Measurement of plasma channels in the Venus wake

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ABSTRACT

Plasma channels have been suggested to account for the observation of ionospheric holes in the Venus nightside ionosphere. They are produced by the erosion of the solar wind on the magnetic polar regions of the Venus ionosphere, and are related to a sharp plasma transition that extends along the flanks of the wake and that is located downstream from the bow shock. The sharp plasma (intermediate) transition is a feature that has been detected with instruments onboard all the main spacecraft that have probed the Venus wake. From the early flyby transit of the Mariner 5 spacecraft to the later orbit crossings of the Venera 10, the Pioneer Venus and more recently the Venus Express there has been accumulated evidence of the presence of that transition by the flanks of the Venus wake. We report here measurements made with the ASPERA-4 instrument of the Venus Express that were conducted in orbit crossings by the midnight plane over a 4 year period (between 2006 and 2009), and that show different positions of the intermediate transition in the Venus wake at locations closer to the sun-Venus axis near solar minimum conditions by 2009. Measurements conducted in this latter time period also indicate that the intermediate transition by the midnight plane derives from the plasma channels and that is replaced by a broad velocity layer in orbits that probed farther away from that plane. It is argued that changes in the position of the intermediate transition with respect to the plasma channels are related to processes produced by the transport of solar wind momentum to the Venus polar ionosphere. The energy spectra of planetary ions measured in VEX orbits that probed by the midnight plane show momentum transport from the solar wind protons. This result is contrary to the conclusions reported by Collinson et al. (2014) in the sense that there is ‘no difference in the peak energy of the ionospheric outflow’ when measured inside and outside an ionospheric hole.

1. Introduction

The early plasma and magnetic field measurements conducted during the transit of the Mariner 5 and the Venera spacecraft by the flanks of the Venus magnetosheath (Bridge et al., 1967; Shefer et al., 1979; Vaisberg et al., 1976; Romanov et al., 1979) showed that in addition to a bow shock crossing there is evidence of a different plasma transition located downstream from that feature (Spreiter et al., 1970). That transition marks changes in the properties of the solar wind (decreased values of its speed, density, and magnetic field intensity with also enhanced temperature values) that apply throughout the inner part of the flanks of the magnetosheath. Such changes are different from those expected at the boundary of an induced magnetosphere where the magnetic field intensity increases as a result of the pileup of magnetic field fluxes (Bertucci et al., 2011). Further and more repeated measurements of the latter transition (labeled intermediate transition IT) were reported from the Pioneer Venus observations with indications that there is a drastic change in the shape of the distribution function of the measured ion population at the time where it is detected (Pérez-de-Tejada et al., 1995). At the same time it was found that the intermediate transition is mostly detected in the vicinity of the magnetic polar regions that occur where the piled up interplanetary magnetic field fluxes slip over the planet to enter the wake. In that respect the position of the IT is organized with respect to the magnetic field direction in the VSE coordinate frame and is seen to mostly occur in the vicinity of the magnetic polar regions (Pérez-de-Tejada, 1997, Fig. 2). Arguments in terms of mass loading processes where a gradual change in the ion composition occurs with decreasing distance from the planet are not applicable since enhanced plasma temperatures are also measured across that boundary (Romanov et al., 1979; Verigin at al., 1978).

Issues related to the location and distribution of the IT in the wake have not been addressed nor its position with respect to that of plasma...
holes detected in the Venus nightside ionosphere (Brace et al., 1982). Extensive studies of the latter features have been conducted in terms of processes associated to magnetic field aligned electric fields that eject plasma (Grebowsky and Curtis, 1981), gravitational acceleration towards the planet (Grebowsky et al., 1981), deformation of the nightside ionopause at low magnetic latitudes by magnetosheath pressure (Marubashi et al., 1985), together with hole production through MHD modeling (Tanaka and Murawski, 1997). More recently Mahajan and Oyama (2001) and Hoegy and Grebowsky (2010) have also examined the observation of ionospheric holes as a function of the solar wind dynamic pressure. In an alternative view ionospheric holes have also been interpreted as resulting from the erosion that the solar wind produces on the magnetic polar regions of the Venus ionosphere with plasma channels that are directed downstream from the planet (Pérez-de-Tejada et al., 2004). It has been suggested that the intermediate transition represents the outer boundary of the ionospheric holes/plasma channels thus implying that the manner in which the IT is distributed through the wake is also applicable to the ionospheric holes.

