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The Venusian induced magnetosphere: A case study of plasma and magnetic field measurements on the Venus Express mission

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Abstract

Plasma and magnetic field measurements made onboard the Venus Express on June 1, 2006, are analyzed and compared with predictions of a global model. It is shown that in the orbit studied, the plasma and magnetic field observations obtained near the North Pole under solar minimum conditions were qualitatively and, in many cases also, quantitatively in agreement with the general picture obtained using a global numerical quasi-neutral hybrid model of the solar wind interaction (HYB-Venus). In instances where the orbit of

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Venus Express crossed a boundary referred to as the magnetic pileup boundary (MPB), field line tracing supports the suggestion that the MPB separates the region that is magnetically connected to the fluctuating magnetosheath field from a region that is magnetically connected to the induced magnetotail lobes.
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1. Introduction

The study of the Venus–solar wind interaction is one of the scientific objectives of the Venus Express (VEX) mission. The spacecraft arrived on Venus on April 11, 2006. The particle instruments making up the VEX ASPERA-4 instrument suite include an ion mass spectrometer (IMA), electron spectrometer (ELS), and two sensors (NPI and NPD) for measuring energetic neutral atoms (Barabash et al., 2007). The onboard magnetometer (MAG) provides simultaneous measurements of the magnetic field (Zhang et al., 2006).

This instrumentation enables studies of many scientific issues that could not be properly addressed by the plasma and field instruments flown onboard Pioneer Venus Orbiter (PVO) during 1978–1992. In this regard, the IMA/VEX mass spectrometer is the first instrument that can distinguish fast ($10\,\mathrm{eV/e} < E < 36\,\mathrm{keV/e}$) escaping planetary ions (He^+, O^+, O_2^+) from the solar wind ions (H^+, He^{++}). Moreover, the PVO plasma analyzer (OPA) was primarily designed for solar-wind monitoring with a low time resolution of about 10 min, while the highest temporal resolution of ASPERA-4 IMA for providing a three-dimensional ion distribution is 32 s. Furthermore, the high pericenter latitude of VEX (~80°N) and its low pericenter altitude (~250 km) makes it possible to study the low altitude region near the terminator plane in detail under solar minimum conditions.

This paper presents a case study where IMA and MAG observations on June 1, 2006, are interpreted with reference to a three-dimensional numerical quasi-neutral hybrid (QNH) model. The aim of the study is to (1) analyze IMA and MAG data, (2) compare *in situ* measurements with the global model and (3) study the morphology of the magnetic fields produced in the Venus–solar wind interaction.

2. Hybrid model and the dataset

The numerical, self-consistent QNH model used in this study treats ions as particles and electrons as a massless charge-neutralizing fluid. We used a run that has already been documented in detail elsewhere (Kallio et al., 2006) and so we describe here only basic features of the model most relevant to the present study.

The model version used here, which we call HYB-Venus, contains H^+ ions originating from the solar wind and O^+ ions originating from Venus' hot oxygen corona and ionosphere. The coordinate system of the model is VSO (Venus Sun Orbital), where the x-axis points from Venus toward the Sun, the z-axis is perpendicular to the planet's orbital velocity and the x-axis, and positive in the northern ecliptic hemisphere, and $+y$ completes the right-handed coordinate system. The size of the simulation box is $-3R_V < x < 3R_V$ and $-4R_V < y$, $z < 4R_V$ ($R_V \equiv 6051.8$ km). The assumed solar wind velocity is (−430, 0, 0) km/s and the density of the solar wind protons is $14\,\mathrm{cm}^{-3}$. The IMF x-component is $10\,\mathrm{nT} \times \cos(36^\circ) \sim 8.09\,\mathrm{nT}$. The IMF component perpendicular to the flow is $\mathbf{B}_{\mathrm{perp}} = [\mathrm{B}y, \mathrm{B}z]$, is $[\sin(\alpha_{\mathrm{clock}}), \cos(\alpha_{\mathrm{clock}})] \times \sin(36^\circ) \times 10\,\mathrm{nT} = [\sin(36^\circ), 0] \times 10\,\mathrm{nT} \sim [5.88, 0]\,\mathrm{nT}$, where $\alpha_{\mathrm{clock}} = 90^\circ$ is the IMF clock angle ($\alpha_{\mathrm{clock}} = 0^\circ$ is northward).

