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Chapter

Solar Cycle Variations in the Position of Vortex Structures in the Venus Wake

H. Pérez-de-Tejada and R. Lundin

Abstract

Measurements conducted with the Venus Express (VEX) spacecraft at its entry and exit through vortex structures in the Venus wake reveal that their position varies with the solar cycle. Both crossings are consistently measured closer to Venus during minimum solar cycle conditions and are gradually encountered at larger distances downstream from the planet along the solar cycle. At the same time their width along the VEX trajectory on the plane transverse to the solar wind direction is larger during minimum solar cycle conditions and show a gradual decrease along the solar cycle. As a result the vortex structures are envisioned as features that gradually become thinner as they extend along the Venus wake and agree with the geometry of a vortex flow in fluid dynamics whose thickness decreases with the downstream distance from an obstacle. Similar conditions should also be applicable to Mars and other bodies within the solar system and also possibly to exo-planets in external stellar systems.

Keywords: Venus Wake, Vortex Structures, Pressure Balance Conditions

1. Introduction

Measurements conducted with various spacecraft across the Venus wake: the Mariner 5, the Venera, the Pioneer Venus Orbiter (PVO), and the Venus Express (VEX) spacecraft have provided evidence of plasma features that resemble vortex structures in fluid dynamic problems. It has been noted that the anti-solar directed flow of the plasma particles in the Venus wake is rotated to even become oriented back to Venus. The early measurement of that effect was reported by Pérez-de-Tejada et al. [1–3] from the PVO plasma data and that gave place to conditions that could be assessed as resulting from a vortex structure. Further information on the observation of vortex structures in the Venus wake was reported by Lundin et al. [4, 5] from measurements conducted with the ASPERA instrument onboard VEX. In this case it was possible to identify the scale size and position of vortex structures with information on the distribution of the velocity vectors of the solar wind and planetary ions that stream within and around those features.

A general view of the shape of a vortex structure is reproduced in the left panel of **Figure 1** showing in the plane transverse to the solar wind direction a vortex structure with a scale size comparable to that of the planet with a circulation sense that is counterclockwise when seen from the wake back to Venus. A circulation

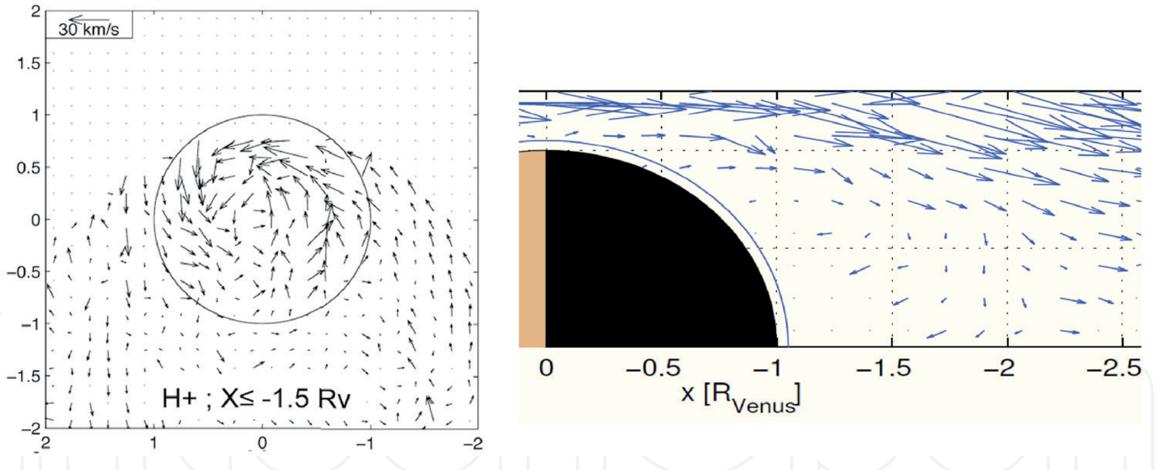

Figure 1.
*(left panel) velocity vectors of H+ ≈ 1–300 eV ions measured with the VEX spacecraft in the Venus wake projected on the YZ plane transverse to the solar wind direction. Data are averaged in 1000 x 1000 km columns at X < −1.5 R_V (adapted from **Figure 4** of [5]). (right panel) average direction of solar wind ion velocity vectors across the Venus near wake collected from many VEX orbits and projected in cylindrical coordinates [15].*