Correlated to this issue is the distribution of the velocity vectors of the H+ and O+ ions measured in the Venus near wake and that show a pervasive deflection towards the + Y direction. A complete account of that orientation was reported by Lundin et al. (2011) from measurements conducted in many VEX orbits and that is reproduced in Fig. 1. The velocity vectors show a common tendency to be deflected towards the + Y direction over the nightside ionosphere and in the near wake region. Such behavior is compatible with the east-west displacement of the Venus upper ionosphere that was reported by Miller and Whitten (1991) from measurements conducted with the ORPA instrument of the PVO together with a similar zonal deflection in the position of the ionospheric holes reported by Brace et al. (1982) from the OETP PVO data.

A corresponding analysis in the position of the IT in the wake will be presented below to show that such boundary also exhibits a similar zonal displacement as it drifts towards the Y+ direction. A study will be conducted on a set of selected VEX orbits that probed by the midnight plane of the Venus wake and that convey consistent speed profiles across plasma channels in their interpretation of ionospheric holes as resulting from erosion processes produced by the solar wind on the Venus ionosphere. A similar constraint is imposed by the observation that the changes in the shocked solar wind that are encountered at the intermediate transition do not necessarily imply conditions that are only locally applicable as it would be the case as a result of effects produced by a sheet current. Instead, they extend throughout the inner part of the flank magnetosheath thus suggesting conditions that apply to the bulk shocked solar wind, and that may be related to a vortex structure as that inferred from the ASPERA measurements in the Venus wake (Lundin et al., 2013).

### Table 1

<table>
<thead>
<tr>
<th>Date and time (in UT)</th>
<th>Intermediate Transition (IT)</th>
<th>Bow Shock (BS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23-08-06</td>
<td>17-11-07</td>
<td>27-06-08</td>
</tr>
<tr>
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<td>−3.00</td>
</tr>
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<td>0.10</td>
</tr>
<tr>
<td>Z</td>
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<td>−1.35</td>
</tr>
<tr>
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<td>00:10</td>
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</tr>
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<td>Y</td>
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<td>0.19</td>
</tr>
<tr>
<td>Z</td>
<td>−4.48</td>
<td>−4.35</td>
</tr>
</tbody>
</table>

1.1. ASPERA-4 plasma data in selected orbits between 2006 and 2009

From the Venus Express orbits that probed the Venus wake since 2006 a selection was made to consider only those in which the spacecraft was traced by the near vicinity of the midnight plane. Since the orbital plane of the spacecraft around Venus remains constant with time as the planet moves around the sun there is a gradual daily shift in the orientation of that plane with respect to the midnight plane; namely, the orbital plane of the spacecraft sweeps a different section of the wake in every orbit. For this reason it is necessary to select the appropriate orbit in each range of transit across the wake in which the spacecraft moves by the midnight plane. That selection was conducted in the 4 orbits listed in Table 1 and that probed by that plane in the Venus wake. As it will be discussed below the orbits included in Table 1 are peculiar in that they contain clear evidence of a transition with a sudden drop in the speed value of the solar wind protons. Such condition only occurs in these orbits and is replaced by a gradual change of that variable that is observed in the neighboring orbits that are traced farther away from the midnight plane. A useful example of the orbits indicated in Table 1 is that corresponding to June 27–2008 and that is reproduced in Fig. 2. The top panels show the energy spectra of the solar wind protons and the planetary ions measured as the spacecraft moved across the wake from the southern hemisphere toward periapsis near the north polar region. The third and fourth panels provide the speed panels of both particle populations with a noticeable and sharp drop of the proton speed at 03:23 UT at the same time when there is also a significant decrease of the H+ density values shown in the fifth

**Fig. 1.** Distribution of velocity vectors of the solar wind H+ (left panel) and the planetary O+ ions (right panel) in unit vector values collected from data obtained in many orbits of the Venus Express spacecraft across the Venus wake projected on the XY-plane (Lundin et al., 2011).
That change in the solar wind proton speed is similar to those reported earlier from the plasma data of other orbits of the Venus Express (Pérez-de-Tejada et al., 2011) and is also compatible with the earlier measurements conducted with the Mariner 5 and the Venera spacecraft (Shefer et al., 1979; Romanov et al., 1979). As a whole such measurements are consistent with the presence of that transition as a permanent feature along the flanks of the Venus magnetosheath, and that is also available in the plasma data of the other selected orbits in Table 1.

