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Chapter

Vortex Dynamics in the Wake of Planetary Ionospheres

Hector Pérez-de-Tejada and Rickard Lundin

Abstract

Measurements conducted with spacecraft around Venus and Mars have shown the presence of vortex structures in their plasma wake. Such features extend across distances of the order of a planetary radius and travel along their wake with a few minutes rotation period. At Venus, they are oriented in the counterclockwise sense when viewed from the wake. Vortex structures have also been reported from measurements conducted by the solar wind-Mars ionospheric boundary. Their position in the Venus wake varies during the solar cycle and becomes located closer to Venus with narrower width values during minimum solar cycle conditions. As a whole there is a tendency for the thickness of the vortex structures to become smaller with the downstream distance from Venus in a configuration similar to that of a cork-screw flow in fluid dynamics and that gradually becomes smaller with increasing distance downstream from an obstacle. It is argued that such process derives from the transport of momentum from vortex structures to motion directed along the Venus wake and that it is driven by the thermal expansion of the solar wind. The implications of that momentum transport are examined to stress an enhancement in the kinetic energy of particles that move along the wake after reducing the rotational kinetic energy of particles streaming in a vortex flow. As a result, the kinetic energy of plasma articles along the Venus wake becomes enhanced by the momentum of the vortex flow, which decreases its size in that direction. Particle fluxes with such properties should be measured with increasing distance downstream from Venus. Similar conditions should also be expected in vortex flows subject to pressure forces that drive them behind an obstacle.

Keywords: vortex Venus plasma wake, solar wind-Venus interaction, plasma acceleration in the Venus wake

1. Introduction

Measurements conducted with the Pioneer Venus Orbiter (PVO) and the Venus Express spacecraft (VEX) around Venus have provided evidence on the existence of vortex structures in the Venus plasma wake [1–5]. Much of what has been learned led to estimate the (~ 1 R_V) scale size of those features across the wake, which are shown in the left panel of **Figure 1** with a view of the velocity vectors projected on the plane transverse to the solar wind direction. The flow pattern corresponds to a vortex gyration of the velocity vectors of the solar wind H+ ions, which is also accompanied by a similar distribution of the velocity vectors of the planetary O+ ions that have been dragged by the solar wind from the Venus upper ionosphere. Comparative indications on the presence of vortex structures in the Mars plasma environment have also

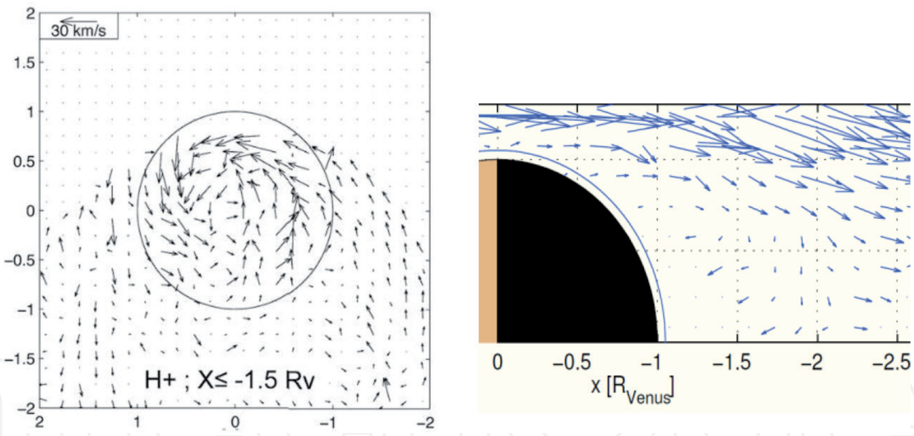

Figure 1.
(Left panel) Velocity vectors of H + ≈ 1–300 eV ions measured with the VEX spacecraft in the Venus near wake projected on the YZ plane transverse to the solar wind direction. Data are averaged in 1000 × 1000 km columns at X < −1.5 R_V (adapted from ***Figure 4*** *of [2]). (Right panel) Average direction of solar wind ion velocity vectors across the Venus near wake collected from many VEX orbits and projected in cylindrical coordinates [7].*

been inferred from the observation of ionospheric-sheath boundary oscillations from the MAVEN plasma data [6]. In this case, measurements suggest Kelvin-Helmholtz oscillations with a periodicity of ~3 min but that have not yet completed a full vortex turn. At Venus, there is evidence of a reversal in the direction of the velocity vectors of plasma particles that lead them back to the planet in the central part of the Venus wake as is shown in the right panel of **Figure 1**.

