Chapter

Mass Flux in Corkscrew Flow Vortices in the Venus Plasma Wake

Hector Pérez-de-Tejada and Rickard Lundin

Abstract

Measurements conducted with the Venus Express spacecraft (VEX) around Venus have provided evidence for the presence of a vortex structure in its wake. A configuration of the form of a corkscrew flow with a cross-section comparable to the planet's radius has been inferred from those measurements and exhibits a rotation in the counterclockwise sense when viewed from the wake back to Venus. Such structure is generated by the solar wind and also by planetary ions driven along the wake as inferred from the analysis of data obtained in several orbits of that spacecraft. It has also been learned that the width of the corkscrew structure gradually decreases with distance along the wake and its position varies along the solar cycle occurring closer to the planet during minimum solar cycle conditions. Measurements also show that the flow speed of the planetary ions driven from the nightside ionosphere is modified as they move through the corkscrew flow structure and become accelerated as the width of a corkscrew structure decreases with increasing distance downstream from Venus. Measurements also show that the mass flux of the planetary ions increases at high altitudes above the planet when they are conducted across the narrow part of a corkscrew shape in the particle distribution along the wake.

Keywords: plasma vortex in the Venus wake, mass flux in the Venus wake, particle acceleration in the Venus wake, mass flux conservation, momentum exchange in the Venus wake

1. Introduction

Among the various features inferred from measurements conducted with the Pioneer-Venus (PVO) and the Venus Express (VEX) spacecraft in orbit around Venus there has been evidence of a vortex structure present along its wake [1–3]. As a whole its width in the near wake is comparable to the Venus radius and it is seen to exhibit a rotation in the counterclockwise direction when viewed from the wake [4]. In addition, the position of the vortex structure varies along the solar cycle and becomes more closely located to Venus under minimum solar cycle conditions [5, 6].

An implication of this latter behavior is that the gradual decrease of the vortex width with the downstream distance from Venus implies the acceleration of the planetary ions that stream in vortex structures that have smaller widths together with those that move along the wake direction. This effect is produced by the enhanced values of the kinetic energy of planetary ions that are forced to move in smaller-width vortex structures since it is required that the integrated energy flow value across the wake is preserved [7]. As a whole, the process is produced by the expansion of the solar wind plasma into the wake together with the planetary ions that are eroded from the ionosphere as they move over its magnetic polar regions [8].

In general terms, the momentum flux of the solar wind is gradually transferred to Venus upper ionosphere through viscous processes as it moves to the magnetic polar regions by the dayside [9]. As a result of the momentum transport through a velocity boundary layer adjacent to the ionopause a fraction of the available energy is dissipated and then is used to increase the local plasma temperature [10–12], Phillips and McComas [13]. Under such conditions, there is a forced entry of the plasma into the wake [8] which in turn gradually decreases with distance downstream from Venus thus decreasing the width of the ionospheric vortices. In this scheme vortex structures produced across the wake are subject to being restricted to move within an ever-decreasing region in the central wake thus leading to enhance the kinetic energy of the particles that stream in that region to maintain the integrated energy of vortex motion across the wake [7].

Much of that activity should ultimately result from wave-particle interactions between the local plasma populations and turbulent and fluctuating oscillations of the magnetic field convected by the solar wind and that have been measured in the Venus plasma environment [14, 15]. In that view, electrostatic and proton cyclotron waves [16–19] may be responsible for modifying the predicted large-scale trajectories of the planetary ions along the Venus plasma wake [20]. At the same time, those processes could influence the transport of solar wind momentum and its dissipation to account for the measured plasma heating in that region.

