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Vortex Structure in the Plasma Flow Channels of the Venus Wake

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Abstract

An overall description of the solar wind that streams into the Venus wake and the ionospheric plasma that is driven from that planet's magnetic polar region is examined from measurements conducted with the various spacecraft that have probed the Venus plasma environment (Mariner 5, Venera 9-10, Pioneer Venus Orbiter, Venus Express). It is shown that the plasma properties in the Venus wake describe conditions that are less suitable for steady gyrotropic trajectories of the planetary particles but require the assumption that they are also subject to a fluid dynamic description that introduces structures similar to those generated through kinetic forces. Most notable is that there is evidence of decelerated solar wind proton fluxes measured within plasma channels that are mostly populated by outflowing planetary ions and that the solar wind particles moving in the wake execute trajectories that resemble motion along a vortex shape with motion directed even back toward the planet in the Venus inner wake. The plasma flow channels are mostly restricted to the vicinity of the midnight plane and extend downstream from the magnetic polar region.

Keywords: solar wind in the Venus wake, vortex structures in the Venus wake, plasma channels in the Venus ionosphere, erosion of the Venus ionosphere, acceleration of planetary ions in the Venus wake

1. Introduction

From the early measurements of the Venus plasma environment conducted with the Mariner 5 and the Venera 9-10 spacecraft it was noted that the profiles of the dynamic properties of the

solar wind particles and those of its convected magnetic field exhibit sudden fluctuations that reveal sharp variations of the particles' physical properties and that result from instabilities unrelated to steady gyrotropic trajectories. At the same time, measurements show changes in the temperature and speed of the solar wind that indicate variations different from those produced by mass loading with planetary ions. A suitable example was provided from measurements conducted with the Venera spacecraft [1] and that are reproduced in **Figure 1**. The temperature and speed profiles obtained as the vehicle probed the Venus wake show a bow shock crossing by 00:00 MT, which is marked by a brief burst in the ion temperature profile and a minor decrease in the speed profile. Further within the boundary layer of the Venus wake there is a more noticeable transition marked with a sudden increase of the ion temperature by 01:50 MT, which is followed by a subsequent rise downstream with irregular sharp changes before reaching a third transition by 03:00 MT at the outer extent of the wake. Together with such variation there is also a sharp decrease of the solar wind speed at the same transition by 01:50 MT and that is followed with subsequent lower values further downstream leading to a velocity boundary layer. The presence of that sharp transition is significant in the sense that marks a feature unexpected from mass loading processes where gradual changes in the plasma properties should be produced when approaching the planet. Most notable, however, is the fact that enhanced ion temperatures are encountered at and downstream from that transition. The higher temperatures revealed from the data in **Figure 1** at and downstream from that transition are not expected either from mass loading processes but suggest that other physical processes become dominant. At the same time, the various temperature ion peaks shown in the temperature profile downstream from the plasma transition at 01:50 MT indicate variations more accordant with instabilities than with conditions expected along a steady gyrotropic trajectory. Additional information on enhanced plasma temperatures within the boundary layer of the Venus wake and that was measured with a different experiment in the Venera spacecraft [2] was obtained from data taken in different orbits. Their results show that enhanced temperatures are measured with decreasing distance from the wake in a pattern that could not be expected from mass loading processes.

Equally significant are the kinetic and thermal speed profiles together with the magnetic field profiles that were reported from the flyby of the Mariner 5 spacecraft along and near the Venus wake as it moved towards the dayside [3, 4]. Such profiles are reproduced in **Figure 2** to show that enhanced thermal speed values U_T and hence larger ion temperatures are measured across a boundary layer located between -100 min and -40 min before closest approach throughout the crossing of that spacecraft around Venus. Strong and frequent changes in the magnitude and direction of the magnetic field are also observed (top panel). The observed fluctuating orientation of the magnetic field leads as well to question the conventional description of the motion of the planetary ions in terms of steady gyrotropic trajectories since their acceleration through the convective electric field of the solar wind will be rapidly modified to produce, instead, stochastic trajectories. Similar fluctuating variations of the magnetic field direction were also recently reported from the Venus Express measurements conducted in a comparable region of the Venus wake [5].