Evidence of vortex structures in the Venus wake is also available from changes in the magnetic field direction in the VEX measurements. In previous reports [4, 8], it has been pointed out that at the time when a vortex structure is identified by a local increase of the plasma density in the Venus wake, there is an accompanying

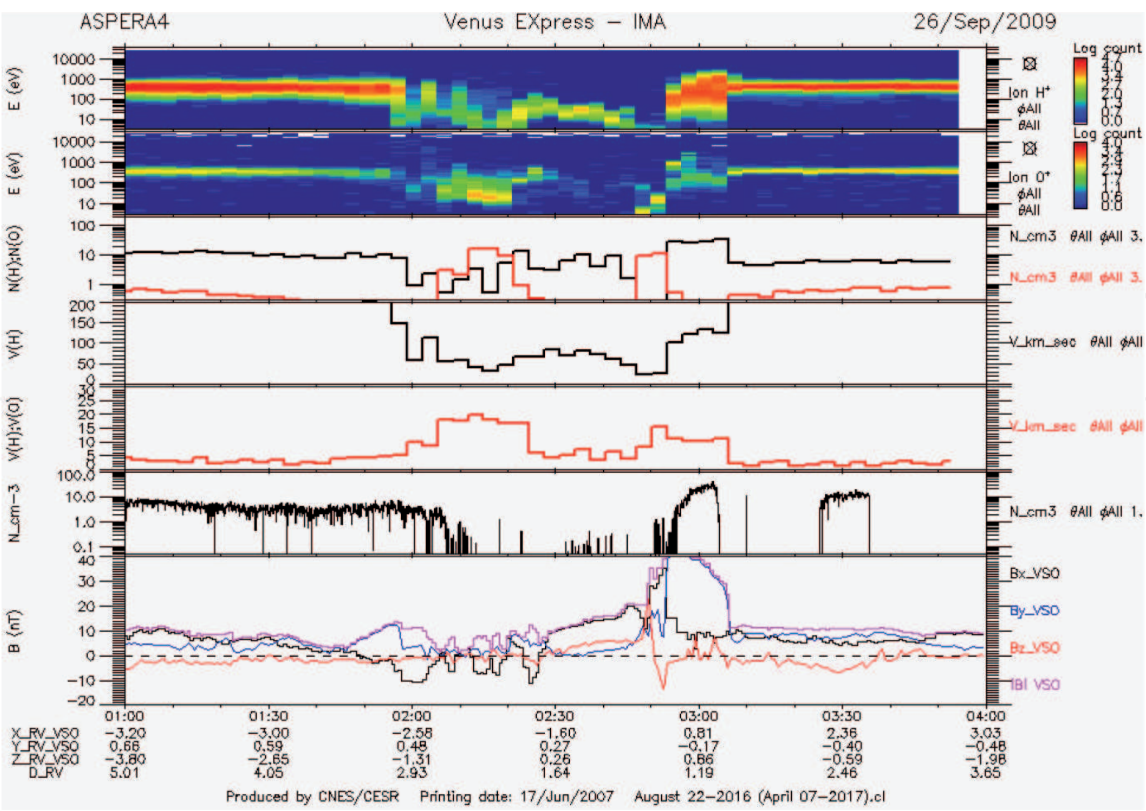

Figure 2.
Energy spectra of the H+ and O+ ions (upper panels) with measurements in the Sept 26–2009 VEX orbit where there are strong oscillations in the magnetic field components between 02:05 UT and 02:30 UT (bottom panel). In that time span there are enhanced density and speed values of the O+ ions (third and fifth panels).

decrease of the local magnetic field convected by the solar wind with distinct changes in the orientation of its components. A useful example with such properties is reproduced in **Figure 2** to show evidence of sudden changes in the orientation of the magnetic field components between 02:00 UT and 02:30 UT (bottom panel) when the plasma density and speed of planetary particles in the Venus wake show enhanced values (third and fifth panels). Despite the fact that the data has provided notable information on the general characteristics of vortex structures, there remains to address important aspects related to their origin and to the dynamics of their motion. These issues will be examined by considering the various fluid forces that are imposed by the solar wind on the planetary ions that stream in the wake. The description to be addressed here refers to the Venus observations where there is ample evidence on the geometry, distribution, and time variations of vortex structures. Despite the presence of small fossilized magnetic field areas in the Mars surface [9], much of the information for the Venus wake will apply to plasma vortices that stream along the Mars plasma wake.