2. The VEX data

From measurements conducted with the ASPERA instrument in the VEX spacecraft, there are density and speed profiles of the solar wind and the planetary ions with altitude above the planet that indicate the way those variables vary along the dusk-dawn meridian plane and also in the noon-midnight plane. These are reproduced in **Figures 1** and **2** to show notable changes that occur at different altitudes. Even though the density values in the dawn-dusk plane (left panel in **Figure 1**) maintain decreasing values (down to ~20 cm^{-3}) at altitudes higher than the ionopause boundary labeled IP (by ~1000 km) there is a notable difference in the noon-midnight plane (left panel in **Figure 2**) where more intense density values are measured in the density profile above ~5000 km. This is particularly the case between 8000 and 10,000 km where much higher density values (reaching up to ~ 80 cm^{-3}) were recorded. At the same time, the speed profiles of the H+ and the planetary O+ ions first show a gradual similar variation with height above the ionopause in the right panel of both figures and that reaches a (~10 km/s) value by 3000–5000 km, thus implying a velocity shear above that boundary. At higher altitudes, the speed values in both figures begin an unexpected increase to higher (~ 40 km/s) values by ~10,000 km. This later variation is seen in the right panel of both figures and reveals the presence of different phenomena.

A possible interpretation of these changes can be advanced by considering that the Venus ionospheric plasma that is eroded by the solar wind from the nightside moves

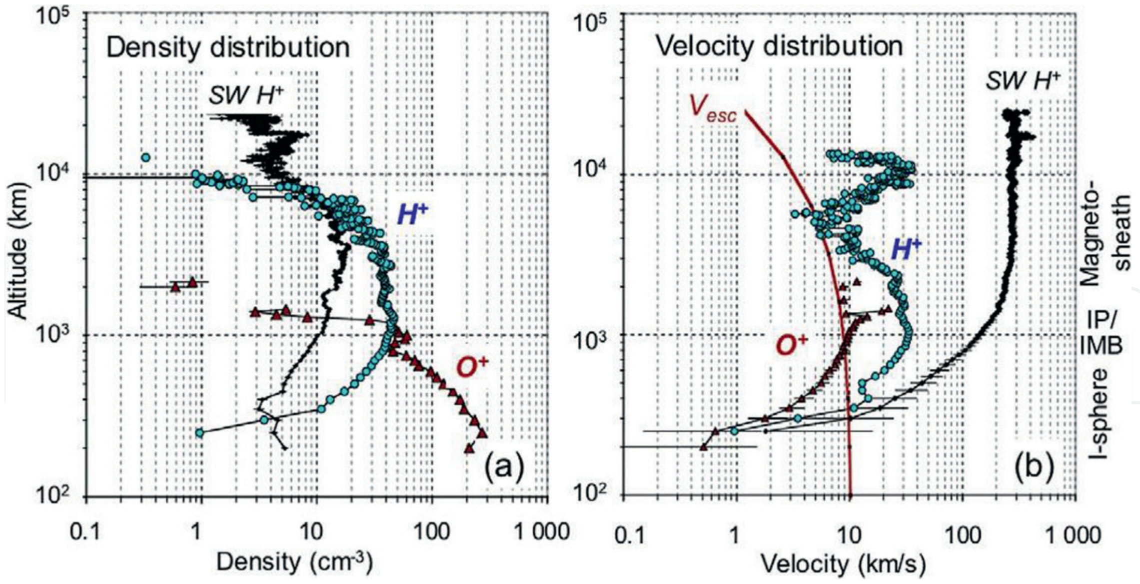

Figure 1.
Dawn–dusk Meridian. Number densities (a) and flow velocities (b) versus spacecraft altitude for solar wind H^+ *ions, and also for ionospheric* H^+ *and* O^+ *ions. Curve marked* V_{esc} *illustrates escape velocity versus altitude above Venus. The data points represent average values in 50 km altitude intervals, sampled within* $Y = \pm 0.5\ R_V$ *of the Dawn–dusk meridian. Error bars give the accuracy of individual measurement points. Regions and boundaries encountered are marked out on the right-hand side as: I-sphere (the core ionosphere), the Ionopause (IP/IMB), and the magneto-sheath (from [1]).*