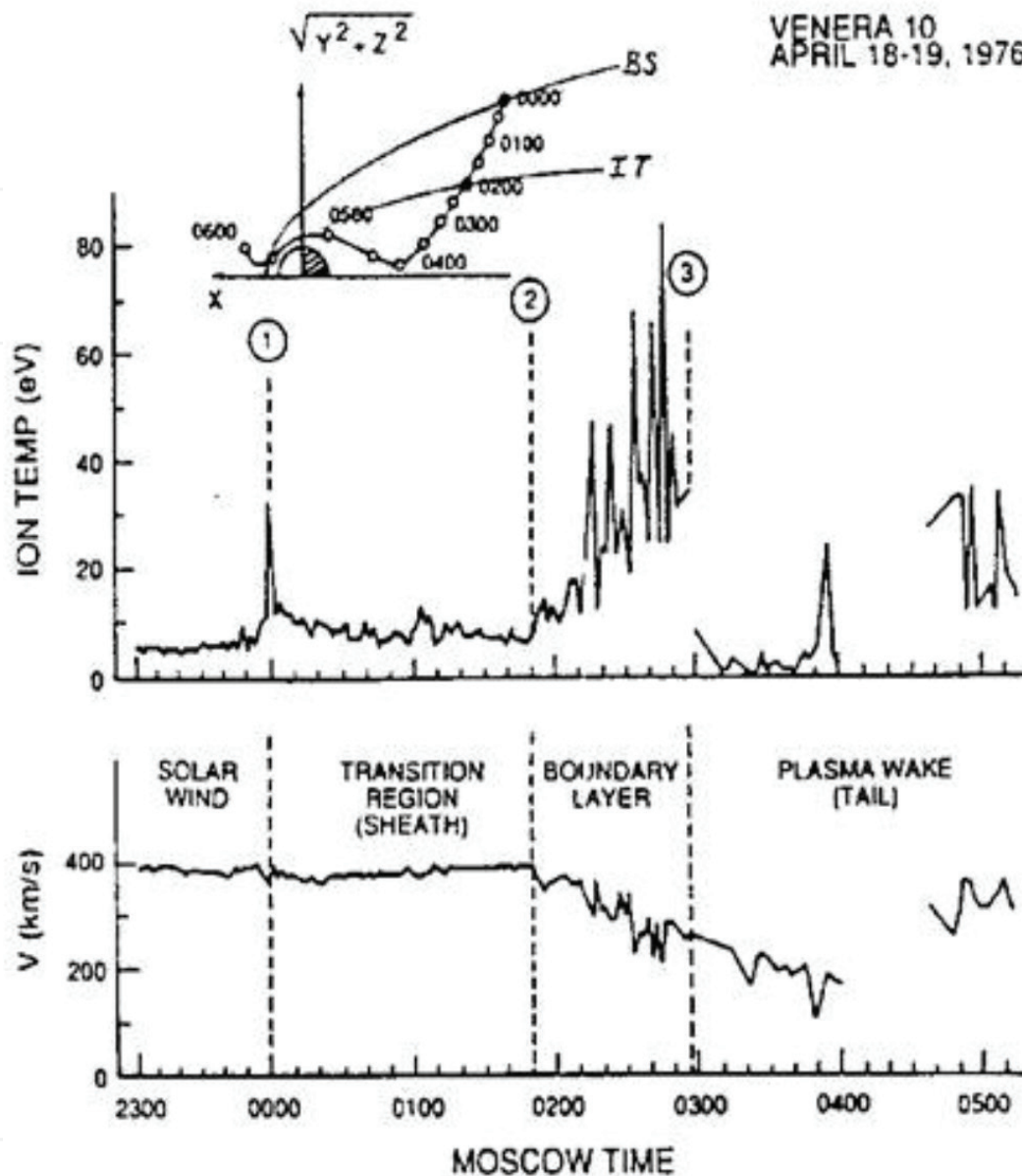


Figure 1. Ion speed and temperature measured along the orbit of Venera 10 on April 19, 1976. The orbit of Venera is shown at the top. The temperature burst was recorded during a flank crossing of the shock wave. The boundary layer is apparent by the increase in temperature and decrease in speed and is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

As a whole, the experimental evidence indicates that mass loading processes and gyrotropic trajectories derived from the application of a steady convective electric field of the solar wind to the planetary ions are not sufficient to account for the observed changes in the plasma properties in the Venus magnetosheath; namely, the presence of a sharp plasma transition embedded in that region together with enhanced ion temperatures seen at and downstream from that transition.