2. Fluid dynamic forces in the Venus wake

A dominant feature in the motion of the solar wind particles that stream around the Venus ionosphere is that different from the pile-up of magnetic field fluxes convected by the solar wind over the dayside hemisphere, the plasma experiences local heating processes when it moves by the terminator of the Venus ionosphere. Indications of that plasma heating were first obtained from the Venera measurements through crossings of that spacecraft across the Venus wake with enhanced plasma temperature values along the flanks of the Venus ionosheath and that is reproduced in **Figure 3** [10, 11]. The heating derives from dissipation processes produced by the transport of solar wind momentum mostly over the Venus polar ionosphere where the local pile-up of the solar wind magnetic field fluxes is not strong. A suitable added information in the data of **Figure 3** is the presence of a plasma transition in the temperature and speed profiles (at ~02:00 Moscow time), which together with the vortex structure shown in **Figure 1** are unrelated to the dynamics expected from sling shot effects produced by the magnetic field fluxes draped around Venus [12]. While measurements have shown an antisolar directed motion of planetary ions in the Venus wake, a vortex flow configuration like that shown in **Figure 1** is more complex than that expected from a slingshot geometry.

As a result of the enhanced plasma temperature values, the solar wind expands by thermal pressure forces and then moves into the Venus wake from both polar regions. An implication of that displacement is that there are two separate flows of plasma particles reaching the central wake from two opposite directions along the Z-axis. They move from both polar regions where the planetary $O+$ ions are first subject to low values of the rotation of the Venus ionosphere, and then they are displaced to equatorial latitudes where the rotation speed of the Venus ionosphere is larger. Since both plasma flows are also streaming along the X-axis following the solar wind direction, there should be a Coriolis force that deflects them in opposite directions along the Y-axis. For both flows the deflection of the particles should not be in the same sense since in the northern hemisphere the particles will move in the –Z direction and in the southern hemisphere in the +Z-direction. In addition to such opposite deflection along the Y-axis, the streaming particles will also be influenced by the effects of the aberrated direction of the solar wind and a general Magnus force that drive all planetary ions in motion around the planet with a velocity component directed in the +Y sense ([13], see their Fig. 15; [14]). Since that effect is contrary to the direction of motion along the -Y sense imposed by the