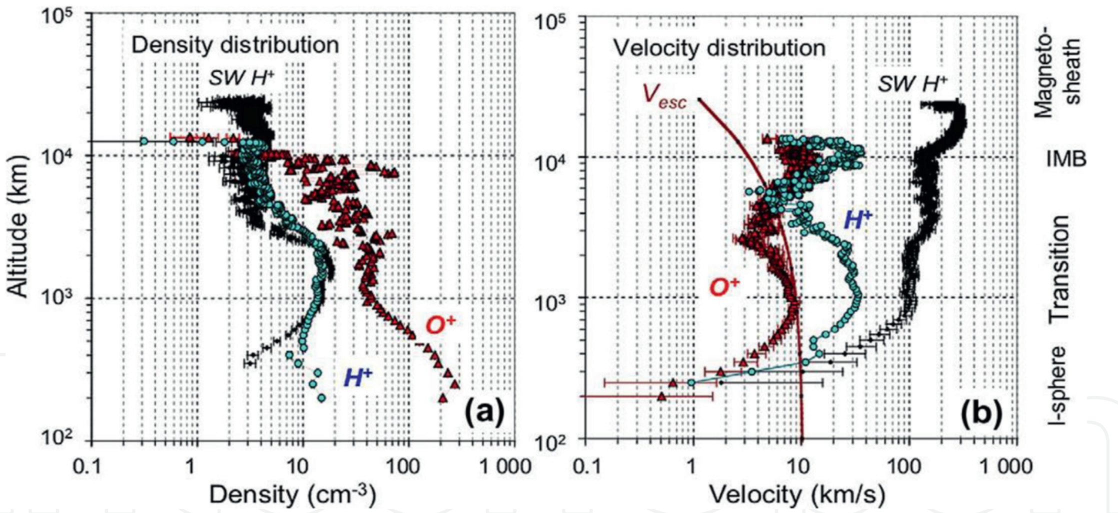

Figure 2.
Noon-midnight Meridian. Density and speed values of the solar wind and ionospheric ions as a function of spacecraft altitude as in **Figure 1** *measured in the noon-midnight meridian (from [1]).*

through a corkscrew geometry as illustrated in **Figure 3** and that corresponds to conditions like those in a similar fluid dynamic configuration. In the solar wind that streams past Venus and that is pressed into the wake behind the planet by thermal pressure forces [8, 21], there are plasma vortices whose width gradually decreases with distance along the wake [5]. In this scheme, particles that stream in the central part of the wake become accelerated by energy accumulated from vortices whose width gradually becomes reduced along that direction [7].

It is to be noted that the speed enhancement by ~10,000 km altitude in **Figures 1** and **2** is more intense in the noon-midnight meridian and that at even higher altitudes

Figure 3.
Corkscrew flow configuration. View of a corkscrew vortex flow in fluid dynamics. Its geometry is equivalent to that expected for a vortex flow in the Venus wake with its width and position varying during the solar cycle. The vortex flow becomes thinner along the radial direction in the wake axis when measured on a plane transverse to that of the figure further downstream from Venus [5].

there is also a sudden increase in the speed profile of the solar wind ions. In general terms, it can be stated that the conditions encountered by the noon-midnight meridian are more intense than those measured by the dawn-dusk meridian and it is possible that they become accumulated from the flow driven along the sides of the planet and they are led to the noon-midnight region of the wake.

3. The corkscrew flow

There are two main properties in the density and speed profiles in the panels of **Figures 1** and **2**. While the density values in the left panels of both figures follow a nearly smooth decrease with altitude above the ionopause at ~10^3 km (most notable in the dawn-dusk meridian figure), there are notable density variations above the 5000 km altitude in the noon-midnight distribution. At that altitude, there is also a sudden change in the speed profiles in the right panel of both figures with increasing values that reach ~40 km/s by 10,000 km. The latter change in the altitude gradient is peculiar since it points out an effect that occurs as a result of a different fluid dynamic configuration. The geometry presented in **Figure 3** can account for such change since it may derive from the spacecraft first moving away from the main ionospheric body and crossing later the narrow shape of a corkscrew flow configuration.

