solar wind may be gradually accelerated along the Venus wake.

A velocity variation in that sense can be inferred from the speed profile of the planetary ions shown in both panels of **Figure 6** [12] where in addition to a gradual decrease of their speed with altitude by and above the ionopause (by ~10^3 km), there is a sudden and unexpected change in the altitude gradient by ~5 10^3 km and that produces enhanced speed values from ~10 km/s by ~5 10^3 km to ~40 km/s by ~10^4 km and that peak at that altitude. That variation is nearly the same in both panels of **Figure 6** and suggests the participation of a different process. In particular, larger speed values imply the acceleration of the planetary ions that can be estimated in terms of a change in the cross section of their motion. The acceleration of those particles can be estimated in terms of the cross section of the vortex structure encountered along the spacecraft trajectory. In fact, since the width of a vortex structure decreases with distance along the wake as a result of the expansion of the solar wind into that region (Pérez-de-Tejada, 1986), the total energy content of the vortex motion should be

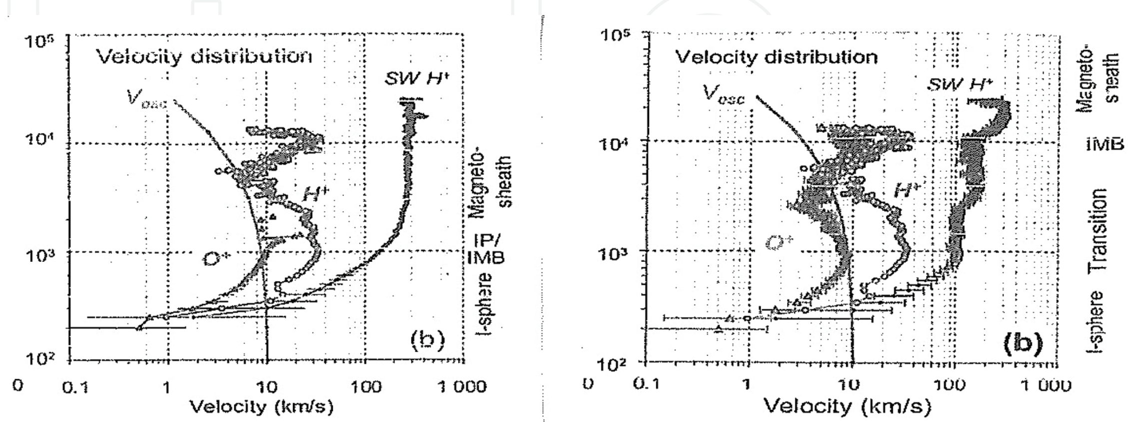

Figure 6.
Measured flow velocities versus VEX altitude for solar wind H+ ions, and ionospheric H+ and O+ ions. The curve marked v_{esc} illustrates escape velocity versus altitude above Venus. The data points represent average values in 50 km altitude intervals sampled within Y = +0.5 of the dawn-dusk Meridian (left panel) and of the noon-midnight Meridian (right panel). Regions and boundaries are marked on the right-hand side as the I-sphere (the ionopause (IP), and the ionosheath (IMB). From Lundin et al. [12].

maintained, and thus a fraction of the energy released will be provided to the particle population that preserves that motion. Following the shape of a vortex structure downstream from Venus that is similar to that indicated in the equivalent form past an object in **Figure 5**, we can suggest a shape that by a distance of two planetary radii along the Venus wake, the thickness of the vortex has decreased significantly. The outcome of that geometry is that when the thickness of the corkscrew flow has decreased, the speed of the particles has to be larger so that their kinetic energy density integrated over the area of the cross section is maintained. Such variation is comparable to that expected from the shape of the corkscrew flow in **Figure 5** where larger speed values are expected where the cross section of the vortex structure is smaller. Thus, the data points in **Figure 6** at low altitudes refer to the gradual motion of the spacecraft through a wide vortex in a region close to Venus and that at higher altitudes apply to the region where the cross section of the vortex is smaller and hence the flow speeds are larger. An implication also consistent with the shape of a corkscrew flow shape in **Figure 5** is the abrupt ending of the speed profile by ~$1.5\ 10^4$ km altitude in **Figure 6** and that is not related to any drastic change in the density profile since comparable density values were measured above and below that altitude. Instead, the abrupt ending of the speed profile at that altitude may imply the exit of the spacecraft from the corkscrew flow region along its trajectory. In summary, vortices along the Venus wake seem to be confined within a region whose cross section decreases with distance downstream from Venus and with a population of accelerated planetary ions.