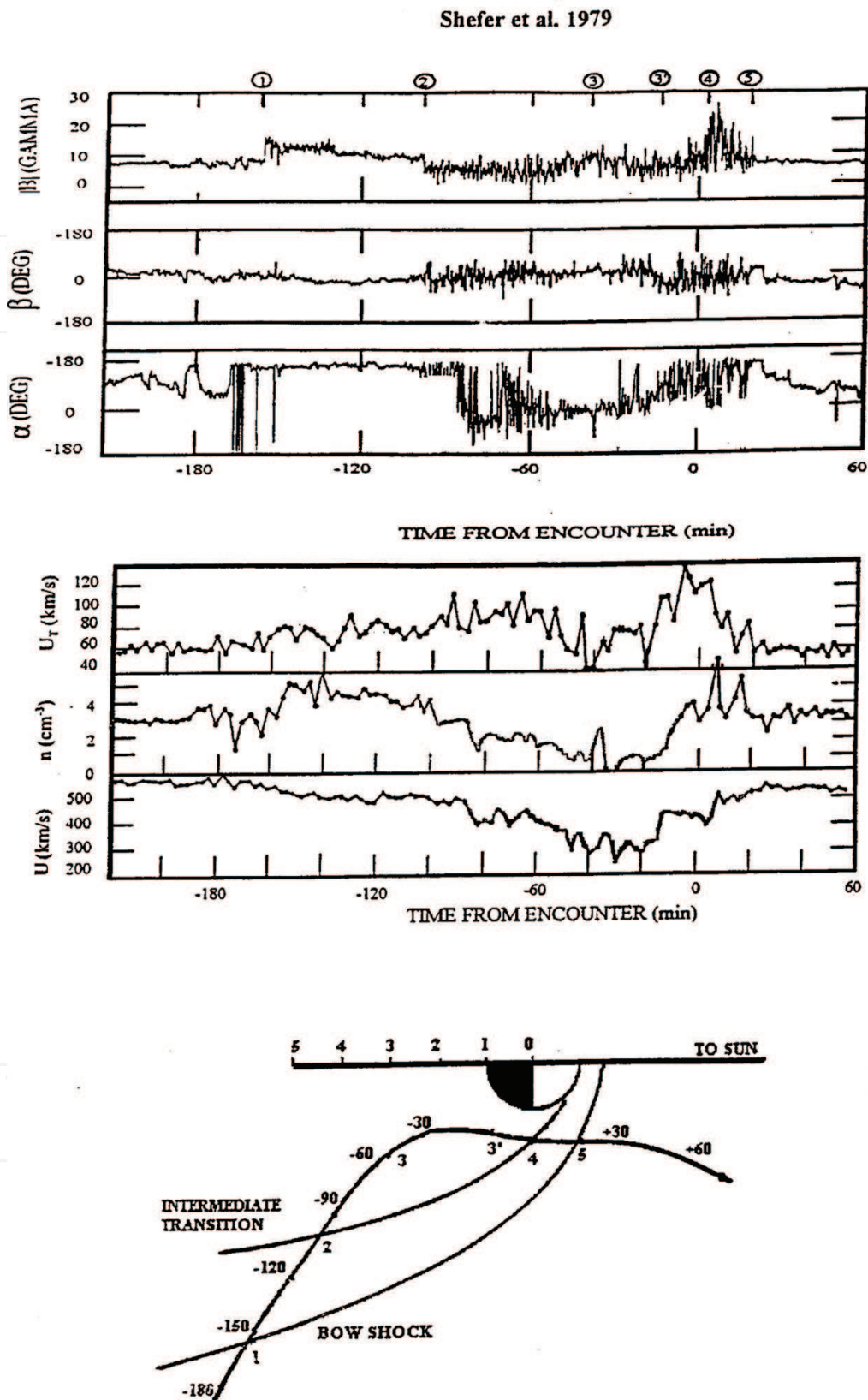


Figure 2. (Upper panel) Magnetic field signature (magnitude $|B|$ and direction angles), thermal speed U_r , density n , and kinetic speed U of the solar wind measured near Venus with the Mariner 5. (Lower panel) Flyby trajectory of the Mariner 5 near Venus in cylindrical coordinates [3].

2. Magnetic and kinetic forces

It is currently accepted that magnetic forces are sufficient to drive planetary ions away from the Venus wake. From measurements conducted with the Venus Express spacecraft it has been found, however, that conditions in the wake show the opposite since the motion of the plasma particles is super-Alfvénic [6]; namely, their kinetic energy density is larger than the local magnetic energy density. An example of this behavior is shown in **Figure 3** where the energy spectra of the solar wind and those of the O⁺ planetary ions measured in orbit 123 of the Venus Express are shown in the top panels. Their density and speed values (third, fourth, and fifth panels) together with the magnetic field intensity (bottom panel) lead to the kinetic energy density of the particle ions in the wake and the magnetic energy density profiles that are shown in **Figure 4**. Those profiles are important since they unveil that the kinetic forces in the wake are dominant in directing the motion of the planetary ions. As a result, the effects of the magnetic forces in the region where the planetary ions are measured are not dominant. In those regions the magnetic forces do not dictate the manner in which the planetary ions stream and are distributed through the wake. Much of this behavior is conducted through wave-particle interactions that enable the planetary ions to become accelerated and produce in turn the enhanced plasma temperatures that are measured at and downstream from the plasma transition in the magnetosheath as shown in **Figures 1 and 2**.