For simplicity let us assume that **Figure 3** is on the noon-midnight meridian and it represents the inner part of its wake which extends to the far-left side. At the same time, the VEX spacecraft follows a linear trajectory that leaves the ionosphere from the north-right side of the figure moves then nearly above its boundary and later enters and crosses the thinner part of the corkscrew flow which is formed by ionospheric plasma that has been eroded by the solar wind. Since we cannot make a quantitative estimate of the thickness of the later region nor the inclination of the spacecraft trajectory it is only possible to provide a schematic description of the proposed model.

4. Mass flux profiles

The deformed shape of the Venus nightside ionosphere implied from **Figure 3** should be acquired as a result of the erosion produced by the solar wind that streams over its polar regions leading to the corkscrew flow geometry. Even though there is no direct information available on the thickness and extent of the central wake it is of interest to consider that its crossing can be assumed to be a separate event in the ionospheric density and speed profiles measured by the VEX spacecraft as it moves through that region. Such an interpretation can be made from **Figures 1** and **2** since the enhanced density and speed values measured in the 8000–10,000 km altitude range are unrelated to those in the lower altitude nightside ionosphere. Instead, they occur under different conditions since at high altitudes they disrupt the gradual and persistent density decrease in their profiles and also include high values in the velocity profiles more clearly shown in the right panel of **Figure 2**.

As a result, the unexpected high speed and density values at high altitudes can be viewed as crossing the narrow part of the corkscrew flow that extends downstream in the central Venus wake. The purpose of that feature can be explored by examining changes that are implied on the density and speed of the flow when VEX is subject to stream within the thin part of the corkscrew flow. In fact, since the cross-section of the flow vortex decreases with distance along the wake the area integrated value of the mass flux should be confined within a region with smaller cross-section along the wake thus implying higher speed and density values that should be encountered.

The results provided by the data are presented in **Figure 4** where values of the mass flux derived from the profiles presented in **Figures 1** and **2** describe its distribution with altitude for the dawn-dusk meridian (left panel) and to the

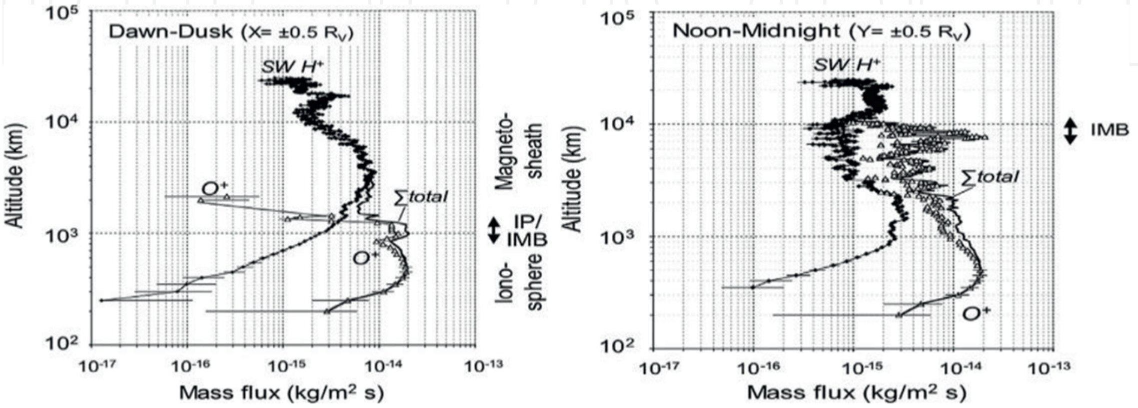

Figure 4.
Mass flux profiles. (left) average solar wind H^+, ionospheric O^+ (triangles), and total mass flux values on the dawn–dusk meridian (left) and to the noon-midnight meridian (right). The data are averaged in 50 km altitude intervals. The average position of the Ionopause and the induced magnetosphere boundary is marked by IP and IMB (from [1]).

noon-midnight meridian (right panel). The dominant feature is that superimposed on the values corresponding to an undisturbed density data distribution as that obtained in the dawn-dusk meridian there is a notable increase of the mass flux by the 8000–10,000 altitude range where in the right panel it reaches (~ 2.10^{-14} kg/m^2 s) values at high altitudes and that are twice as large as those in the left panel (~ 6.10^{-15} kg/m^2s).