A further peculiarity in the energy spectra of the proton component in Fig. 2 is a brief dip in the speed profile at 02:00 UT in the third panel. That variation is accompanied by a slight increase in the density of the proton population shown in the sixth panel and also a more evident increase in the value of the magnetic field intensity profile presented in the seventh panel. These changes suggest the inbound crossing of the spacecraft across the bow shock by the flanks of the wake, with larger density and magnetic field intensity values measured within the magnetosheath. Similar variations across the inbound crossing of a bow shock are also present in the speed, density and magnetic field profiles derived from the energy spectra in the data of the other selected orbits in Table 1. Important information is also available in that table regarding the X, Y, and Z coordinate values of the Venus Express at the time when it encountered the intermediate transition and the bow shock. Most notable is that the intermediate transition occurs at small Y values indicating that the spacecraft is located close to the midnight plane. Nearly comparable values are also applicable to the bow shock crossings thus supporting the view that the spacecraft moved close to the midnight plane throughout most of those orbits. Larger negative or positive Y values are obtained along the trajectories of orbits that occurred before or after those included in Table 1.

A suitable manner to examine the relative position of the intermediate transition and the bow shock crossings in space is to plot their position in the XZ plane as shown in Fig. 3. As a whole there is a general tendency for both data sets to remain distant from each other and also there is a gradual pattern for the X and Z values to become smaller with time between 2006 and 2009. The intermediate transition and the bow shock crossings in the wake are located closer to Venus by 2009 at the time when a minimum in the solar cycle was approaching as smaller values of the solar wind momentum were measured. Such change in the position of the bow shock is consistent with that reported by
Table 2
Date and universal time (UT) together with the X, Y, and Z coordinates (in Venus radii) of the Venus Express at 12 crossings of the intermediate transition in different orbits during Sept 2009.

<table>
<thead>
<tr>
<th>UT</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<th>n_{sw}</th>
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</tr>
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<td>8</td>
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<tr>
<td>Sept 16–2009 01:52</td>
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<td>−0.62</td>
<td>230</td>
<td>4</td>
</tr>
<tr>
<td>Sept 17–2009 01:55</td>
<td>−2.20</td>
<td>−0.17</td>
<td>−0.52</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
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<td>−1.43</td>
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<td>9</td>
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<tr>
<td>Sept 19–2009 01:47</td>
<td>−2.57</td>
<td>−0.04</td>
<td>−1.19</td>
<td>260</td>
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<td>0.04</td>
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<td>200</td>
<td>10</td>
</tr>
<tr>
<td>Sept 21–2009 01:56</td>
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<td>0.14</td>
<td>−1.90</td>
<td>200</td>
<td>11</td>
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<tr>
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<td>−2.52</td>
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<td>Sept 23–2009 01:57</td>
<td>−2.53</td>
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<td>−1.12</td>
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<td>4</td>
</tr>
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<td>Sept 25–2009 02:04</td>
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<td>0.38</td>
<td>−0.97</td>
<td>250</td>
<td>2</td>
</tr>
<tr>
<td>Sept 26–2009 01:58</td>
<td>−2.58</td>
<td>0.48</td>
<td>−1.31</td>
<td>220</td>
<td>5</td>
</tr>
</tbody>
</table>

Slavin et al. (1980) between solar minimum and solar maximum in cycles 20 and 21 (Venera and Mariner 5 and PVO measurements). However, the 4 bow shock data points in Fig. 3 also fit expected values within the bow shock pattern that has been derived from many PVO and VEX observations. More extended data analysis will be required to further examine the change of the bow shock position during the current solar cycle (McComas et al., 2008). A similar issue should also be raised regarding the shape of the intermediate transition and its change during the current solar cycle (Martinez et al., 2009).

1.2. The intermediate transition across the plasma wake

The position of the intermediate transition IT closer to Venus in the September 19–2009 orbit is suitable to examine the plasma conditions across that transition. In order to explore the width of the region where that feature is observed a study of the speed profiles of the solar wind was conducted using 12 orbits that probed the wake before and after the September 19–2009 orbit. That set of orbits is listed in Table 2 with indications of the time and the X, Y, and Z coordinates of the spacecraft when a sharp drop of the solar wind speed values was measured. The IT is distributed through the magnetosheath as a disturbance that is initiated within the plasma channels that are produced at the magnetic polar regions. The collection of orbits in Table 2 has been divided into 2 parts with noticeable differences in the coordinate values of the IT. In the first 4 orbits the X and Z coordinates maintain nearly uniform values that are smaller than those of the other 8 orbits. At the same time the negative value of the Y coordinate of the speed drop in the first 4 orbits indicates that it occurs in the dusk side of the planet and that it gradually shifts to positive values in the other 8 orbits. The larger negative values (in magnitude) of the X and Z coordinates that apply to the set of 8 orbits with respect to the first 4 orbits imply that the drop in the speed profile occurs in different regions of space and that in each case maintain nearly the same values. Such difference does not seem to be produced by changes in the solar wind dynamic pressure since comparable values of that parameter were observed in both sets of orbits. Also, there are no important changes in the direction of the IMF in the 12 orbits thus implying that no changes in its orientation could have modified the position of the magnetic polar regions on the terminator plane.