Different from the conditions encountered within the magnetic barrier in the vicinity of the dayside ionopause where the local solar wind flow is sub-Alfvénic and thus the magnetic forces become dominant in the acceleration of the planetary ions, the recovery of the solar wind flow as it streams around Venus towards the wake leads to a plasma regime in which kinetic forces are strengthened and dominate the motion of the planetary particles. Such peculiar evolution can be appreciated in the magnetic field profile in **Figure 3** where small (≤ 5 nT) magnetic field intensity values are measured (between 01:30 UT and 01:50 UT) by the (01:45 UT - 01:55 UT) time range where the kinetic energy density of the planetary ions is large as it is shown in **Figure 4**. As a result, the trajectory of those particles is guided in a manner different from that produced by magnetic forces and their motion should be more accordant with that expected from fluid dynamics. In particular, the solar wind flow that streams over the magnetic polar regions of the Venus ionosphere where smaller magnetic field intensity values are measured may directly carve the upper ionosphere and produce plasma flow channels that extend downstream into the wake. Evidence of those features is available from measurements in the Pioneer Venus Orbiter (PVO) and in the Venus Express spacecraft (VEX). In the PVO plasma data there are regions within the nightside ionosphere where the local electron density drops to small values in the form of ionospheric holes [7]. In such regions there are enhanced magnetic field intensity values but, in the wake, the measured magnetic field decreases and the speed and density of the solar wind lead the planetary ions to move under super-Alfvénic flux conditions.

The data in **Figure 3** provide a good example where the speed and the density of the H⁺ and the O⁺ ions together with the low magnetic field intensity values measured in the near wake in the 01:30–01:50 UT time interval lead to a super-Alfvénic ion flow as shown in **Figure 4**.

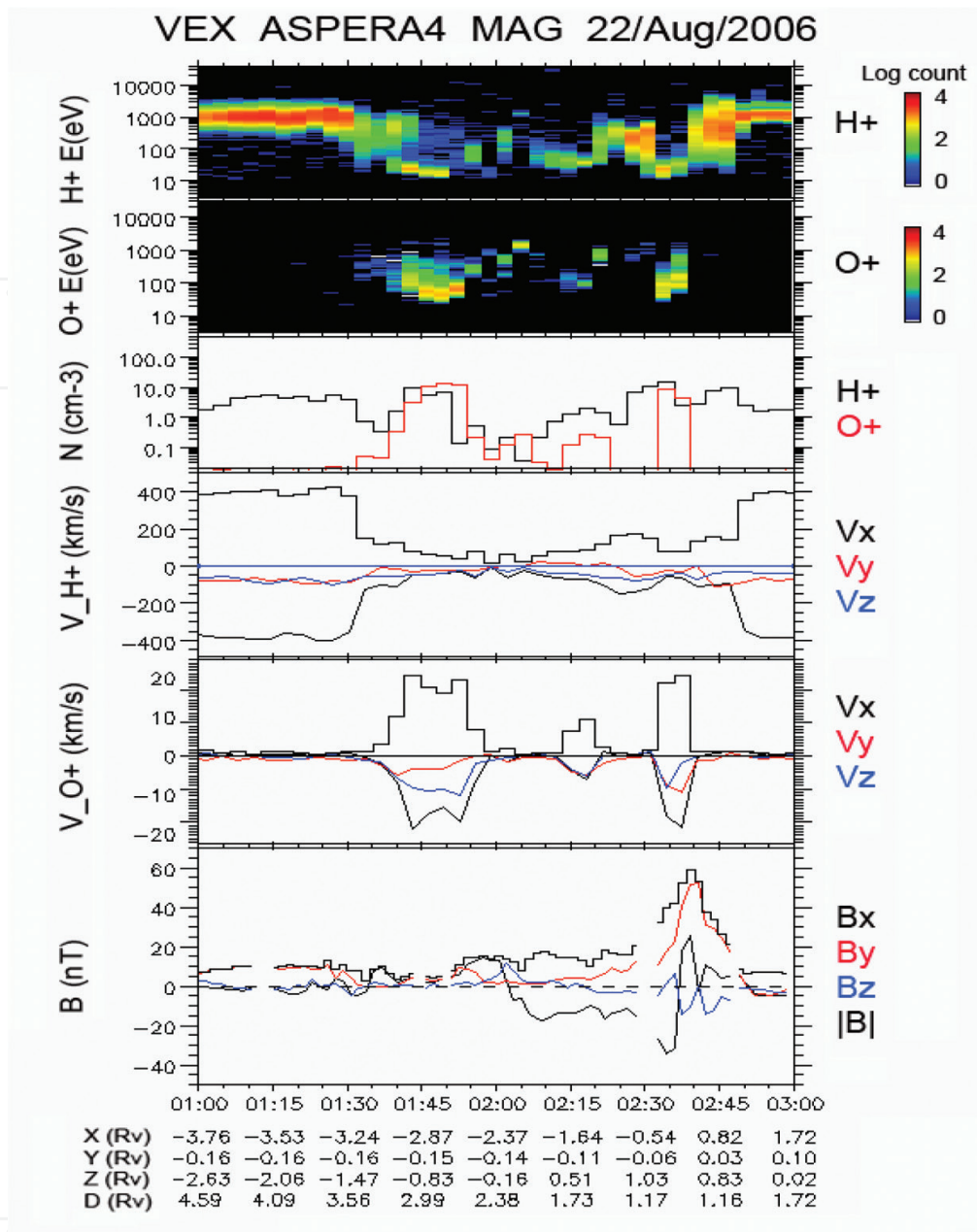


Figure 3. Energy spectra of H⁺ and O⁺ ion fluxes (first and second panels) measured in the Venus wake during orbit 123 of the Venus Express spacecraft [6]. Density and speed values of those ion components are shown the third, fourth, and fifth panels. The magnitude and the components of the magnetic field vector are shown in the bottom panel.