5. Calculations

A detailed evaluation of the corresponding mass flux values expected from the density and speed altitude profiles reproduced in **Figure 4** can be obtained by estimating changes in the cross-section value of the flow as it moves along the wake. A useful view is available from the distribution of the length of the vortices measured across the Venus wake during the VEX years of operation between 2006 and 2013. This is shown in two separate circles in **Figure 5** representing conditions measured before the minimum solar cycle between 2006 and 2009 (left circle) and those that occurred during and after those conditions between 2010 and 2013 (right circle). It is notable that segments are placed at a position on the vertical axis that corresponds to the time duration of the vortex between the entry and the exit of the spacecraft and are located at a higher value

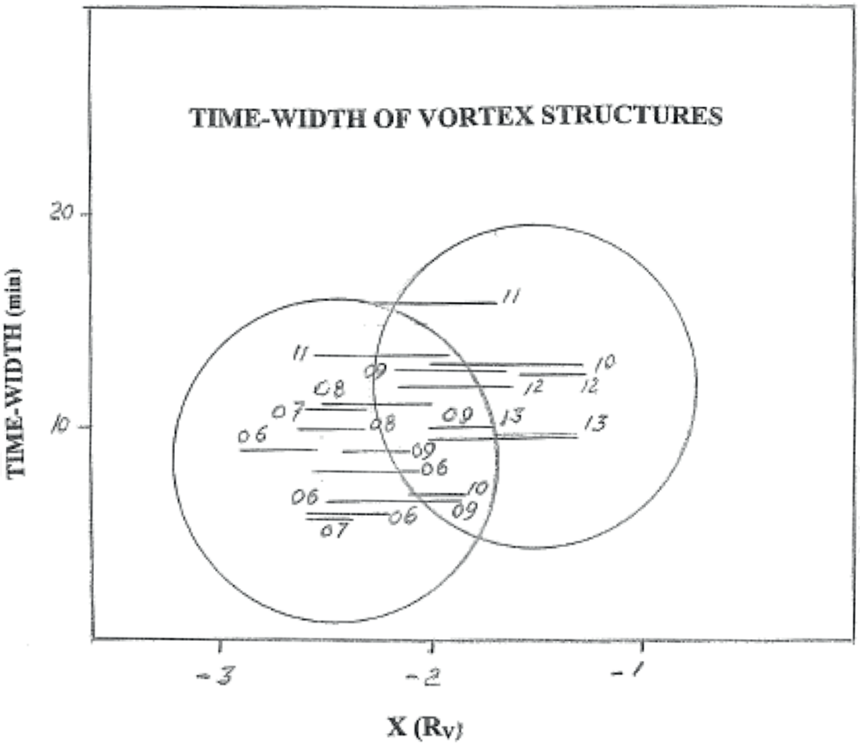

Figure 5.
Vortex position between 2006 and 2013. Corrected values of the time-width (in minutes) between the VEX inbound and outbound crossings of vortex structures as a function of the X-distance (R_V) downstream from Venus that were measured in 20 orbits. The numbers at the side of each segment represent 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 [5].

in the right circle than those in the left circle. At the same time, they extend as well through smaller X-distances (along the Sun-Venus line) in the right circle than those in the left circle (downstream along the tail). Such differences imply the varying position and width of the vortices with thicker values in the right circle that occur closer to Venus. This general characteristic of the vortices is the same as that described in **Figure 3** for a corkscrew flow where their width is wider on the right-hand side.