A well defined correlation in the position of the intermediate transition in all 12 orbits is depicted in Fig. 4 to show how the X and Z coordinate position vary from small negative values in the first 4 orbits (labeled I) to larger negative values in the main set of 8 orbits (labeled II). The nearly linear dependence of the data points indicates that in the southern hemisphere the intermediate transition spreads away from the wake with the downstream distance from the planet. The relative position of the intermediate transition as detected across the wake is also illustrated when its position is plotted on the ecliptic XY plane as shown in Fig. 5. In this case the first 4 orbits that occur with significant negative Y values are clearly separated from the set of 8 orbits placed across and beyond the midnight plane. The distribution of the data points in space can be further appreciated in a plot on the YZ plane transverse to the solar wind direction as shown in Fig. 6. The data points show a tendency to be displaced in the positive Y direction as it...
was inferred from the observation of ionospheric holes in the PVO measurements (Brace et al., 1982).

The decrease in the proton speed profile at the intermediate transition varies significantly in the 12 orbits listed in Table 2 with two different configurations. As shown in Figs. 7–9 the first 3 orbits (September 12–16) and the last 4 orbits (Sept 22–26) show proton speed profiles with a gradual decline toward a minimum value which can be interceded with short fluctuations. On the other hand the speed profiles in the Sept 17–21 orbits contain a more drastic decrease that reach rapidly minimum values. The description of these variations in Figs. 7–9 also include the speed profiles of the planetary ions measured in the same time intervals of the proton speed profiles. The escalated steps in the speed profiles that lead to minimum values within the wake in the September 12–16 orbits are similar to the gradual decrease of the flow speed by the boundary of the wake that was reported from the Venera-10 measurements (Romanov et al., 1979). In all these cases

Fig. 7. Speed signatures for the Sept 12, 15, 16 and 17 orbits of the Venus Express corresponding to the H+ (top) and O+ (bottom) ions measured at negative values of the Y coordinate across the Venus wake.
there is an indication of a velocity boundary layer that is applicable to the plasma that streams within the wake. Similar conditions are also noticeable in the proton speed profiles available in the Sept 22–26 orbits where the escalated steps in the decrease of the flow speed of the proton population are accompanied by a comparable increase of the flow speed of the planetary ions (it should be noted that this variation is also applicable when there are fluctuating speed values as it is the case in the Sept 23 and Sept 26 orbits).

The sharp drop in the speed profiles of the proton population in the Sept 17–21 orbits, which occur at large $X$ and $Z$ coordinate values and
in the absence of a velocity boundary layer, reveal conditions that are different from those in the previous orbits. In particular, different from the Sept 12–17 orbits there are bulk O+ planetary ion fluxes in the Sept 18–21 orbits with enhanced flow speeds by the vicinity of the steep drop in the speed profile of the proton population. The presence of fast moving planetary ions after the sharp decrease in the speed profile of the proton population is compatible with what would be expected to occur within the plasma channels that extend downstream from the magnetic polar regions of the Venus ionosphere. In that view the solar wind removes planetary ions within those regions through momentum transport processes which then acquire speeds that are significantly smaller than those of the solar wind (Lundin et al., 2011; Pérez-de-Tejada et al., 2013). A further property that agrees with the transit of the Venus Express through a plasma channel beginning at the sudden drop of the proton flow speed in the Sept 18–21 orbits is the direction that the magnetic field acquires at that time. In fact, from Fig. 2 it can be appreciated that the \( B_y \) and \( B_z \) components of the magnetic field transverse to the solar direction decrease to near zero values at 03:23 UT in the June 27–2008 orbit when the proton speed decreases to very low values, thus implying that the magnetic field becomes mostly directed in the X direction. A similar behavior is also applicable to the magnetic field vector in the other 3 orbits listed in Table 1 implying that the drop in the proton speed value in those orbits at the intermediate transition is accompanied by the rotation of the magnetic field.

Fig. 9. Speed signatures at the Sept 22, 23, 25 and 26 orbits of the Venus Express corresponding to the H+ (top) and O+ (bottom) ions measured at positive values of the Y coordinate across the Venus wake.
direction. The implication here is that different plasma flow conditions are observed before and after the spacecraft moved across the intermediate transition.