An important property of the plasma flow channels that have been further identified in the Venus wake from the Venus Express measurements is that they are observed mostly in the vicinity of the midnight plane as they evolve from the magnetic polar region. The plasma data reproduced in **Figure 3** is useful to stress this property since the planetary ions detected as the spacecraft approached the planet from the wake (in the 02:30–02:40 UT time interval) are located at small $Y \sim 0.05$ coordinate values and thus in the vicinity of the midnight plane. In such time interval there is evidence of O⁺ ion fluxes together with decelerated solar wind protons (with spectra in the 10–100 eV energy range) showing that a large fraction of their

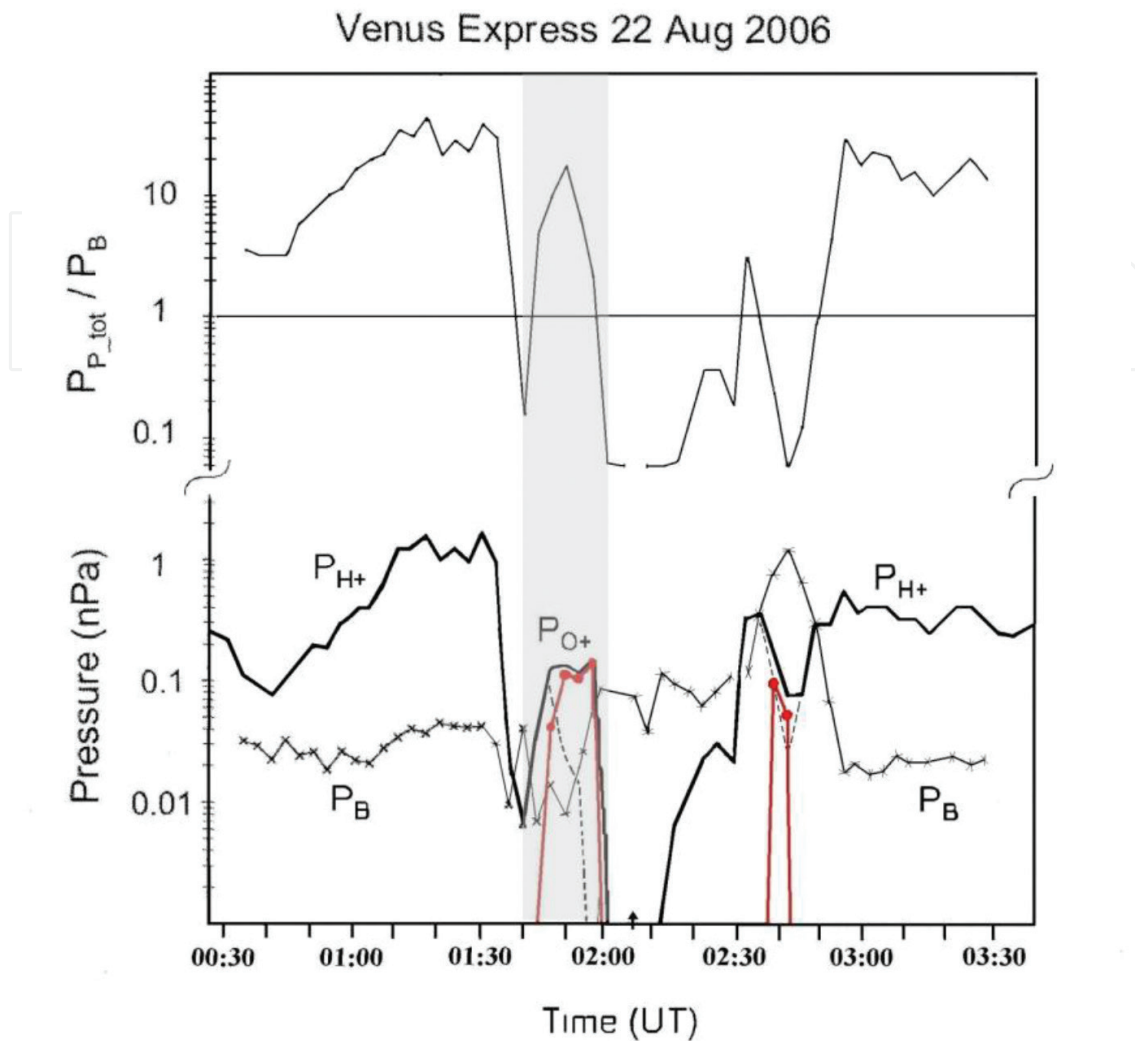


Figure 4. (Lower panel) Kinetic pressure of the O⁺ ions (profiles marked in red) and the H⁺ ions, together with the profile of the magnetic field pressure measured through the Venus wake during orbit 123 of the Venus Express spacecraft [6]. (Upper panel) Ratio values of the total kinetic pressure of the plasma to the magnetic field pressure derived from the profiles shown in the lower panel. The outbound bow shock crossing occurs at ~02:53 UT and the peak value of that ratio detected at ~01:50 UT is provided by the kinetic pressure of the O⁺ ions.