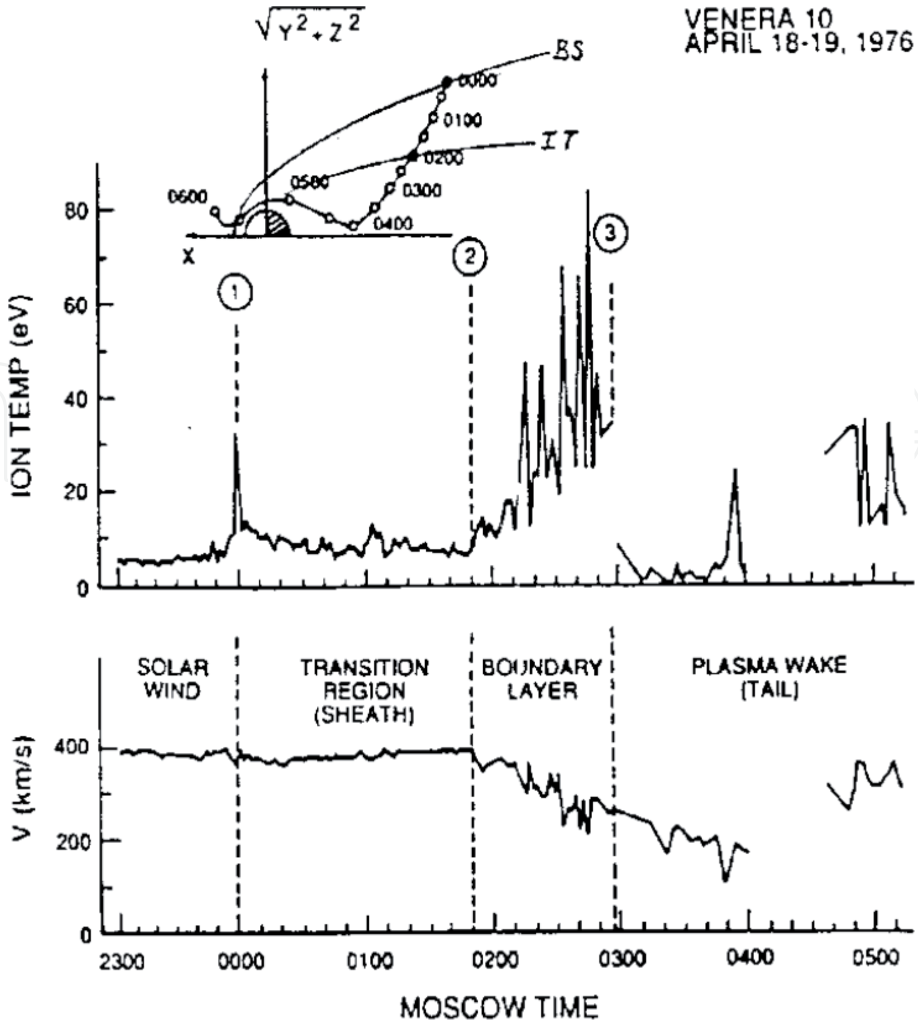

Figure 3.
Ion speed and temperature measured along the orbit of Venera 10 on Apr. 19, 1976. The Venera orbit in cylindrical coordinates is shown at the top. The temperature burst at position 1 was recorded during a flank crossing of the shock wave. The boundary layer is apparent by the increase in temperature and decrease in speed and is initiated by the intermediate transition at position labeled 2. The discontinuity in the boundary layer temperature profile corresponds to the boundary of the magneto-tail. (from [10]).

Coriolis force to the O+ ions that stream in the southern hemisphere, their resulting total velocity will be smaller than that of the O+ ions in the northern hemisphere where the velocity components implied by the Coriolis and the Magnus force are oriented in the same sense along the +Y direction.

An implication of that velocity difference between both hemispheres is that the momentum flux of the O+ ions along the Y-axis in the southern hemisphere will be smaller than the momentum flux of the O+ ions in the northern hemisphere. Consequently, a fraction of the momentum flux of the O+ ion fluxes that move north along the Z-axis in the southern hemisphere from the polar region (derived from the enhanced thermal pressure force at that region) will be transferred to that in the Y-sense to compensate for the smaller values of their momentum flux with respect to the larger Y-directed momentum flux of the O+ ions that stream in the northern hemisphere. Thus, in addition that the larger momentum flux of the O+ ions in the XY plane in the northern hemisphere over that of the O+ ions in the southern hemisphere, there will also be smaller values for the momentum flux of the O+ ions that move north along the Z-axis in the southern hemisphere. Under such conditions the momentum flux of the O+ ions that are directed south in the northern hemisphere will be dominant over that directed north in the southern hemisphere. As a result, the motion of the O+ ions in the northern hemisphere will force the vortex structure to be displaced toward the –Z direction. Such an effect

	Inbound					Outbound						
Date	**UT**	**X**	**Y**	**Z**	**v**	**UT**	**X**	**Y**	**Z**	**v**	**δ**	**Δ**
Aug 22/06	01.44	−2.90	−0.15	**−0.85**	25	01:54	−2.55	−0.15	**−0.40**	25	0.35	0.45
Aug 23/06	01:56	−2.75	−0.07	**−0.60**	15	02:05	−2.20	−0.07	**−0.20**	15	0.35	0.40
Aug 24/06	02:10	−2.45	−0.01	**−0.20**	30	02:20	−2.05	−0.02	**0.20**	30	0.40	0.40
Aug 28/06	02:22	−2.40	−0.28	**−0.35**	20	02:28	−1.90	0.20	**0.00**	20	0.50	0.35
Sep 19/09	01:54	−2.38	−0.04	**−0.80**	15	02:03	−2.11	−0.05	**−0.40**	15	0.30	0.40
Sep 21/09	02:02	−2.30	0.09	**−0.65**	15	02:12	−1.95	0.06	**−0.12**	15	0.35	0.53
Sep 25/09	02:14	−2.10	0.33	**−0.45**	20	02:27	−1.60	0.23	**0.25**	28	0.50	0.70
Sep 26/09	02:12	−2.30	0.42	**−0.70**	20	02:21	−1.95	**0.35**	**−0.20**	20	0.35	0.50

Table 1.
VEX coordinates along the X, Y, and Z-axis (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 a vortex structure in selected VEX orbits across the Venus wake (the last two columns are the extent of the vortex structure measured in the X and in the Z directions in R_V).

agrees with the data of the VEX position of the vortex structures measured in the XZ plane during the 2006 and 2009 orbits listed in **Table 1** and that is also represented in their profiles in **Figure 4** showing how they become directed to lower –Z values with increasing distance downstream from Venus ([8], see their **Figure 3**). As a result, the outcome of the different momentum flux of the planetary O+ ions in the northern and in the southern hemispheres in the Venus wake is related to the