An important feature in the analyzed HYB-Venus run is that it can be used to describe all those IMF cases which have $B_{\mathrm{par}} = B_x = 8.09\,\mathrm{nT}$ and $B_{\mathrm{perp}} = 5.88\,\mathrm{nT}$ by rotating the solution around the x-axis so that the model has the same IMF clock angle as observed. In this paper, the optimal orbit of VEX for a comparison with the described model run was identified by examining all VEX orbits for which cleaned MAG data were currently available. This dataset includes orbits from May 9, 2006 to June 29, 2006. The orbit on June 1, 2006, was chosen because (1) the pertaining direction of the IMF was relatively stationary and (2) the measured IMF was close to the IMF that was used in the simulation. In this case, the $\mathbf{B}_{\mathrm{perp}}$ vector pointed almost in the $-z$-direction, as will be discussed later. The plasma and magnetic field data shown in this paper are, therefore, derived for $\alpha_{\mathrm{clock}} = 180^\circ$.

3. Results

Time energy spectrograms based on the IMA measurements made on June 1, 2006, together with the density and the bulk energy of ions derived from the hybrid model, are presented in Fig. 1. According to the H^+ ion dataset, VEX was first in the solar wind (SW), crossed the bow shock (BS) at ~01:23 UT and entered the hot magnetosheath (Fig. 1b).

After that, the VEX entered a region where the fluctuations of the magnetic field decreased (as will be discussed later in relation to Fig. 2) at the position marked in Fig. 1 as the magnetic pileup boundary (MPB) at about 01:32 UT. Near Venus, the flux of protons became lower than the sensitivity of the IMA at a location which is labeled as the proton dropout boundary (PDB) in Fig. 1. Thereafter (see Fig. 2) VEX crossed the cross-tail current sheet (CTCS). This crossing was associated with the detection of >1 keV/e heavy, accelerated, planetary ions

