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ScienceDirect
Planetary and Space Science 56 (2008) 780–784
Planetary and Space Science
www.elsevier.com/locate/pss

# Location of the bow shock and ion composition boundaries at Venus—initial determinations from Venus Express ASPERA-4

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Received 16 February 2007; accepted 9 July 2007
Available online 31 December 2007

**Abstract**

For the first time since 1992 when the Pioneer Venus Orbiter (PVO) ceased to operate, there is again a plasma instrument in orbit around Venus, namely the ASPERA-4 flown on Venus Express (inserted into an elliptical polar orbit about the planet on April 11, 2006). In this paper we report on measurements made by the ion and electron sensors of ASPERA-4 during their first five months of operation and, thereby, determine the locations of both the Venus bow shock (BS) and the ion composition boundary (ICB) under solar minimum conditions. In contrast to previous studies based on PVO data, we employ a 3-parameter fit to achieve a realistic shape for the BS. We use

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0032-0633/$ - see front matter 
doi:10.1016/j.pss.2007.07.007

a different technique to fit the ICB because this latter boundary cannot be represented by a conic section. Additionally we investigate the dependence of the location of the BS on solar wind ram pressure (based on ASPERA-4 solar wind data) and solar EUV flux (using a proxy from Earth).


*Keywords:* Venus; Solar wind interaction; Solar wind dynamic pressure; Venus Express; Bow shock; Ion composition boundary

## 1. Introduction

Current knowledge of the solar wind interaction with Venus comes almost entirely from the long lasting Pioneer Venus Orbiter (PVO) mission (1978–1992) which provided a data set that extended over a complete solar cycle (Russell et al., 2006). The plasma boundaries at Venus were originally identified using data measured by the PVO magnetometer and plasma analyzer. Compared with the magnetometer (MAG) and the plasma analyzer (ASPERA-4) on board of Venus Express (VEX) spacecraft the PVO instruments had much lower temporal, energy and angular resolutions. VEX gives us the opportunity to fill the gaps left by the PVO observations and to extend our knowledge of the plasma environment of Venus.

In this study we have determined the locations of the plasma boundaries exclusively from particle measurements obtained by the electron spectrometer (ELS) and the ion mass analyzer (IMA) (see also Zhang et al., in this issue, for respective VEX Magnetometer results). Although PVO made observations over the entire solar cycle, no direct measurements of the near Venus plasma environment during solar minimum were possible due to the high PVO orbital altitude ($>2000$ km) at that time. The VEX spacecraft has a constant periapsis altitude of about 250 km and thus, we can sample this region during solar minimum. Just prior to PVO arrival, the Russian Venera 9 and 10 orbiters (1975–1976) observed the Venus solar wind interaction, including the bow shock and tail during solar minimum (Verigin et al., 1978).

Russell et al. (1988) and Zhang et al. (1990) investigated the Venus bow shock based on nearly 2000 PVO shock crossings and found that the shock location is modulated by the solar cycle and solar EUV flux, the upstream solar wind parameters and the orientation of the interplanetary magnetic field (IMF) (see also Phillips and McComas, 1991; Russell et al., 2006). For modeling the bow shock they have used a simple conic section with its focus at the center of the planet based on PVO data. In the present study we utilize a 3-parameter fit based on ASPERA-4 measurements to achieve a more realistic shape of this boundary. The same technique, i.e. a conic fit with conic focus along the Sun-planet line as a third free parameter, has already been used by Slavin et al. (1980) based on PVO data and was later applied to Mars by Vignes et al. (2000).

The ion measurements suggest an inner boundary of the magnetosheath can be defined by a decrease in energetic protons and energetic electrons. Significant heavy ion fluxes are only observed inside this region, which we call the "ion composition boundary" (ICB). Since it cannot be represented by a simple conic function we use (see below) an alternative approach in order to model it. Spenner et al. (1980) using PVO data identified a boundary they called the ionosheath boundary, which was defined by an ambient decrease in solar wind flux. Also an ionopause was defined by its association with the vanishing of protons. These authors had, however, no nightside observations. Further, Zhang et al. (1991) defined the ionopause and the upper boundary to constitute the limits of a region of increased magnetic pressure.

In this paper the first section deals with our identification of the bow shock and the ion composition boundary based on plasma analyzer data. The next section explains how these boundaries can be fitted and this is followed by a general discussion. We do not consider the influence of the IMF on the location of the bow shock because the relevant magnetic field data are not available to us as yet.

## 2. Observations

The data used in this paper were obtained by the ASPERA-4 instrument on board the VEX spacecraft. It consists of an electron spectrometer, an ion spectrometer and two neutral particle sensors (Barabash and et al., 2007). We utilize here only data from the two spectrometers.