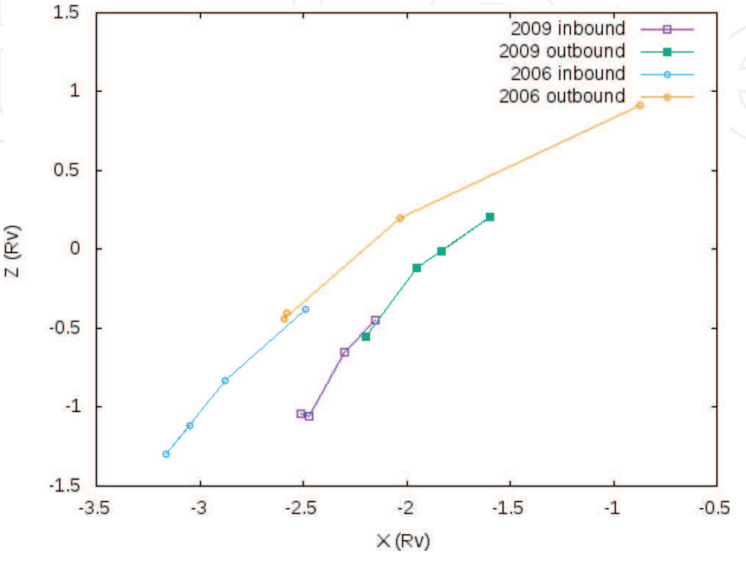

Figure 4.
Position of the VEX spacecraft projected on the XZ plane during its entry (inbound) and exit (outbound) through a corkscrew plasma structure in several orbits. The two traces correspond to four orbits in 2006 and four orbits in 2009 listed in ***Table 1*** *[8].*

effects produced by the Coriolis and the Magnus force and that lead to the southbound displacement of the vortex structures shown in **Figure 4**.

3. Cross section of the vortex structures along the Venus wake

Data corresponding to the 2006–2009 orbits discussed in **Figure 4** have been further addressed to examine the shape of the vortex structures along the Venus wake with results that are presented in **Table 1**. We have separately collected information obtained for the inbound (left side) and for the outbound (right side) columns in each set of orbits. Values for the extent between both crossings along the X and Z-axis are indicated in the two last columns.

A notable aspect of the data in **Table 1** is that the values of the X-coordinate for the inbound and the outbound crossings of the four orbits during 2006 are larger than those for 2009. The implication is that the vortex structure is located closer to Venus during conditions approaching the solar cycle minimum by 2009. The same conclusion has also been inferred from the relative position of the 2006 and 2009 profiles in **Figure 4**. At the same time, the values of the X-coordinate during the inbound crossings in all eight orbits of **Table 1** (left side **c**olumns) are larger than those of the outbound crossings. Such difference derives from the tilted orientation of the trajectory of the VEX spacecraft on the XZ plane, which is directed toward Venus from the wake as it moves from the southern to the northern hemispheres (the inbound crossing of VEX is encountered at a larger distance downstream from Venus in the southern hemisphere as it then moves to a closer distance to Venus during its outbound crossing in the northern hemisphere).

A detail calculation has now been conducted to the data in the orbits of **Table 1** to estimate the width and the location of the vortex structures measured in both the 2006 and the 2009 orbits. The results are shown in **Figure 5** and indicate that there is a tendency for the vortex structures in the 2006 orbits to occur farther away from Venus than those in the 2009 orbits. At the same time there is an indication that the time width ΔT between the inbound and the outbound encounters marked by the vertical coordinate in **Figure 5** occurs at smaller values in the 2006 orbits, which trace the wake farther away from Venus. Such would be the case in a corkscrew flow configuration in fluid dynamics where its width becomes smaller with downstream distance from an obstacle as is represented in **Figure 6**.

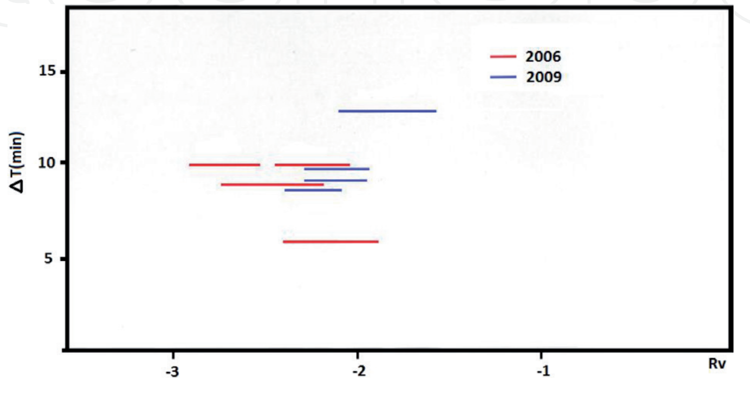

Figure 5.
*Segments measured between the inbound and the outbound crossings of vortex structures by VEX in the eight orbits included in **Table 1** (they are identified by changes in the particle flux intensity measured in the energy spectra of the O+ ions). Their position along the X-axis shows that the 2009 orbits (marked in blue) are located closer to Venus and that the width of the 2006 orbits (marked in red) is smaller since they have lower ΔT values and are encountered further downstream along the wake.*