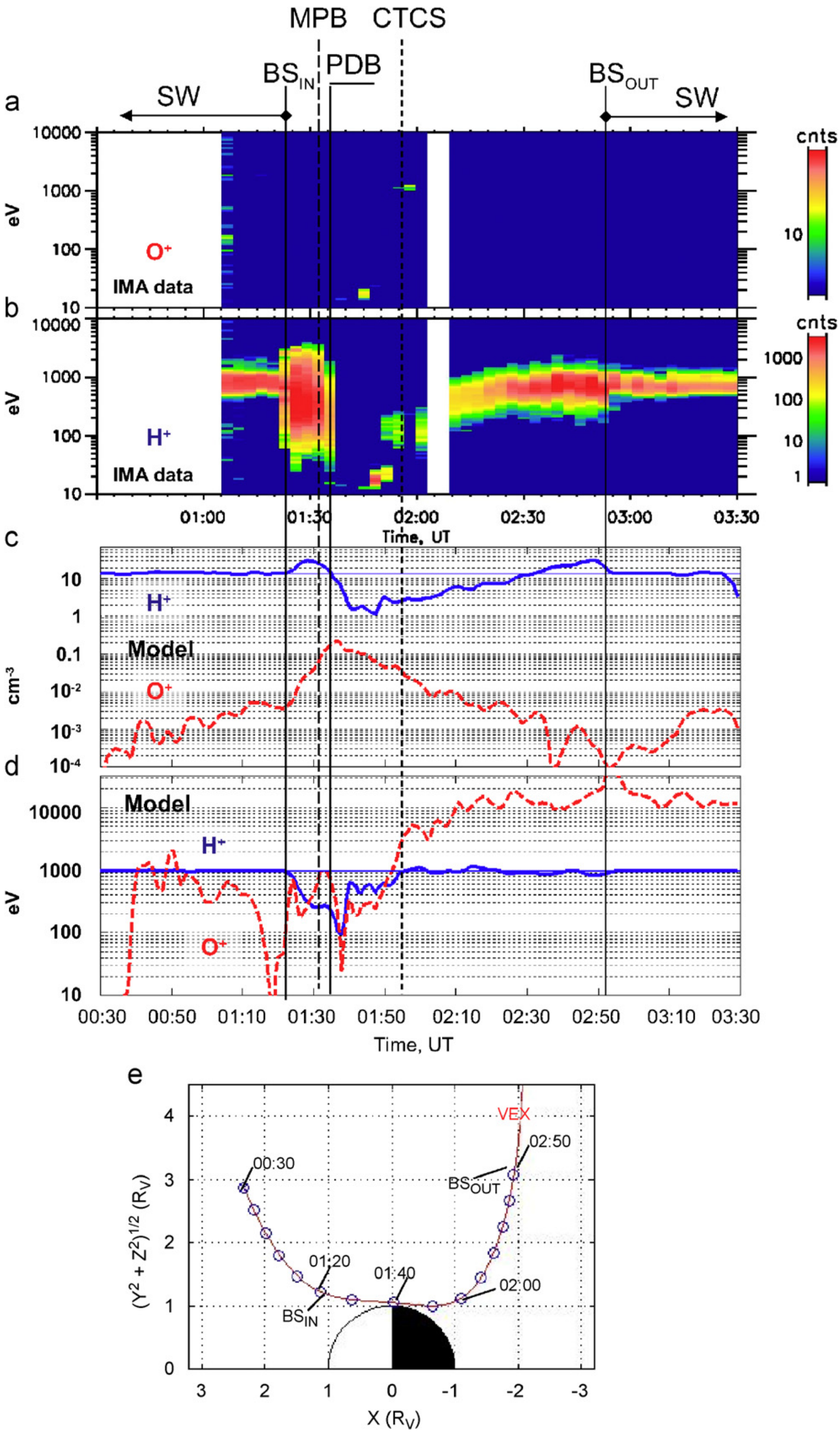

Fig. 1. The observed and simulated plasma parameters on June 1, 2006: (a) IMA observations of planetary O^+ ions; (b) solar wind H^+ ions; (c and d) the density and the bulk energy of H^+ and O^+ ions based on the hybrid model; (e) the orbit of VEX in axially symmetric coordinates. The solid line shows the orbit of VEX at 00:30–03:30 UT and the circles give the location of VEX at 10-min time intervals between 00:30 and 02:50 UT. Marked are the solar wind (SW), the bow shock (BS), the magnetic pile up boundary (MPB), the proton dropout boundary (PDB) and the cross-tail current sheet (CTCS); see text.

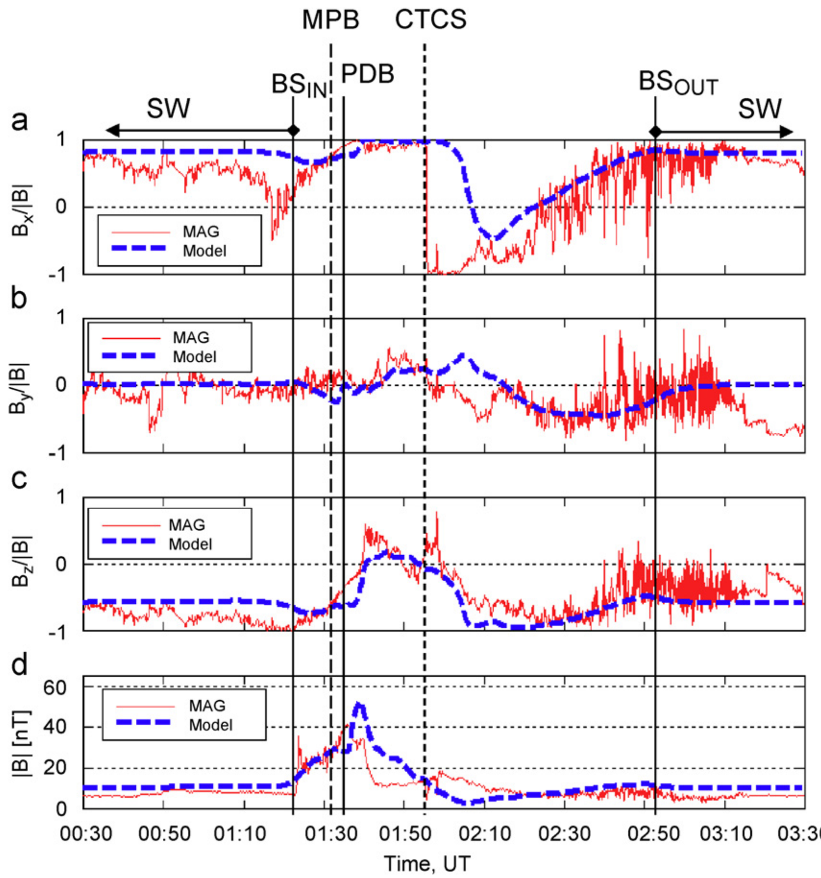

Fig. 2. Comparison of the direction of the magnetic field components based on magnetic field measurements from June 1, 2006 (solid lines) and the hybrid model (dashed lines). Magnetic field data is 8-s averaged data with a 4-s sliding window. The panels from top to bottom are the normalized x-, y-, z-components, and the total magnetic field. Marked boundaries are the same as in Fig. 1.