Measurements with fluctuating speed values of the proton and planetary on populations in the Sept 23 and Sept 26 orbits in Fig. 9 where the intermediate transition is detected at large positive $Y > 0$ values suggest that they may occur by one edge of the plasma wake. At such locations the planetary ions can be removed in an intermittent manner through strays or in a filament configuration. Since no such fluctuations occur in the early $Y < 0$ orbits it is possible that the plasma channel within the wake has been deflected towards the positive $Y$ direction as it was inferred from the position of the data points in Fig. 6. A further result that agrees with this view is the fact that the largest $X = -2.86 R_V$ coordinate value of the data points occurs in the Sept 21 orbit where the intermediate transition is not located by the midnight plane but at $Y = 0.14 R_V$ thus suggesting that the core of the plasma channel is displaced in the positive $Y$ direction.

1.3. Balance of momentum flux across the plasma channels

Issues related to the energy content of ionospheric particle flows that are driven away by the solar wind were recently addressed in VEX orbits that probed by the vicinity of the midnight plane (Pérez-de-Tejada et al., 2013). Measurements show that their thermal pressure is smaller than the magnetic pressure in the lobes (Dubinin et al., 2013) but their kinetic pressure can be larger and thus they can be mostly driven by kinetic forces. It was also noted that the speed of the planetary $O^+$ ions reaches values significantly smaller than those of the solar wind proton component in agreement with the ion speed altitude distribution reported by Lumdín et al. (2011) from measurements conducted in many VEX orbits.

Further indications can be derived from the speed profiles of the planetary $O^+$ ions and solar wind protons that were presented in the Pérez-de-Tejada et al. (2013) report. In particular, we will extend the calculations corresponding to orbit 123 on August 22–2006 (Fig. 1 in that report) to show concurrent variations in the speed profiles of both ion populations. Most notable is that smaller values of the solar wind speed are recorded in the 02:33–02:39 UT time period (fourth panel) at the time when the speed of the planetary $O^+$ ions becomes enhanced (fifth panel). Such variations occurred when the spacecraft moved over the planet in the vicinity of the north polar region near the midnight plane, i.e. between $X = -0.30$ and $X = 0.30$, with $Y = -0.05$ and $Y = -0.01$; and $Z = 1.66$ and $Z = 1.02$, and are related to an effective transport of momentum between both ion populations. This view can be supported by comparing the deficiency of the momentum flux of the solar wind protons in that time period with the local momentum flux of the planetary ions. From the data used in Fig. 1 of the JGR-2013 publication we can take: $V_{O^+} = 23 \text{ km/s}$ with $n_{O^+} = 10 \text{ cm}^{-3}$ (between 02:33–02:36 UT), and $V_{O^+} = 25 \text{ km/s}$ with $n_{O^+} = 4 \text{ cm}^{-3}$ (between 02:36–02:39 UT). These values lead to: $m_O n_O V_O^2 = 1.4 \times 10^{-9} \text{ ergs/cm}^3$ and to $0.7 \times 10^{-9} \text{ ergs/cm}^3$ for their momentum flux at the two time intervals and that can be compared with the deficiency of momentum flux of the solar wind protons that were measured by then. Between 02:33–02:36 UT we have: $V_{p,out} = 140 \text{ km/s}$ and $V_{p,in} = 70 \text{ km/s}$, with $n_{p,out} = 10 \text{ cm}^{-3}$ and $n_{p,in} = 20 \text{ cm}^{-3}$ (these values were measured before and within the first time interval); while between 02:36–02:39 UT we have: $V_{p,in} = 70 \text{ km/s}$ and $V_{p,out} = 130 \text{ km/s}$, with $n_{p,out} = 3 \text{ cm}^{-3}$ and $n_{p,in} = 3 \text{ cm}^{-3}$ (these values were measured within and after the second time interval). The momentum flux of the solar wind protons measured before and after the 02:33–02:36 UT time interval is then: $[m_p n_p V_p^2]_{\text{out}} = 3.3 \times 10^{-9} \text{ ergs/cm}^3$ and $[m_p n_p V_p^2]_{\text{in}} = 1.6 \times 10^{-9} \text{ ergs/cm}^3$. Separately, within and after the 02:36–02:40 UT time interval they are: $[m_p n_p V_p^2]_{\text{out}} = 0.25 \times 10^{-9} \text{ ergs/cm}^3$ and $[m_p n_p V_p^2]_{\text{in}} = 0.85 \times 10^{-9} \text{ ergs/cm}^3$ As a result, the deficiency of momentum flux of the solar wind protons in both intervals is:

$$[m_p n_p V_p^2]_{\text{out}} - [m_p n_p V_p^2]_{\text{in}} = \begin{cases} 1.7 \times 10^{-9} \text{ ergs/cm}^3 \text{ in the 02:33–02:36 UT time interval} \\ -0.6 \times 10^{-9} \text{ ergs/cm}^3 \text{ in the 02:36–02:40 UT time interval} \end{cases}$$