Figure 6.
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 in red) traced in ***Figure 5*** *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.*

A view that can be proposed from such difference is that the width of the vortex structures is larger during the 2009 orbits (when they are located closer to Venus) rather than in 2006 (when they occurred further downstream). A general description of vortex structures measured in the Venus wake is that as shown in **Figure 4,** they are formed closer to Venus during minimum solar cycle conditions by 2009 and at the same time they are wide features. Different properties are encountered as the solar cycle progresses since they will now be formed further downstream from Venus and as shown in **Table 1** and in **Figure 5,** they will now extend across a smaller cross section within the wake. More extended calculations are still required to examine the geometric properties of the vortex structures listed in the 20 VEX orbits reported by Pérez-de-Tejada and Lundin [8]. In particular, it will be necessary to address whether the width of the vortex structures becomes narrower when they are measured further downstream from Venus. It was pointed out in that report that the width of the vortex structures becomes narrower when they are measured further downstream from Venus.

Thus, the thickness of the vortex structures gradually decreases with distance downstream from Venus and 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. A view of the distribution of vortex structures along the Venus wake as they follow the motion of plasma particles can be inferred by comparing their cross section formed between the inbound and the outbound crossings on the XZ plane for the different orbits in **Table 1**. The result of that comparison is presented in **Figure 7** where the width ¨Δ¨ of the vortex structures along the Z-axis is compared with that of their extent ¨δ¨

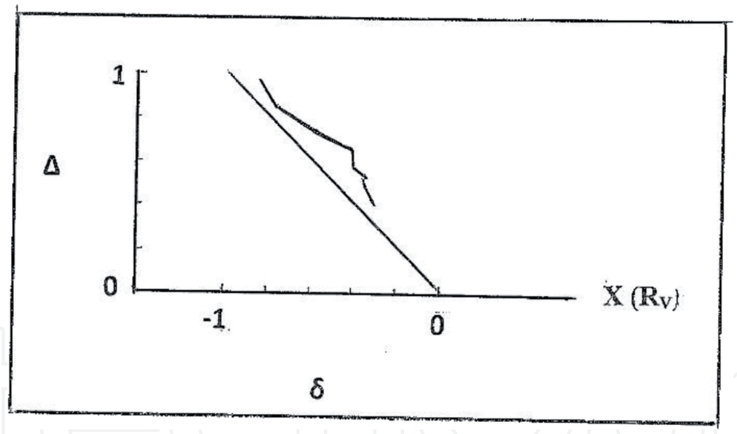

Figure 7.
*Values of the extent ¨δ¨ of vortex structures along the wake (X-axis) and their width ¨Δ¨ along the Z-axis as derived from the data in **Table 1**. Thin features (small ¨Δ¨ values) are obtained in the 2009 orbits while wider vortices correspond to the 2006 orbits.*

along the X-axis. It is notable that this latter quantity is correlated with their width along the Z-axis implying that thin vortices have a shorter extent along the wake and that wide vortices have a larger extent in that direction. A peculiar characteristic of the ¨δ¨ and the ¨Δ¨ values in the trace shown in **Figure 7** is that **Δ** > δ (by comparison, a linear relation between them is shown by the straight line for the case in which they have the same value). Thus, as is indicated in the last two columns of **Table 1,** there is a tendency that along the VEX trajectory the vortex structures have a larger width along the Z-axis (that difference may be due to the tilted orientation of the VEX trajectory on the XZ plane or to enhanced Δ values produced by an asymmetric shape of the vortex structure in that plane).