pattern of the solar wind direction in cylindrical coordinates along the Venus wake is added in the right side panel of **Figure 1** with indications of a sunward directed flow return in the central wake. Comparable variations in the plasma velocity vector have also been recently reported from the VEX measurements [6]. Different from that motion there has also been information derived from the PVO and VEX measurements on an east–west displacement of planetary ion fluxes and that leads to the overall deflection of the trans-terminator ionospheric flow toward the dawn-hemisphere as it moves into the night-side ([7], see Fig. 15; [4], see Fig. 7b). A deflection in that direction can be accounted for in terms of the fluid dynamic Magnus force produced by the joint contribution of the unidirectional solar wind velocity and the rotation of the Venus atmosphere/ionosphere [8, 9].

2. Vortex structures

Ample information on the speed and density values of the solar wind and planetary ions is their energy spectra obtained with the ASPERA instrument onboard the VEX spacecraft. A suitable example is provided by the data of the Sept. 26–2009 orbit reproduced in **Figure 2** and that probed by the near vicinity of the midnight plane (small Y-values shown at the bottom of the figure). The energy spectra of the O+ ion component (second panel) exhibit variations that indicate the presence of appreciable planetary O+ ion fluxes between 02:05 UT and 02:30 UT and that lead to enhanced values of their density and speed (third and fifth panels). At the same time the magnetic field intensity exhibits decreased values within that time interval with an oscillating response of its components (seventh panel). The later indicates the possible presence of a vortex structure within the region where enhanced values of the density and speed of the O+ ion fluxes are clearly distinguished. An important property of the observed values is that the kinetic energy density of such fluxes ($mnv^2 \sim 10\ 10^{-10}$ ergs cm^{-3}) is comparable to the magnetic energy density ($B^2/8\pi \sim 4\ 10^{-10}$ ergs cm^{-3}) measured in the vicinity of that region where B ≈ 10 nT. As a result a near pressure balance condition between values measured outside is suggested within a region with evidence of a vortex structure. It is to be noted that these variations occurred far downstream from the planet (by X < −1.70 R_V with this latter parameter being the Venus radius) and thus are unrelated to the crossing of the VEX