momentum has been transferred to the planetary ions. In fact, from the speed and the density profiles obtained from the spectra of both ion components it is found that at the two consecutive measurements when VEX moved across the plasma channel (at ~ 02:34 UT and at ~ 02:38 UT) the local deficiency in the value of the momentum flux of the solar wind protons is nearly equal to the momentum flux of the O⁺ ion fluxes obtained in each measurement. The outcome of this result strongly supports the view that an efficient erosion process occurs between the solar wind protons and the planetary ions.

As it is indicated schematically in **Figure 5**, the observation of outflowing planetary ion fluxes within the wake is mostly restricted within the plasma channels and in the vicinity of the magnetic polar region near the midnight plane, but the erosion process should not be dominant by the flanks of the wake. This constraint provides an explanation for the absence

of $\sim\text{keV}$ solar wind proton fluxes in an ionospheric hole reported from VEX measurements at large angles from the midnight plane and in the vicinity of the equator [8] (see their Section 4.2). In fact, along the VEX trajectory in the 19 May 2010 orbit reported in **Figure 2** of [8] (between 05:21:37 and 05:30:15 UT) the spacecraft is located by $0.73 < Y < 0.87 R_V$ and between $Z = -0.12$ and $Z = 0.21 R_V$ and thus far from the midnight plane and close to the equatorial plane, and also far from a magnetic polar region since $1.45 < X < 1.72 R_V$. Consequently, the statement indicated in [8] in the sense that H^+ ions fluxes are not measured at the time when the Venus Express is within an ionospheric hole is incorrect. In fact, the spectra of the decelerated solar wind protons shown in **Figure 3** were obtained as the spacecraft traveled through a plasma channel in the close vicinity of a magnetic polar region near the midnight plane.

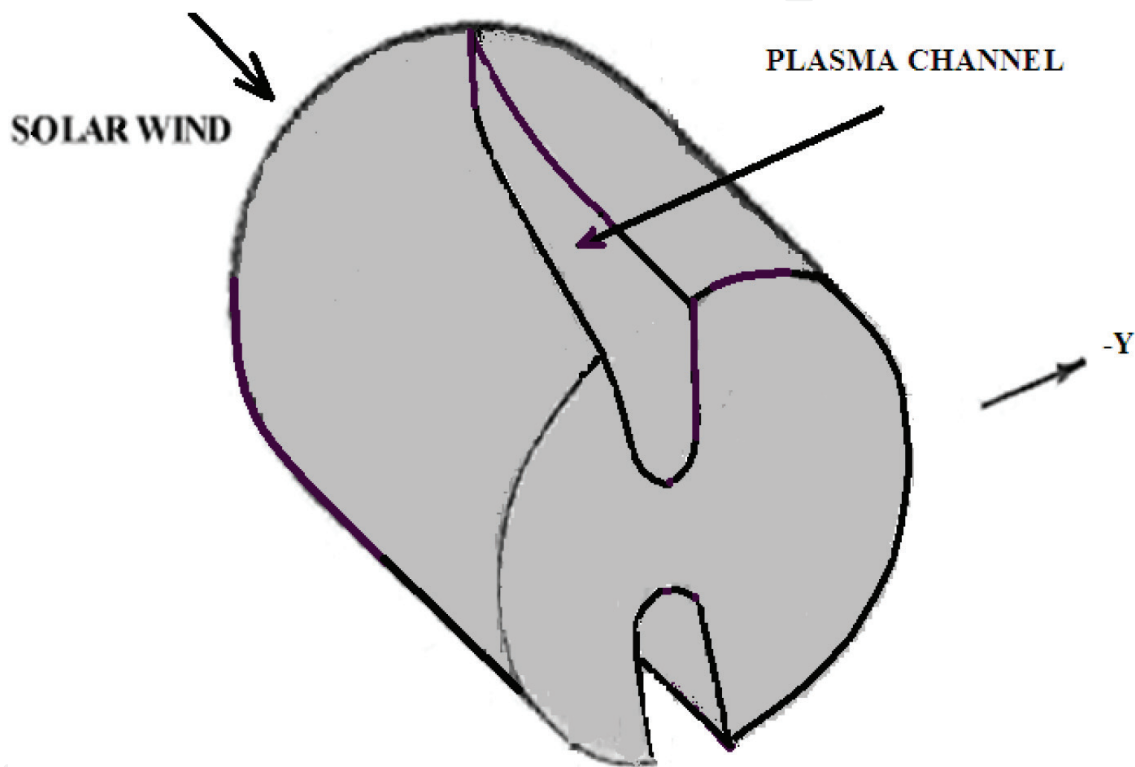


Figure 5. Schematic view of plasma flow channels that form by the magnetic polar regions of the Venus ionosphere and that are then deviated toward the dawn side ($+Y$) direction, together with the region above them where planetary ions are eroded by the solar wind [9].