(Fig. 1a). Finally, VEX moved from the magnetosheath back into the solar wind at ~02:50 UT.

The analyzed orbit makes it possible to study escaping O^+ ions in detail close to but not within the optical shadow of Venus (Fig. 1e). A characteristic of the IMA data was that, in the orbit analyzed, low-energy planetary ions were commonly detected close to pericenter (about 01:40 UT). As can be seen in Fig. 1c, the pericenter region is a location where the simulated density of planetary ions is anticipated to attain a maximum along the orbit of VEX.

After pericenter, the simulated density started to decrease and the simulated bulk energy of oxygen ions to increase (Fig. 1d). The simulation suggests that the IMA could have recorded high-speed escaping O^+ ions at UT > 01:50, had the sensitivity of the instrument been higher than it was and had the instrument field of view pointed into the direction of the escaping ions.

Magnetometer measurements and the simulated magnetic field components are shown in Fig. 2 in VSO coordinates. In this study, one of the main objectives is to study the morphology of the magnetic field. Accuracy in the determination of the magnetic field lines depends on how well the model reproduces the magnetic field direction. Therefore, in Fig. 2a–c, a comparison between the data and the model is made by comparing the normalized magnetic field components.

One can identify several regions in the data presented in Fig. 2. First, the fluctuations in $B_x/|\mathbf{B}|$, in $B_z/|\mathbf{B}|$ and in $|\mathbf{B}|$ decrease noticeably at ~01:30 UT. This location is labeled as the MPB because the decrease of fluctuations has been defined to be a characteristic feature at the MPB crossing (see, for example, Bertucci et al. (2005)). Second, the proton dropout boundary (PDB) is located near the region where the magnetic field is at its maximum. Third, $B_x/|\mathbf{B}|$ changes its sign very suddenly at the location marked as the cross-tail current sheet (CTCS) where it becomes negative between 02:00 and 02:25 UT. Fourth, B_z is positive at UT ~01:40–02:00 UT.

The power of a three-dimensional model in aiding the interpretation of the observations lies in that it can be used to derive a global view of the solar wind–Venus interaction based on *in situ* measurements. Fig. 3 displays the magnetic field lines and B_x based on the hybrid model. According to the model, VEX was at the beginning of the pass in the solar wind. Later, when VEX was in the magnetosheath, it was on draped magnetic field lines which were connected to the solar wind on the dayside and to the magnetosheath on the nightside. Near the pericenter, VEX was connected to the highly draped field lines which form the magnetic tail lobes on the nightside and point almost along the x-axis. Near the pericenter, B_z changes its sign from negative to