4. Velocity vectors unrelated to the J x B force

Unrelated to the acceleration of planetary O+ ions through the decreasing cross section of vortices along the Venus wake, there are other mechanisms that should also contribute to produce that effect. Most notable is the participation of magnetic fields through the Lorentz **J x B** forces. In order to explore that contribution, a review of the

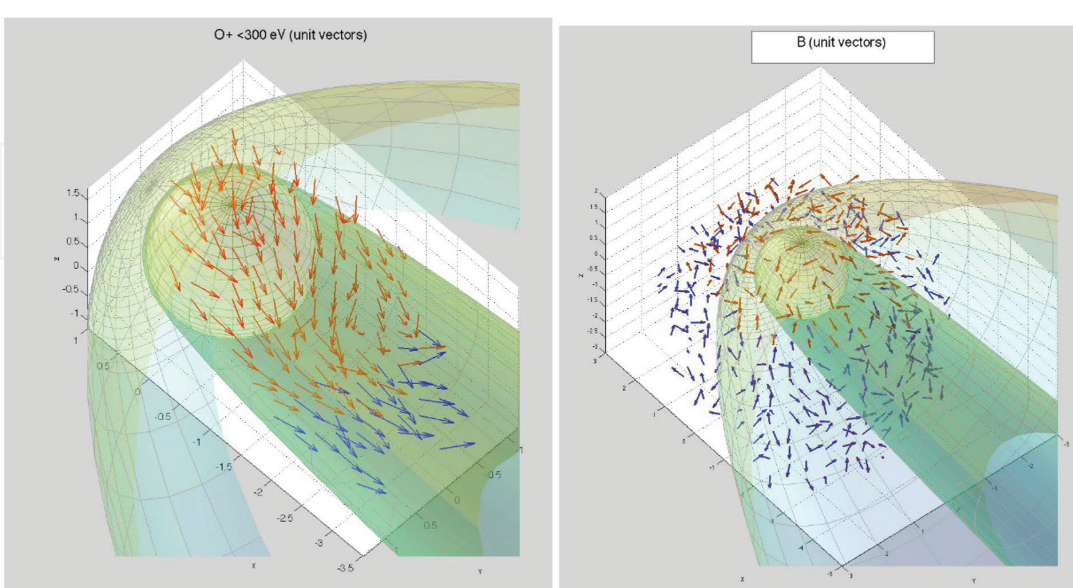

Figure 7.
Average values of the velocity vectors of the planetary O+ ions (left) and the magnetic field vectors (right) measured with the VEX spacecraft along the Venus wake. The direction of the velocity vectors exhibits an orderly configuration while the magnetic field vectors become erratic. Red and blue arrows correspond to $Z > 0$ and $Z < 0$ locations.

available VEX data was conducted to examine the manner in which that force may influence particle motion in the wake and that led to the results presented in **Figure 7**. The left panel describes the average values that the velocity vectors of the planetary O+ ions maintain across the wake. Their orderly configuration exhibits a well-organized speed distribution along the wake with some of them displaying a common deflection toward the Y axis. That pattern is entirely different from the erratic distribution of the magnetic field vector orientation measured over many orbits and that is presented in the right panel of that figure. The varying direction of the magnetic field vectors differs from the well-organized orientation of the velocity vectors of the O+ ions and thus provides information that their acceleration is not solely dependent on the **J x B** forces. Other forces mostly derived from wave-particle interactions are necessary to justify the organized distribution of the velocity vectors of the O+ ions, which follow that of the solar wind ions. The data presented here thus provide an important source of information regarding the orderly direction of the velocity vectors of the planetary O+ ion population along the tail and that is unrelated to the **J x B** forces.

5. Conclusions

From the data analysis made in a representative number of VEX orbits, it has been possible to identify the relative position of vortex structures detected before and in the vicinity of a minimum solar cycle with an indication that they occur closer to Venus along its wake under such conditions. This variation was inferred by considering either a small number of VEX orbits or a more extended sample including those obtained across most of the operation time of that spacecraft. A suitable shape of the vortex structures along the Venus wake was also inferred from the observed decrease of its thickness with the downstream distance and that is similar to that of corkscrew flows in fluid dynamic problems. An implication of their expected smaller cross section along the Venus wake is that energy is provided to particles that stream in that direction, thus leading to their gradual acceleration.