4. Velocity values of plasma particles along the Venus wake

In **Table 1,** there is evidence that the speed values of the planetary O+ ions vary between 15 and 30 km/s by the inbound and the outbound crossings of vortex structures in the 2006 and 2009 orbits. Such values correspond to measurements conducted along the sun-Venus direction (X-axis) and thus are not related to changes produced by the vortex motion whose speed values vary across the wake. Vortex motion involves speed values of the order of ~200 km/s, which are derived from the transit time of particles around structures with a 1 R_V planetary radius during a ~ 3 min rotation period T [6]. With such high-speed values the plasma particles contain a large fraction of the momentum flux brought in by the solar wind and that has been employed to produce the vortex motion that they follow within the wake. As noted above, the vortex features are displaced in a consistent unified manner along the wake with much smaller speed values.

In addition to the different speed of the vortex structures and that of the particles that move within them, it should be noted that vortex motion marks a response different from that expected from motion produced by the convective electric field of the solar wind. Rather than following the directional motion of the solar wind with a gyrotropic trajectory at nearly the same speed as is predicted in that view the available momentum flux is employed to produce, instead, an alternate vortex flow configuration that is displaced coherently with more moderate speeds.

Despite the fact that there is no indication in the data of **Table 1** on the manner in which the speed values of the vortex structure change with distance along the Venus wake, it is possible to obtain that information from the varying values of the width ¨Δ¨ of the vortex structures that is implied from those obtained

during 2006 and 2009. From the data in **Table 1** we can assume $\Delta = 0.765\ R_V$ as the average value for the width of the vortex structures during the 2006 orbits and $\Delta = 0.532\ R_V$ for that obtained in the 2009 orbits. Since such change implies a scale size decrease by a factor of 0.50% in the area ¨A¨ of the vortex structures, we can apply conservation of mass flux $\rho v^2 A$ = cst to suggest that their speed will increase to nearly double values assuming that the plasma density remains the same.
By applying this procedure, it is possible to argue that as the vortex structures become narrower with downstream distance from Venus, the kinetic energy of planetary particles that stream along the wake will be increased as a result of the decreased values of the cross section of the vortex structures. Thus, it should not be unexpected to measure higher-speed planetary ions moving in the far reaches of the Venus wake.

While most measurements of the vortex structures reported in **Table 1** are applicable to conditions that occur near the midnight plane of the Venus wake (small values of the Y-coordinate in the data of **Figure 2**), there are a few cases (orbits Sept 25–26 in 2009 and Aug 28 in 2006 in **Table 1**) where such structures are encountered at large distances away from that plane; that is, with larger Y-values. Those features also involve enhanced values of the O+ ion density values separated from the Venus ionosphere and that are included in the corresponding panels of figures like those shown in **Figure 2**. In particular, the location where the enhanced density

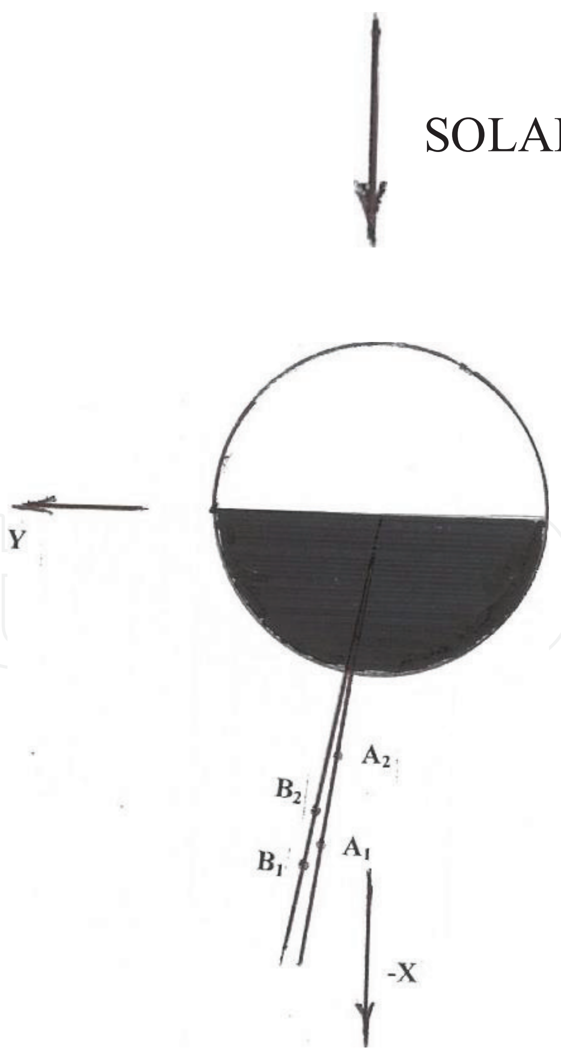

Figure 8.
*Projected orientation of VEX orbits on the ecliptic plane XY with data of vortex structures in **Table 1** during Sept 252,009 (labeled A) and Sept 262,009 (labeled B). The inbound and the outbound VEX crossings have the subscript 1 and 2 for each orbit. In both cases the traces are not directed along the midnight plane but have been shifted in the +Y direction following the effects of the Magnus force on the rotating Venus ionosphere (from [14, 15]).*

values of the O+ ions are observed in those orbits has now been placed in the XY (ecliptic) plane in **Figure 8** to show that they are also shifted to the +Y direction. That region coincides with that where other features produced by the interaction of the solar wind with the Venus ionosphere are shifted in that direction (trans-terminator plasma flow, [16]; ionospheric polar channels, [15]).