Fig. 1 illustrates an example of data obtained on July 9, 2006 showing the main plasma features of the solar wind interaction with Venus. The top panel presents a spectrogram made by the ELS. The energy range of the sensor is 0.1 eV–20 keV but electrons with energies below 5 eV are reflected to avoid saturation of the counters. Shown are counts obtained during 4 s sampling intervals by all 16 anodes of the sensor. The two following panels display the $H^+$ and $O^+$ spectrograms of the ion IMA at 12 s resolution integrated over all 16 anodes of the sensor. A spatial scan during 192 s by electrostatic deflection produces the repeatable pattern visible in the spectrogram. The black vertical bars mark the plasma boundary crossings. Fig. 1 (right) shows the orbit in cylindrical coordinates, where the $x$-axis points from Venus to Sun.

VEX crosses the bow shock (BS) at ~01 : 19 UT, a fast magnetosonic shock wave due to the supersonic solar wind (Russell et al., 1988). We identify the BS by an increase in density of energetic electrons ($E>60$ eV) in the magnetosheath with respect to the solar wind. In cases where the identification is not clear we instead use the temperature increase in protons. Passing the BS, the spacecraft enters the magnetosheath that is characterized by the shocked,

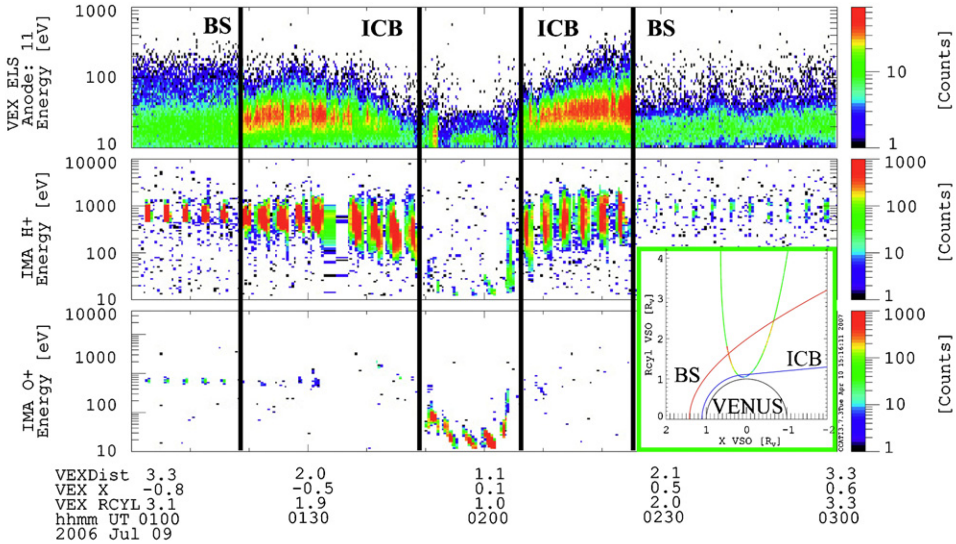


Fig. 1. ASPERA-4 data recorded on July 9, 2006—about an hour before and after the pericenter of that concerned orbit (1 $R_V = 6051.8$ km).

slowed down and heated solar wind. At ~01 : 49 UT VEX crosses another plasma boundary, which we call the ion ICB. This separates the thermal plasma of the ionosphere from the hot magnetized plasma of the magnetosheath. It is identified by the vanishing of solar wind protons ($E > 300$ eV) and the appearance of planetary ions. During most orbits energetic electrons also vanish at the ICB. Due to the definition used and the fact that no pressure balance investigation was carried out in the course of this study, we decided to adopt the term ICB instead of ionopause or magnetic barrier. Between ~01 : 49 UT and ~02 : 06 UT VEX is located inside the ionosphere. On the outbound pass the spacecraft crosses again all the above mentioned regions but in reverse order.

## 3. Bow shock and ion composition boundary fits

From May 14 to October 15, 2006, 248 Venusian BS crossings and 212 ICB crossings were identified in ELS and IMA data (as described in Section 2). On some orbits the ICB was difficult to identify because the solar wind particles decreased gradually and no clear boundary was visible in the ion spectra. To avoid outliers we omitted such cases from our study and as a result, more BS than ICB crossings were considered overall.