The distribution of planetary ions through the Venus wake is arranged by the combined participation of wave-particle interactions on their large-scale gyrotropic trajectories [13]. Their effects should be substantial [14–16] since they will allow the magnetic field forces to be influenced by oscillations and fluctuations of the magnetic field that has draped around the Venus ionosphere and at the same time to the convected electric field of the solar wind. Measurements conducted with the Mariner 5, the PVO, and the VEX spacecraft have contributed with observations of notable magnetic turbulence that is suitable to support that view [17, 18] and that are required to account for the transport of momentum between the solar wind and the ionospheric plasma. Similar conditions should also be applicable to the solar wind/Mars ionosphere interface where there are observations of plasma heating across the flanks of a velocity shear [19], and also that magnetic field wave oscillations have been reported from the MAVEN measurements [20].

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Author details

H. Pérez-de-Tejada[1*] and R. Lundin[2]

1 Institute of Geophysics, UNAM, Mexico

2 Swedish Space Research Institute, Kiruna, Sweden

*Address all correspondence to: hectorperezdetejada@gmail.com

References

[1] Pérez-de-Tejada H et al. Plasma vortex in the Venus wake. Eos. 1982;**63**(18):368

[2] Pérez-de-Tejada H, Lundin R, Intriligator D. Plasma vortices in planetary wakes. In: Olmo G, editor. Chapter 13 in: Open Questions in Cosmology. London, UK: Intech; 2012

[3] Lundin R et al. A large scale vortex in the Venus plasma tail and its fluid dynamic interpretation. Geophysical Research Letters. 2013;**40**(7):273

[4] Miller K, Whitten R. Ion dynamics in the Venus ionosphere. Space Science Reviews. 1991;**55**:165

[5] Phillips J, McComas D. The magnetosheath and magnetotail of Venus. Space Sciences Reviews. 1991;**55**:1. (Fig. 35)

[6] Brace L, et al. Holes in the nightside ionosphere of Venus. Journal of Geophysical Research. 1982;**87**:199

[7] Pérez-de-Tejada H et al. Measurement of plasma channels in the Venus wake. Icarus. 2019;**321**:1026-1037

[8] Delva M et al. Proton cyclotron waves in the solar wind at Venus. Journal of Geophysical Research. 2008;**113**:E00B06

[9] Pérez-de-Tejada H, Lundin R. Solar cycle variations in the position of vortex structures in the Venus wake. In: Bouvaquia, editor. Chapter 3 in: Solar Planets and Exoplanets. London, UK: INTECH-OPEN; 2021. DOI: 10.5772/96710

[10] Pérez-de-Tejada H, Lundin R. Vortex dynamics in the wake of planetary ionospheres. In: Vortex Dynamics – From Physical to Mathematical Aspects. London, UK: IntechOpen; 2022. DOI: 10.5772/IntechOpen.101352

[11] Romanov SA et al. Interaction of the solar wind with Venus. Cosmic Research. 1979;**16**:603. (Fig. 5)

[12] Lundin R et al. Ion flow and momentum transfer in the Venus plasma environment. Icarus. 2011;**215**:7

[13] Luhmann J et al. A comparison of induced magnetotails of planetary bodies; Venus, Mars, Titan. Journal of Geophysical Research. 1991;**96**:1199

[14] Shapiro V, Shevchenko V. Astrophysical plasma turbulences. Astrophys and Space Science Reviews. 1968;**6**:427

[15] Szego K et al. Physical processes in the plasma mantle of Venus. Geophysical Research Letters. 1991;**18**(12):2305

[16] Dobe Z et al. Interaction of the solar wind with unmagnetized planets. Physical Review Letters. 1999;**83**(2):260-263

[17] Bridge A et al. Plasma and magnetic fields observed near Venus. Science. 1967;**158**:1669-1673. (see Fig. 2)

[18] Vörös Z et al. Intermittent turbulence, noisy fluctuations and wavy structures in the Venusian magnetosheath and wake. Journal of Geophysical Research. 2008;**113**:ED0B21, 200. DOI: 1029/2008JE003159

[19] Dubinin E et al. Plasma characteristics of the boundary layer in the Martian magnetosphere. Journal of Geophysical Research. 1996;**101**:27061

[20] Ruhunusiri S et al. MAVEN observations of partially developed Kelvin-Helmholtz vortices at Mars. Geophysical Research Letters. 2016. DOI: 10.1002/2016GL068926