These numbers show a very close correlation with the momentum flux of the $O^+$ ions in each time interval and thus support the view that an effective transport of solar wind momentum takes place with the $O^+$ ion population. The approximate value between the deficiency of momentum flux of the solar wind protons and the momentum flux of the planetary ions applies separately at each time interval despite the fact that between both cases there is an up to a 2 times difference factor in their magnitude. As a result the balance of momentum flux occurs as a local process in a strong dynamic interaction. It should be noted that the planetary ions follow the same ($X$-dominated) direction of the solar wind independently of that ($Y$-directed) of the magnetic field (bottom panel in Fig. 1 of the JGR-2013 article). Thus, the motion of the planetary ions appears to be dominated by the kinetic energy of the solar wind rather than by the local piled-up magnetic field. Further downstream (between 01:30 UT and 02:00 UT) there are also planetary ions moving with comparable speed and densities in the presence of much weaker magnetic field intensities.

In the energy spectra shown in the top panel of Fig. 1 of the Pérez-de-Tejada et al. (2013) report there is evidence of planetary ion fluxes measured at the time when there is momentum transport from the solar wind protons in the 02:33 UT–02:39 UT time period and whose incident upstream energy is $\sim 1000 \text{ eV}$. In fact, planetary $O^+$ ions with $\sim 100 \text{ eV}$ energies are measured in that time period together with decelerated solar wind protons. Such conditions are different from those implied by Collinson et al. (2014) who stated that there is only an outflow of $\sim 20 \text{ eV}$ proton and heavy ions across the ionospheric hole as reported in Fig. 2 of their publication. A similar disagreement with that statement is also encountered in the energy spectra shown in Fig. 3 of the same publication for orbit 132 on August 31–2006 where there are also planetary ions with $\sim 100 \text{ eV}$ energies in the 03:09 UT and 03:12 UT time range when the flux intensity of the $\sim 1 \text{ keV} \text{ H}^+ \text{ ions}$ has decreased. Both examples examined in the same report invalidate the disqualification of momentum transport as the formation mechanism of ionospheric holes/plasma channels that was stated in the Collinson et al. (2014) publication.

A more detailed comparative view of such differences can be appreciated in the top and middle panels of Fig. 10 where the energy spectra of the $H^+$ and $O^+$ ions obtained in the August 22–2006 and the August 31–2006 orbits are presented, together with that for the May 19–2010 orbit shown in the lower panel. Such profiles indicate that the different energy spectra of the planetary ions measured in the VEX orbits of Figs. 1 and 3 in the 2013 Pérez-de-Tejada et al. report with respect to those examined in Fig. 2 by Collinson et al., may have been due to differences in the orientation of the trajectory along those VEX orbits. While the two orbits discussed in the 2013 publication are traced in the vicinity of the midnight plane (small $Y$ values) and close to the north pole ($Z \sim 1$) the spacecraft trajectory for the orbit reported by Collinson et al. (2014) is traced across the ecliptic plane (between $Z = -0.12$ and $Z = 0.21$) at event 7 where the ionospheric hole was detected (between 05:23 UT and 05:29 UT). That location occurs nearly one planetary radius away from the midnight plane ($0.87 > Y > 0.73$) and far downstream from the terminator plane (between $X = -1.72$ and $X = -1.45$). From such difference it is clear that the plasma channels are going to be less populated with increasing distance from the magnetic polar regions. Care should be taken when selecting data from one particular orbit to ‘eliminate’ alternative views.