3. Vortex structure in the Venus wake

From the early analysis of the motion of the solar wind in the Venus wake with the PVO plasma data it was noted that in specific orbits the solar wind fluxes can be directed back into the planet from the wake [10, 11]. The velocity distribution of those particles in the inner wake is reproduced in **Figure 6** (upper panel) in cylindrical coordinates to indicate that the solar wind ions are forced to execute a nearly $\sim 180^\circ$ turn in their trajectory direction following the form of a fluid dynamic vortex structure. This issue was more extensively examined using the Venus Express measurements by collecting the direction of motion of the solar wind

particles observed in many orbits across the Venus wake [12]. A summary of those results is reproduced in **Figure 6** (lower panel) where the solar wind velocity vectors are also presented in cylindrical coordinates. The figure applies to the Venus inner wake where the velocity vectors clearly show a gradual deviation away from the incident solar wind direction until they become oriented back into the planet (R. Lundin, personal communication 2016). An alternative interpretation of the sunward directed motion of the solar wind particles in that region in terms of magnetic forces is not consistent with the measured super-Alfvenic flow conditions in which the kinetic energy density of the plasma in the wake is larger than the local magnetic field energy density [6].

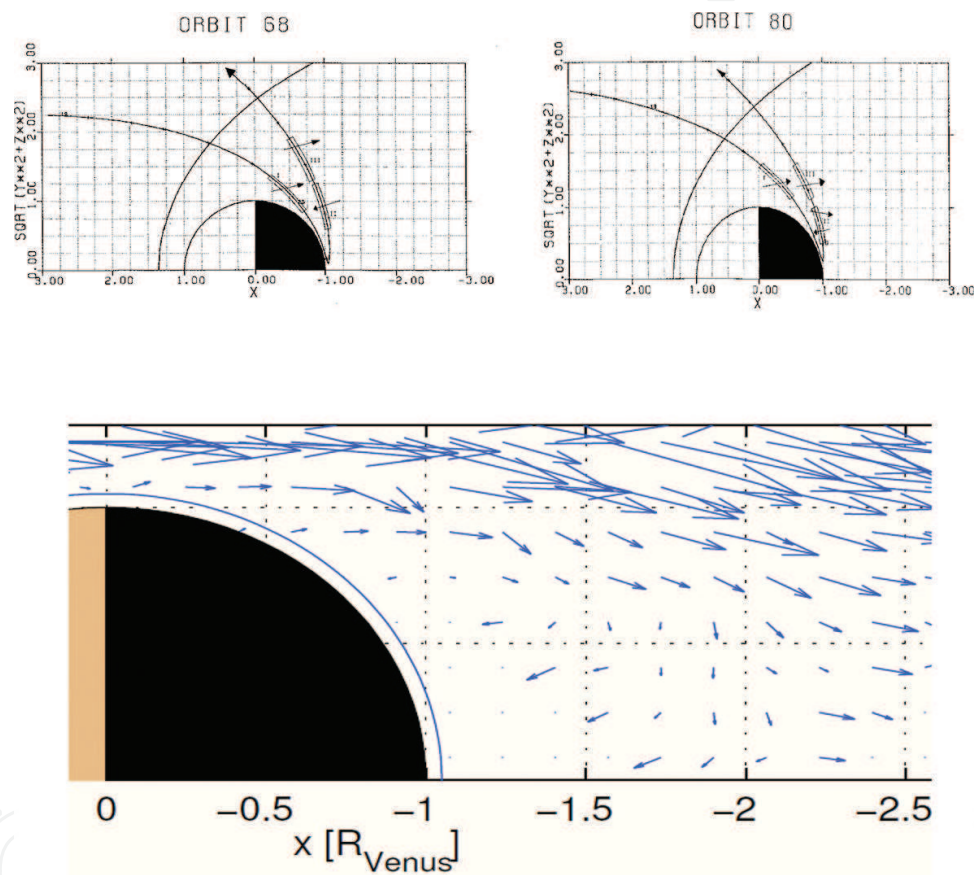


Figure 6. (Upper panel) Velocity vectors of the solar wind ion fluxes measured during different energy cycles marked with rectangles in two PVO orbits projected on one quadrant across the Venus wake in cylindrical coordinates [10, 11]. (Lower panel) Average updated direction of solar wind ion fluxes collected from many VEX orbits projected on cylindrical coordinates (Lundin, R., personal communication, 2016).