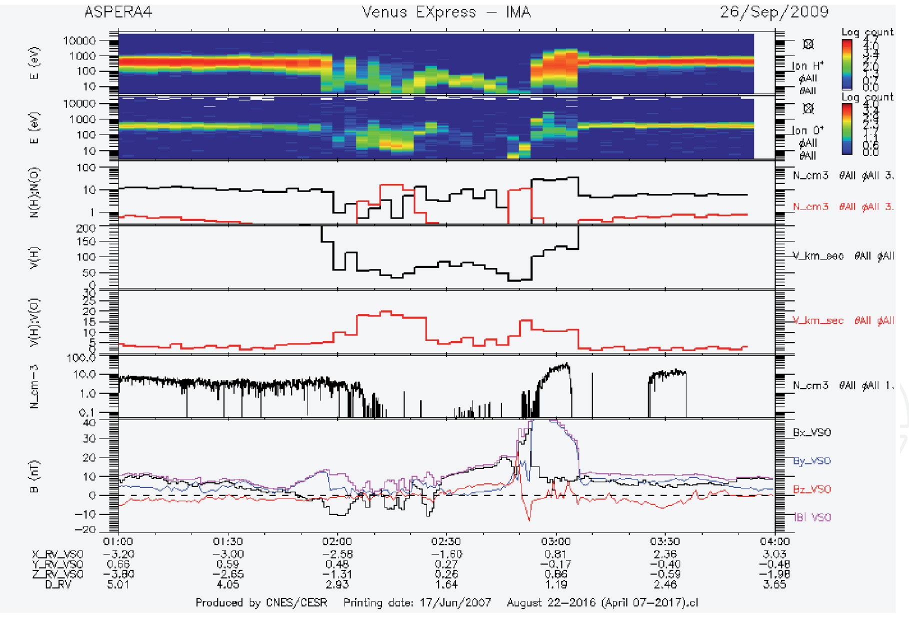

Figure 2.
Energy spectra of the H+ and O+ ions (upper panels) measured during the sept 26–2009 VEX orbit in the Venus wake by the midnight plane (small Y-values below the figure). In measurements between 02:05 UT and 02:30 UT there are oscillations in the magnetic field components (bottom panel) indicating a vortex structure. In that time interval there are also decreased values of the magnetic field intensity with enhanced O+ density and speed values (third and fifth panels).

spacecraft near the Venus ionosphere where X ≈ 0 (X, Y, and Z represent Cartesian coordinates indicating, respectively, the Venus-sun direction, the direction opposite to the motion of Venus around the sun, and the axis transverse to the plane formed by both vectors).

Similar conditions have also been identified in other VEX orbits that were traced by the vicinity of the midnight plane and that exhibit as well a near pressure balance condition between the region where enhanced density and speed values of the planetary ions are measured with the magnetic energy density of the magnetic fluxes encountered in their vicinity [10]. At the same time there is no evidence of a sudden and strong reversal in the direction of the B_x magnetic field component as it would be expected across a plasma sheet embedded by the middle of the wake. On the contrary the enhanced values of the density of the O+ ion population measured by the vortex structure indicates that there is not a local plasma expansion in that region.

3. Distribution of vortex structures in the Venus wake

Different from those properties it is necessary to examine changes of the vortex structures in their position along the nearly 8 years of observations conducted with the VEX spacecraft (between 2006 and 2013). A quantitative analysis of their location was made when VEX entered and exited those structures that was derived from the energy spectra of the planetary ions in the 20 VEX orbits listed in **Table 1**. A comparative view of the distribution of the vortex structures on the XZ plane of the solar wind velocity direction is presented in **Figure 3** to show the position of the VEX entry and exit crossings in orbits that probed near the midnight plane. Two sets with 4 orbits corresponding to measurements made in 2006 and in 2009 indicate a different displacement of the vortex structures in the Z-direction. There is a general preference of those features to occur closer to Venus in the 2009 measurements since their passage across the Z = 0 axis is by X = −1.7 R_V in that set while it reaches X = −2.2 R_V in the 2006 measurements.