For the bow shock we applied the curve fitting technique developed by Slavin and Holzer (1981) which has also been used by Trotignon et al. (2006) for modeling the plasma boundaries at Mars. The observed shock locations have first to be transformed into an aberrated solar ecliptic system ($X'$, $Y'$, $Z'$; VSO), where the $X'$ axis is anti-parallel to the mean solar wind flow direction in the Venus frame of reference assuming a 5° aberration. Then, a conic function in polar coordinates, assuming cylindrical symmetry along the $X'$ axis, is least-square fitted to the observed BS positions. In order to get the best fit to the observations we used an offset of the conic focus along the symmetry axis as introduced by Slavin et al. (1980). Thus, the shock surface is represented by $r = L/(1 + \varepsilon \cdot \cos \vartheta)$ where the polar coordinates $(r, \vartheta)$ are measured with respect to a focus located at $(x_0, 0, 0)$. $L$ is the semi-latus rectum and $\varepsilon$ is the eccentricity (see Table 1).

Table 1
Venusian BS fit parameters from VEX in comparison with Venera 9/10 and PVO results at solar minimum

| | $L$ [$R_V$] | $\varepsilon$ | $x_0$ [$R_V$] | $r_{tsd}$ [$R_V$] |
|---|---|---|---|---|
| This study | 1.303 | 1.056 | 0.788 | 1.984 |
| Slavin et al. (1984) | 1.68 | 1.03 | 0.45 | 2.096 |
| Russell et al. (1988) | 2.14 | 0.609 | 0 | 2.14 |
| Zhang et al. (1990) | 2.131 | 0.66 | 0 | 2.131 |

For modeling the position of the ICB we used a somewhat different approach because we found that the observations on the dayside and on the nightside cannot be represented by a single conic function, as was also noted in the case of the magnetic pile-up boundary (MPB) at Mars (Trotignon et al., 2006). Thus, we separated the measurements into dayside ($X > 0$) and nightside ($X < 0$) observations. The ICB crossings on the dayside were fitted by a circle ($r_c = 1.109$) and the data set on the nightside were fitted by linear regression ($y = k \cdot x + d$, $k = -0.097$, $d = 1.109$).

Fig. 2 (left) displays the axisymmetric BS and ICB fits derived using the first 5 months of ELS and IMA observations in an aberrated VSO coordinate system. The red curve is the fit to all BS crossings (circles) obtained by Slavin's method and the blue curve is the fit to all ICB crossings (triangles) obtained using the approach discussed above.

Additionally, we investigated the variation of the BS position at the terminator as a function of the solar wind dynamic pressure (Fig. 3). All BS crossings were extrapolated

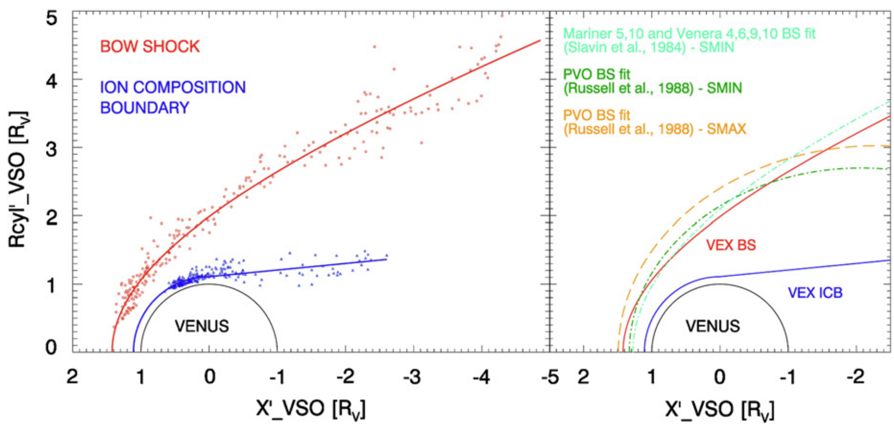


Fig. 2. Left: Venus BS (red line) and ICB (blue line) fits. Right: VEX BS in comparison with other BS models based on different data sets at solar minimum and solar maximum. Slavin et al. (1984) also used a 3-parameter conic section for modeling the upstream and downstream BS ($\varepsilon > 1$ hyperbola). Russell et al. (1988) fitted the dayside BS crossings with a 2-parameter conic function where its focus is fixed at the center of the planet ($\varepsilon < 1$ ellipse).