A useful configuration of the velocity vectors in a vortex flow structure is also available from their projection on the YZ plane (perpendicular to the solar wind direction) which is reproduced in **Figure 7** [13]. While the region of observation mostly extends over the southern hemisphere in the near wake ($X < -1.5 R_V$) there is a clear rotation of the velocity vectors centered around a position located north from the ecliptic plane (at $Z = 0$) and east from the midnight plane (at $Y = 0$). Also peculiar is that the magnitude of the velocity

vectors directed toward positive Y values by the upper part of the diagram is larger than that of the velocity vectors directed toward negative Y values in the lower part of the diagram. This difference may imply that the velocity vectors of the solar wind particles have a larger component along the Sun-Venus direction (away from the figure) in the Southern Hemisphere thus producing a more extended vortex structure along the X -axis in that hemisphere. Further studies are required to examine the rotation period of the solar wind as it moves in the vortex structure together with its evolution and extent in the YZ plane. Much of what has been addressed here stresses the value of fluid dynamic concepts to the interpretation of the plasma data and that has been obtained in measurements around Venus and in its wake [14]. However, the physical principles that substantiate the fluid response of the solar wind as it streams around the Venus ionosphere and that should be related to wave-particle interactions among the particle populations have not yet been properly identified.

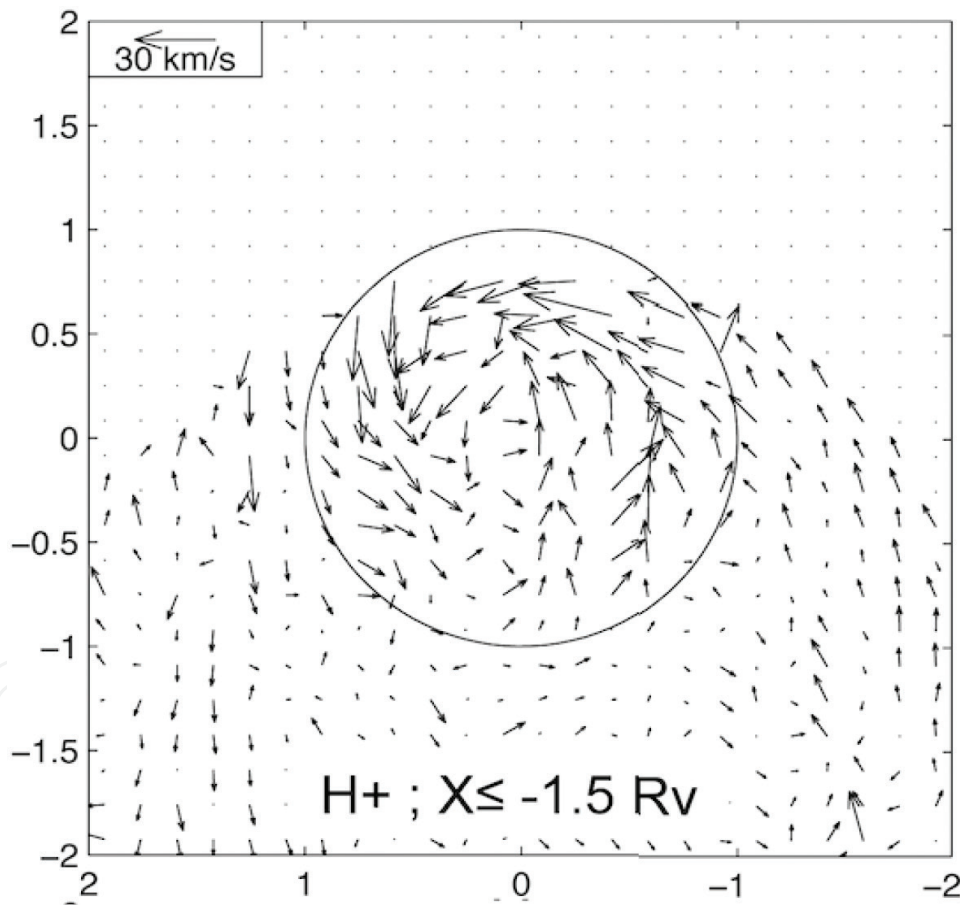


Figure 7. Velocity vectors of the solar wind H⁺ ions (1-300 eV) measured with the Venus Express spacecraft in the Venus near wake when projected on the YZ plane transverse to the solar wind direction (Y and Z are the horizontal and the vertical axis). Data are averaged in 1000×1000 km columns at $X < -1.5 R_v$ [13].

In summary, from the analysis of the plasma and magnetic field measurements conducted with various spacecraft across the Venus wake it has been learned that planetary ions that stream in the vicinity of the midnight plane are mostly seen to be accelerated by the kinetic

energy of the solar wind rather than by the local magnetic field forces. Plasma channels with decelerated solar wind ion fluxes are mostly detected near the midnight plane, and contrary to the claims made in Ref. [8], there should not be a conflict when they are not encountered by the equatorial flanks of the wake and far from the midnight plane [15]. Under such conditions the decelerated solar wind ions follow trajectories that are consistent with fluid dynamic motion and that lead them to produce vortex structures in the Venus wake.

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