Date	UT	X	Y	Z	n	v	(ρv^2)	ΔT
Aug 22-2006	01:45	-2.87	-0.15	-1.12	10	20	10	9
Aug 22-2006	01:54	-2.55	-0.15	-0.40	10	20	10	9
Aug 23-2006	01:59	-2.64	-0.07	-1.30	10	15	**6**	6
Aug 23-2006	02:05	-2.40	-0.07	-0.44	10	15	**6**	**6**
Aug 24-2006	02.10	-2.48	0.01	-0.83	10	30	23	10
Aug 24-2006	02:20	-2.04	0.01	0.20	10	30	23	10
Aug 28-2006	02:22	-2.40	0.28	-0.38	20	20	20	6
Aug 28-2006	02:28	-2.18	0.07	0.91	20	20	20	6
Nov 13-2007	00:56	-2.60	-0.22	-0.70	10	20	10	7
Nov 13-2007	01:03	-2.38	-0.21	-0.38	10	20	10	7
Nov 15-2007	00:57	-2.60	-0.08	-0.65	10	20	10	6
Nov 15-2007	01:03	-2.40	-0.08	-0.38	10	20	10	6
June 27-2008	03:26	-2.60	0.03	-0.14	5	15	**3**	10
June 27-2008	03:36	-2.30	0.04	-0.20	5	15	**3**	10
June 28-2008	03:33	-2.52	0.04	-0.14	5	15	**3**	12
June 28-2008	03:45	-1.96	0.01	-0.20	5	15	**3**	12
Sept 19-2009	01:54	-2.42	-0.04	-1.04	10	15	6	9
Sept 19-2009	02:03	-2.11	-0.05	-0.55	10	15	6	9
Sept 21-2009	02:02	-2.30	0.08	-0.65	10	15	**6**	10
Sept 21-2009	02:12	-1.95	0.06	-0.12	10	15	**6**	10
Sept 25-2009	02:14	-2.15	0.33	-0.45	10	20	10	13
Sept 25-2009	02:27	-1.60	0.23	0.21	10	20	10	13
Sept 26-2009	02:12	-2.30	0.42	-0.70	10	20	10	10
Sept 26-2009	02:22	-1.95	0.34	-0.20	10	20	10	10
Aug 22-2010	08:24	-1.80	0.01	0.25	6	25	10	7
Aug 22-2010	08:31	-2.08	0.01	0.04	1	18	8	7
Aug 23-2010	08:16	-1.25	0.05	0.68	10	15	6	13
Aug 23-2010	08:29	-2.02	0.05	0.02	8	7	10	13
July 23-2011	02:53	-2:53	-0.14	-0.90	2	18	16	13
July 23-2011	03:06	-1.93	-0.13	-0.40	2	12	7	13
July 29-2011	03:07	-2.25	-2.25	-1.00	10	20	10	16
July 29-2011	03:23	-1.70	0.17	-0.10	7	15	4	16
Mar 05-2012	06:23	-2.07	-0.04	-0.60	30	25	48	12
Mar 05-2012	06:35	-1.50	-0.05	0.15	30	20	31	12
Oct 16-2012	01:26	-2.00	-0.02	-0.85	2	28	4	13
Oct 16-2012	01:39	-1.70	-0.03	0.10	6	13	26	13
May 29-2013	04:28	-1.70	-0.01	-0.14	8	20	8	10

Date	UT	X	Y	Z	n	v	(ρv²)	ΔT
May 29-2013	04:38	-1.28	-0.02	0.40	3	20	3	10
May 30-2013	04:20	-2.00	0.07	-0.73	2	15	1	10
May 30-2013	04:30	-1.68	-0.04	-0.12	1	10	<1	10

Table 1.
VEX coordinates (in R_V) at the time of its crossing (in UT) during an entry and exit (third to fifth columns) through a plasma structure within the Venus wake. Values for the density (cm^{-3}) and speed v (km/s) of planetary O+ ions together with their kinetic energy density ρv^2 (10^{-10} ergs/cm^{-3}) are given in the sixth to eight columns, and the last column has the time width of the vortex structure measured between the inbound and the outbound crossings (the segment between x = −2.30 R_V and x = −1.95 R_V is the same for both the sept 21–2009 and the sept 26–2009 orbits).