Since polar plasma channels are mostly distributed near the midnight plane of the Venus wake rather than by its flanks [15], vortex structures should follow them and as shown in the data of **Table 1** maintain small Y values. However, vortex structures should also be subject to the effects of the aberrated direction of the solar wind and also from the fluid dynamic Magnus force both being directed in the +Y direction. **Figure 8** shows the position of the inbound and outbound VEX encounters of vortex structures along the Sept 25, 2009 and also Sept 26, 2009 orbits that trace the wake with a ~ 10° angle from the midnight plane. It should be noted that both crossings of each orbit occur nearly at the same position in the XY plane despite the fact that they are located at different values along the Z-axis. Thus, vortex structures develop as a near planar structure. Different conditions are encountered in the August 24, 2006 orbit where a wide vortex structure extends along all three coordinates. In fact, similar distances are measured between the inbound and the outbound crossings in the X and in the Y axis. As a result, the structure should not be viewed as a feature that mostly extends in the X direction but that equally applies along the Y direction. Thus, vortex structures may turn out to be complicated features distributed along the wake.

5. Summary of results

A basic issue that is ultimately responsible for the fluid dynamic interpretation employed to account for the motion of the plasma particles within vortex structures is related to their acceleration. Rather than solely applying the convective electric field $E = V \times B$ of the solar wind along their trajectories (V and B being its velocity and magnetic field intensity), it is remarkable that other sources are required to account for the complicated features that are measured. In particular, slingshot trajectories applied to the ionospheric plasma by the magnetic polar regions of Venus and Mars are not sufficient to explain the intricate configuration that is produced from the particle motion and that gives place to the complex vortex flow configuration of their velocity vectors indicated in the left panel of **Figure 1**. A more internal contact between the solar wind and the planetary ions is necessary to deflect their streamlines in a manner that the projection of the velocity vectors on the YZ plane accounts for the peculiar aspect of a vortex flow.

At the same time, while the convective electric field of the solar wind is useful to describe differences in the density and speed of the accelerated planetary ions between the hemispheres where it has a different direction away or toward the planet [12], it is not sufficient to justify the generation of a sharp plasma boundary as that reproduced in **Figure 3** from the Venera measurements. Charge exchange activity between the solar wind hydrogen ions and heavy planetary particles is not satisfactory because it is unrelated to the notable temperature increases reported in those measurements. Instead, concepts based on a fluid dynamic approach rely on arguments that seem to be more accessible to a different acceleration process by invoking wave-particle interactions as the origin of the manner in which both particle populations share their properties. Such condition is expected from the oscillations and fluctuations in the direction and magnitude of the magnetic field measured around the wake [17, 18] and serves to produce the transfer of statistical properties among both plasma populations.

In terms of that description it is of interest to note that it has been useful to account for the following main aspects discussed in this report and that are related to: (i) There is a correlation indicated in **Figure 7** between the width Δ and the extent δ of the vortex structures along the Z axis and the X axis, with Δ > δ values implied from the data of **Table 1**; (ii) as noted in **Figure 4,** vortex structures are measured closer to Venus near solar minimum conditions by 2009; (iii) a notable property in the distribution of vortex structures in the Venus wake is the tendency of their width to become smaller with increasing downstream distance from Venus as can be inferred from the position of their segments in **Figure 5**. That difference implies that the thickness of the vortex region decreases along the wake and thus is reminiscent of a corkscrew flow in fluid dynamics represented in **Figure 6**; (iv) an important consequence in the shape of that region is that mass flow conservation across the vortex structure implies larger speed values of particles that move along the wake (particles with larger speeds should be detected far downstream from Venus); (v) as noted above in **Figure 8,** planetary O+ ion fluxes can also be significantly shifted along the Y-axis in response to effects produced by the aberrated direction of the solar wind and the Magnus force on the motion of planetary O+ ions that are dragged by the solar wind.

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