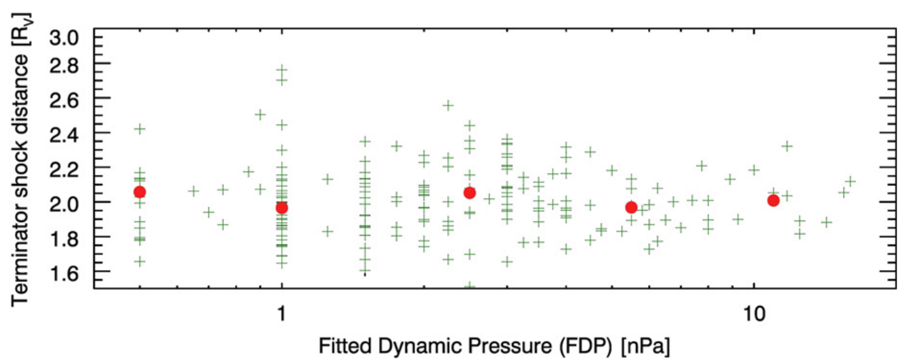


Fig. 3. The dependence of the bow shock position at the terminator on the fitted dynamic pressure of the solar wind (FDP) derived from ASPERA-4 measurements. No normalization has been applied to the data. The red points represent median values.

to the terminator plane using a conic section curve with a fixed focus and eccentricity (see Table 1) and a variable $L$ value: $L = \sqrt{(X' - x_0)^2 + Y'^2 + Z'^2} + \varepsilon \cdot (X' - x_0)$. Then the terminator shock distance is given by $r_{\mathrm{tsd}} = \sqrt{(L \cdot (L + 2 \cdot \varepsilon \cdot x_0) + x_0^2 \cdot (\varepsilon^2 - 1))}$. We find that the BS position is independent of the solar wind dynamic pressure in agreement with results obtained by Russell et al. (1988) and by Zhang et al. (2004) based on PVO observations.

## 4. Discussion and conclusions

In this paper we determined the positions of the Venusian BS and ICB at solar minimum based on ASPERA-4 observations made on board the Venus Express spacecraft. The observed VEX crossings of the plasma boundaries were transformed into an aberrated solar ecliptic system, assuming a 5° aberration angle. The BS is represented by a conic section, expressed in polar coordinates under the assumption of cylindrical symmetry along the $X'$ axis (i.e. opposite to the solar wind flow direction) and with an offset of the focus which is allowed to move along the symmetry axis. The ICB is represented by a circle on the dayside and by a line fit on the nightside in order to obtain a satisfactory fit to the data.

Currently there is no ICB data below 50° SZA and thus, the ICB fit provides a boundary which is too far away from the planet on the dayside (~600 km) compared with PVO results (~300 km) at solar maximum. At solar minimum there are no in situ PVO measurements of the ionopause due to the increasing PVO orbital altitude. However, electron density profiles measured by the radio occultation experiment on PVO showed that the ionopause was strongly depleted during solar minimum with an altitude of ~250 km everywhere on the dayside (Zhang et al., 2006). In order to get a more realistic ICB fit from VEX data it is necessary to include crossings at the subsolar region expected later in the VEX mission. Zhang et al. (1991) determined a terminator altitude for the ionopause of around 700 km, which agrees with the altitude we determined for the ICB. On the dayside our ICB definition coincides with that of the ionopause by Spenner et al. (1980), and on the nightside it coincides with the tail boundary by Russell et al. (1988).

We also examined the effect of the solar wind dynamic pressure on the terminator BS location. We find that the shock position is insensitive to changes in the dynamic pressure of the solar wind, at least during solar minimum, as was earlier reported by Russell et al. (1988) and by Zhang et al. (2004). We observed that the spread in the terminator distance was much lower in our dataset than in that investigated by Zhang et al. (2004) (see Fig. 3), despite the fact that these authors tried to correct for EUV and IMF influence. One reason may be that solar conditions in our 5 month data set varied less than was the case in the course of the long duration PVO observations. Also, Zhang et al. (2004) used in their fits a focus fixed at the center of the planet, which fits the bow shock shape less well.

Since the solar wind interaction with Venus is dependent on the phase of the solar cycle, we also investigated the dependence of the terminator BS position on the solar EUV flux. At solar minimum the BS is found to be closer to the planet than at solar maximum by PVO (Fig. 2) due to lower ionization and ion pick up rates. In our data set we do not observe yet an effect on the terminator BS position because the EUV flux variation is small over the period of observation. We conclude from our measurements that the BS position is relatively stable and the nightside ICB position is highly variable.

## Acknowledgements

We thank all members of the ASPERA-4 team for the big effort which led to the successful operation of the instrument and the calibration of the data. For this paper we are especially grateful to Emmanuel Panou and Andrei Fedorov at CESR for data preparation and IMA calibration and Andrew Coates at MSSL for calibration of the ELS sensor data. The ELS was constructed under NASA contract NASW-0003.

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