A general view of the manner in which the IT as the outer boundary of plasma channels may be distributed within the plasma wake is shown in Fig. 11 together with the traces of selected Venus Express trajectories projected on the $XY$ plane. The sense of rotation across the night-side
Fig. 10. (top and middle panels) Energy spectra of the H+ and O+ ions measured at the time when VEX moved across ionospheric channels in the August 22–2006 and August 31–2006 orbits reported by Pérez-de-Tejada et al. (2013). (bottom panel) Energy spectra of the H+ and O+ ions measured across the ionospheric hole in the May 19–2010 orbit reported by Collinson et al. (2014). The entry and exit of the spacecraft at their boundaries limit a region with low ion density and/or low speed values. These are represented by the symbol (*) above or below each panel.
ionosphere indicates that the plasma channels should be deflected in the positive Y direction so that the region probed by the spacecraft in the orbits labeled II is also drifted in that direction towards the edge of the wake. Such a drift complies with the observed Y-directed displacement in the position of the data points of the intermediate transition presented in Figs. 3–6. At the same time, the position of the intermediate transition of the 12 orbits projected on the XY plane in Fig. 5 has also been added to show that the larger X coordinate values obtained in the orbit set labeled II derive from the region of the wake that is probed along the spacecraft trajectory during the latter orbits. A 3D schematic view of the plasma channels that is implied from these measurements is presented in Fig. 12 as derived from the data points in Fig. 11 to indicate how they are deviated in the Y > 0 (dawn-ward) direction, in agreement with the displaced position of the main population of ionospheric holes reported from the OETP measurements of the Pioneer Venus (Brace et al., 1982). It should be noted that along the Venus Express trajectory through the southern hemisphere across the wake the spacecraft approaches periapsis in the northern pole and thus it will only encounter one side of a plasma channel as it is indicated in Fig. 12. The origin and geometry of the channels is consistent with that reported earlier from measurements related to the removal of planetary ions through momentum transport produced by the solar wind (Pérez-de-Tejada, 2004). The Y > 0 deviation of the plasma channels indicated in Fig. 11 is unrelated to the change of polarity of the B\textsubscript{y} component detected in the inner wake (Zhang et al., 2010), and could be associated to effects produced by a plasma vortex as can be noted in the left panel of Fig. 1 (see also Lundin et al., 2013).

The dawn-ward deviated form of the plasma channel indicated in Fig. 12 derives from the gradual and cumulative displacement of the intermediate transition in that direction indicated in the set of orbits shown in Fig. 11. That transition represents the outer boundary of the velocity boundary layer or region within the channels where the speed of the solar wind protons begins a gradual decrease. This view is applicable to the data of VEX orbits that are traced through the wake away from the midnight plane (top panels in Fig. 7). In orbits that scan closer to that plane the slope of the velocity profile becomes more pronounced and the intermediate transition takes the form of the outer boundary of the plasma channels (examples in Fig. 8).

2. Discussion

In addition to the compiled discussion of the energy spectra of the H\textsuperscript{+} and O\textsuperscript{+} ions showing that across plasma channels the latter ion fluxes are measured with energy values larger than those reported by Collinson et al. (2014) within an ionospheric hole evidence has also been provided to support the view that the position of the intermediate transition as the outer boundary of the plasma channels is shifted towards the Y direction in the same sense as that of the velocity vectors of planetary ions obtained from measurements in many VEX orbits reproduced in Fig. 1. A summary of the position of the latter boundary derived from the data in Figs. 7–9 is presented in Fig. 11 to show its general shift towards the Y direction from the 12 orbits that were examined.

A relevant implication that can be inferred from the position of the

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**Fig. 11.** Relative position of the X and Y coordinate values of the intermediate transition identified in the 12 orbits listed in Table 2 together with the trace of the trajectory of the Venus Express projected on the XY plane. The position of the data points reveal a certain deflection towards the dawn side (Y > 0). As a result of transport of solar wind momentum to the Venus upper ionosphere the solar wind proton speed is smaller within the plasma channels.

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**Fig. 12.** Schematic view of plasma channels by the magnetic polar regions of the Venus ionosphere that are deviated toward the dawn side (+Y) direction as indicated in Fig. 11, and in agreement with the downward deviation of the planetary O\textsuperscript{+} fluxes measured in the near Venus wake shown in the right hand panel of Fig. 1 (after Pérez-de-Tejada, 2004). The position of the plasma channels has been oriented with respect to the direction of the B\textsubscript{L} component along the Y axis (after Pérez-de-Tejada, 1997).
data points in Fig. 11 is a calculation of the width of the plasma channels. Different from the speed profiles of the proton population in the first and later orbits included in Figs 7–9 a sharp decrease was observed in the H+ ion profiles of the Sept. 17 and Sept. 21 orbits in their negative Z value measurements. Using the Y coordinate value of that decrease at both orbits it is possible to estimate that the distance between the sharp change in the speed profiles between them is \( L = 0.3 \) \( R_V \) (∼2000 km) as an approximate width of the plasma channel measured by the spacecraft at \( X = -2.5 \) \( R_V \) (data points ‘d’ and ‘g’ in Fig. 11). That property should gradually become wider with the downstream distance from the Venus ionosphere and in turn implies \( L \sim 1000 \) km for its width by \( X = -1 \) \( R_V \).