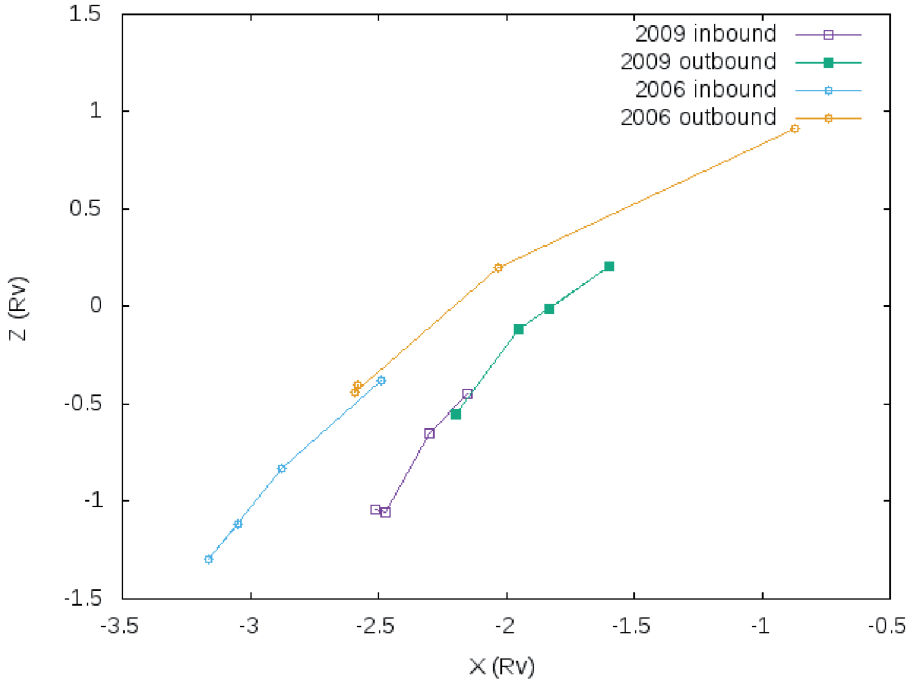

Figure 3.
Position of the VEX spacecraft projected on the XZ plane during its entry (inbound) and exit (outbound) through a corkscrew plasma structure in orbits traced by the midnight plane. The two traces correspond to 4 orbits in 2006 and 2009 [10].

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 during that cycle.

A more extended description of the position and geometry of the vortex structures implied by the data of the orbits listed in **Table 1** is depicted in **Figure 4** to show changes in their location and extent during 8 years of VEX operation. 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 with a number that marks the two last digits of the year when measurements were made (they include the 4 orbits for 2006 and 4 for 2009 that were discussed in **Figure 3**). Most notable is that the segments identify 2 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 set of orbits that are located either far away from Venus between 2006 and 2009 (left circle) and

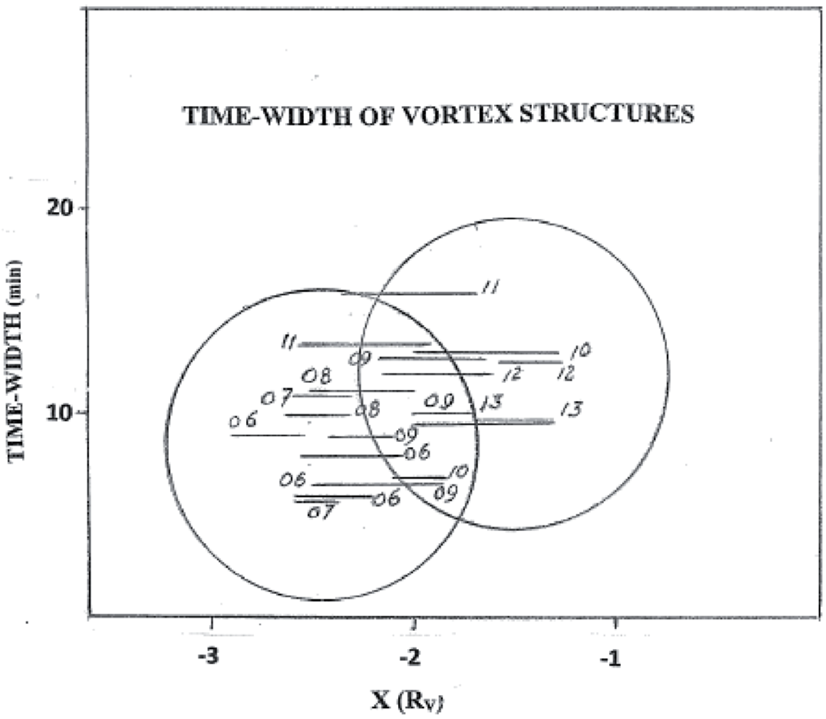

Figure 4.
Time-width (in minutes) measured between the VEX inbound and outbound crossings of a vortex structure as a function of the X-distance (R_V) downstream from Venus in 20 orbits. The numbers at the side of each segment represent the two last digits of the year when measurements were made in different orbits between 2006 and 2013 (four orbits were examined during 2006 and 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 that period.

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 **Figure 3** vortex structures occur closer to Venus during minimum solar cycle conditions.

Equally notable 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 2009–2013 orbit range (larger values in the right circle). As a result the thickness of the vortex structures located far away from Venus (left circle) becomes smaller with increasing distance along the wake thus implying that like in a corkscrew flow they thin out with distance downstream from Venus.