A case-by-case analysis of this peculiarity was conducted by calculating the average values of both variables (position and width) for each orbit during the VEX entry and exit across the vortices. The results are shown in the two circles of **Figure 5** with numbers indicating the two last digits of the year of each measurement. Most remarkable is that smaller ΔT width values were obtained for the 2006–2009 orbits (left circle) corresponding to vortices in the thin section of the corkscrew flow configuration in **Figure 3**. This agreement provides evidence for a similar description of plasma motion in the Venus wake. As a whole, it can be stated that there is a general downward displacement of the segment position between those in the 2010–2013 orbits (right circle) and those in the 2006–2009 orbits (left circle). In fact, the segments in the latter case occur by $X = -2.5\ R_V$ in the vicinity of ΔT ~7 min while those for the former orbits (right circle) are placed in the $X \sim -1.5\ R_V$ region with a larger (ΔT ~12 min) time span. As a result, the different displacement is equivalent to an overall loss of about 5 minutes between the width of the vortices in both sets of orbits. The implication here is that we can estimate the corresponding reduction of the vortex width across the wake between 2006 and 2013. Since the average VEX speed around Venus is nearly 7 km/s the spacecraft would reduce an equivalent ~2100 km travel distance difference in a 5 min travel time difference by moving through a vortex structure in the 2006 orbits with respect to those in the 2013 orbits. Thus, it is possible to argue that the vortex width decreases by nearly a ~ 2100 km distance across the wake between two different positions separated by a ~ 1 R_V distance at ~1.5 R_V and at ~2.5 R_V along the X axis between both orbit sets.

Since the mass flux of planetary ions that move across a vortex is given by: $F = nUA$ where $A \sim r^2$ is the area of the vortex structure with r being the transverse distance to the vortex it is possible to require a constant value for the area integrated mass flux across the entire vortex as it decreases its size along the wake. By having a smaller distance r across the vortex the total mass flux will be more concentrated in the inner wake and hence larger values of the flow speed U will result (provided the density remains unchanged). For example, if we assume that in the ΔT ~ 12 min time span for the orbit set where the vortex width is closer to Venus (right circle) so that $r_1 \sim 6000$ km (~1 R_V) at $X \sim -1.5\ R_V$, and that further downstream (by $X \sim -2.5\ R_V$) the width decreases to $r_2 \sim 3000$ km (so that ΔT ~ 6.5 min as it would be suitable for the left circle), we can infer that Δr ~ 3000 km is the transverse distance decrease (Δr ~ $R_V/2$) between both orbit sets. With such a smaller cross-section size the area integrated mass flux indicated above is now compressed and thus in order to maintain its same value the flow speed should be larger by a factor of 4.

Such a speed increase is to be compared with the increase of the speed of the planetary ions that is estimated from the speed profiles in the right panels of **Figures 1** and **2** where it rises from ~10 km/s by the ~5000 km altitude to ~40 km/s by ~8000 km. The agreement between both variations supports the view that the enhanced speed values in the right panel of **Figures 1** and **2** are related to the VEX motion through the narrow section of a corkscrew flow as shown in **Figure 3**.

6. Conclusions

The peak mass flux values in the noon-midnight meridian in **Figure 4** occur by the 8000–10,000 km altitude range where large speed values of the planetary ions in **Figures 1** and **2** are measured. That correlation may be related to the fact that as the VEX spacecraft moves into the narrow region of the corkscrew flow (which is depicted in **Figure 3**) it will reach a region where the main bulk of the ionospheric plasma eroded by the solar wind is driven as it moves along the wake. The geometry of the corkscrew flow thus provides a suitable manner in which the eroded plasma that moves into the wake can be accumulated as it moves in that direction. As a result, high mass flux values of that flow should be encountered in the narrow section of the corkscrew flow geometry thus providing an account for the large values measured at high altitudes (by ~8000 km) shown in the right-side panel of **Figure 4**.

The high mass flux values identified at upper altitudes in a region way above the nightside ionosphere represent an implication obtained by forcing that plasma to move into the wake by decreasing its cross-section as in a fluid dynamic analog similar to that of **Figure 3** [8]. As a result, the geometry of the resulting corkscrew flow will ensure that such plasma will be confined within an ever-decreasing cross-section that, in turn, will accelerate the planetary ions that stream through that region.

It should also be noted that notable changes in the density and speed of the planetary ions cannot be clearly identified on the dawn-dusk meridian but mostly in the noon-midnight meridian. The implication here is that the latter represents a phenomenon that is more appropriate by the midnight meridian where the solar wind-driven planetary ions are compressed with the narrower cross-section of the region where they flow.

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