The source of the dawn-ward directed deviation of the plasma channels has been the subject of extensive analyses regarding the participation of different processes. An overall displacement of planetary ions in that direction is implied by the aberration of the solar wind produced by the orbital motion of Venus around the sun. However, Phillips et al (1988) indicated that such an effect is not sufficient to account for the large east-west asymmetry of the Venus ionopause altitude. A large deviation in the plasma motion in the dawn-ward direction was implied from the shifted position of the number of ionospheric holes detected with the OETP instrument of the PVO in the Venus nightside (Brace et al., 1982), together with the dawn-ward oriented deflection of the trans-terminator flow also derived from the PVO measurements (Miller and Whitten, 1991). A viable interpretation of those observations was provided in terms of effects associated to a Magnus force implemented by the combined participation of the directional motion of the trans-terminator flow along the solar wind and the rotation of the lower ionosphere (Pérez-de-Tejada, 2006). That force is responsible for the dawn-ward shift in the position of those features and the displacement of the planetary ions in that direction (Lundin et al., 2011). At the same time it should also be involved in the dawn-ward deviation of the plasma channels along the wake as discussed above.

The distribution of the solar wind hydrogen ions in the left panel of Fig. 1 shows, on the other hand, a flow circulation pattern reminiscent of a vortex structure in the Venus wake that was first suggested from the early PVO measurements and that has now been extensively reported from the Venus Express plasma data (Lundin et al., 2011, 2013; Pérez-de-Tejada, et al. 2017). Such structures together with the velocity boundary layer measured along the flanks of the Venus magnetosheath are consistent with a fluid dynamic behavior in the response of the solar wind as it streams around and behind the Venus ionosphere and that can be ultimately derived from effects produced by wave-particle interactions. From the early observation of the solar wind as it streams around the Venus ionosphere there has been clear evidence of strong variations in the intensity of the magnetic field together with frequent oscillations of its direction downstream from the planet (Bridge et al., 1967; Vörös et al., 2008), and that have led to a variety of wave activity that has been extensively studied (Shapiro et al., 1995; Quest et al.; 1997; Delva et al., 2008).

A further issue of interest is the lined-up position of the intermediate transition in the XZ-plane obtained in Fig. 4 for the 12 orbits of Table 2. The slope of the linear dependence between the X and Z coordinates in the data points is \( \Psi \approx 60^\circ \) away from the X-direction thus suggesting that the intermediate transition deparres severely from that direction with the downstream distance from the planet. The severe value of the \( \Psi \) angle is far larger than that of Mach lines that are traced away from the flow direction in supersonic flows streaming over a flat obstacle geometry. It is possible that the large angle orientation of the intermediate transition that marks the outer position of a velocity boundary layer where there are decreased values of the flow speed derives from conditions produced in the inner Venus wake when the converging solar wind particle flows that are initially directed toward the equatorial plane from the polar regions encounter with each other thus forcing the plasma to diverge away from that plane.

### 3. Conclusions

From the plasma data of the VEX measurements information was presented to indicate the position of the bow shock and the intermediate transition along the flanks of the Venus ionosheath during the solar cycle 23 (between 2006 and 2009). Both boundaries occur at distances that are closer to Venus by solar minimum (near 2009), and the position of the bow shock is in agreement with that reported by Slavin et al., (1980) from measurements conducted in solar cycles 20–21. In fluid dynamics the intermediate transition represents the outermost location within a boundary layer along the flanks the Venus magnetosheath which derives from disturbances produced by the erosion of the solar wind on the polar ionosphere (see Liepmann and Roshko (1967) as a reference of this concept). The data in the set of 12 orbits during September 2009 when the VEX spacecraft probed by the vicinity of the midnight plane in the Venus wake show a gradual and persistent dawn-ward directed displacement of the position of the IT in the spacecraft trajectory. That displacement is in agreement with the overall Y-directed deviation of the O+ ion population in the Venus wake that was derived from measurements obtained in many VEX orbits and that are reproduced in Fig. 1.

Calculations were made to show from concurrent variations in the speed of the solar wind protons in orbit 123 of August 22–2006 that were obtained from the energy spectra shown in the top panel of Fig. 10 that there is an efficient transport of momentum between the H+ and the O + ion populations. This result is contrary to the statement by Collinson et al. (2014) indicating that within a hole transit the ASPERA-IMA observed a cold ionospheric outflow of protons and heavy ions at ∼20 eV as it is reproduced in the energy spectra shown in the bottom panel of Fig. 10. The difference with respect to the energy spectra discussed by Pérez-de-Tejada et al. (2013) is related to the orientation of the VEX trajectory in those orbits. The onset of momentum transport across plasma channels applies by the midnight plane and downstream from the magnetic polar regions, while the VEX orbit examined by Collinson et al. (2014) occurs far away from the midnight plane and is traced across the equatorial plane. In this latter case the ionospheric fluxes and the solar wind proton fluxes arriving from the magnetic polar regions are less populated by the vicinity of the ecliptic plane (between \( X = -1.45 \) and \( X = -1.72 \)) where they are observed.

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