A schematic view of a corkscrew vortex flow structure in fluid dynamics is illustrated in **Figure 5** to represent the equivalent geometry of a similar structure in the Venus wake and that is formed by the distribution of planetary O+ ions eroded by the solar wind from the Venus ionosphere. The shape of the vortex structure in **Figure 5** shows how it becomes thinner with increasing distance from an object that is immersed in a streaming fluid. Such representation is consistent with the wider width of the vortex structures measured closer to Venus in the 2009–2013 orbit set (right circle in **Figure 4**) during solar minimum conditions instead of their thinner width measured in the 2006–2009 orbit set measured before the minimum solar cycle conditions (left circle), and that are located farther away along the Venus wake. As a result the thickness of the vortex structure gradually decreases with distance downstream from Venus and that eventually fade away and diffuse with the solar wind plasma. Further studies of more extended data are required to examine the evolution of the vortex structures far downstream along the Venus tail. It should also be noticed that in addition to changes associated to a solar cycle

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 orbits within the left circle of **Figure 4** and that were conducted before the solar cycle minimum at 2009–2010 thus implying that it becomes thinner when it is detected further downstream along the wake.*

there is evidence that the solar energy output and thus that of the solar wind during the last cycle have decreased with respect to values measured in the previous cycle and thus there is a tendency for the input solar wind pressure to now reach smaller values under solar minimum conditions.

4. Conditions applicable to other planets

The main output of these concepts is that the position of the vortex structures along the Venus wake and their width measured along the VEX trajectory vary along the solar cycle thus implying a continuous displacement of the region where they apply. Similar conditions should also be applicable along the plasma wake of other planets and satellites within the solar system and may as well reach those suitable to exo-planets impacted by stellar winds.

Throughout the solar system the most likely candidates are Venus and Mars which do not have a strong intrinsic magnetic field that deflects the solar wind before it reaches their upper atmosphere/ionosphere. While plasma vortices have been inferred from measurements made along the flanks of the earth's magnetosphere [11–13] changes in their position are not expected to produce local variations as notable as those measured in the Venus wake. On the other hand observations of vortex oscillations have been reported from measurements conducted with the MAVEN spacecraft by the solar wind Mars ionosphere boundary [14] and it is possible that they produce vortex structures similar to those detected in the Venus wake. Comparable conditions may also occur around the Titan ionosphere when it is subject to the solar wind flow and/or to plasma motion within Saturn's magnetosphere when it moves across it. The dynamic pressure of the plasma pressure that reaches Titan is very different in both cases and thus should produce vortex structures that are situated at different locations along its plasma wake. External to the solar system it is also possible that exo-planets moving within stellar systems will be subject to stellar winds that do not have the same intensity and thus arrive from different directions. In such cases vortex structures may be present at varying distances along their wake and be located at varying distances downstream from exo-planets. Stellar winds with different flow intensity, plasma temperature, and stellar irradiance will in addition influence the position and configuration of vortex structures in an exo-planet wake. A notable effect is the subsonic to supersonic speed change that depends on the coronal temperature of a star as implied from the solution of the fluid dynamic Parker equations of solar wind acceleration [15]. Equally important is the requirement that fluid dynamic vortex structures will be influenced by a planetary magnetic field as it is the case along the earth's wake.

5. Conclusions

The fluid dynamic response of the solar wind that interacts with planetary ionospheres is ultimately produced by wave-particle interactions inferred from the observation of frequent oscillations in magnetic field profiles measured in the Venus wake [16–18]. As a whole such interactions provide a mechanism to transfer momentum between both ion populations and thus erode the upper layers of the Venus ionosphere [2]. That process implies in turn local plasma heating [19, see Fig. 35; 20, 21] and the removal of ionospheric plasma in the form of channels or ducts that extend downstream along the Venus wake [22, 23]. These various features are in agreement with phenomena observed in fluid dynamic problems and provide an account of measurements conducted in the Venus wake with various spacecraft. The identification of vortex structures in the Venus wake whose position and width varies during the solar cycle provides a remarkable result that justifies the importance of the fluid dynamic approach.

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