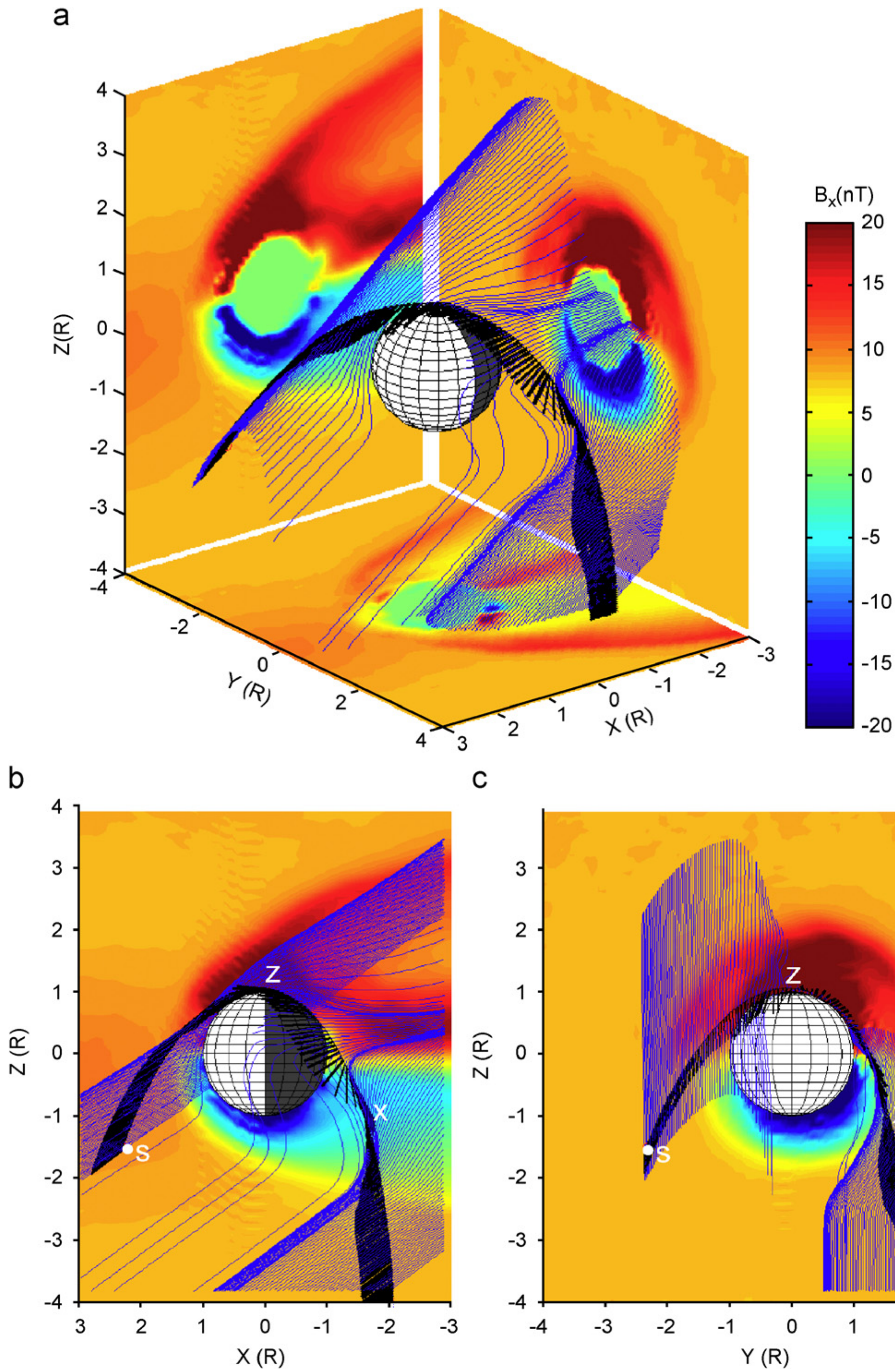

Fig. 3. The morphology of the magnetic field lines (blue lines) based on a hybrid model run viewed in three-dimensional (a), along the y-axis (b) and along the x-axis (c). The magnetic field line tracing was started along the orbit of VEX on June 1, 2006. The black solid line shows the orbit of VEX and the vectors superposed on the orbit show the direction of B at every 1 min based on the model. The color on the three perpendicular planes show the model B_x component at $x = y = z = 0$ planes which are moved to $x = -3R_V$, $y = -4R_V$ and $z = -4R_V$ so that they do not hide the field lines. The letter "S" shows the starting point when VEX was in the solar wind and approaching Venus, the point near the terminator plane (i.e., the $x = 0$ plane) where B_z changes the sign is marked by "Z", and the position where B_x changes its sign from positive to negative is marked by "X".

positive. A change in the direction of B_x is associated with a "knee-shape" in the field line on the $y>0$ hemisphere.

It is finally worth noting that a decrease in the fluctuations that started at the MPB is associated with an increase of B_x and a change in B_z from negative to zero (see Fig. 2). The draping of the magnetic field lines seen in Fig. 3 suggests that VEX had, by then, moved from the magnetosheath to the region that was magnetically connected to the magnetic tail lobes where the magnetic field lines are almost along the x-axis.

4. Discussion and summary

This paper presents a study of VEX plasma and magnetic field observations. A comparison made between the data and a simulation was based on a previously documented and analyzed run for which the IMF approximately matched the measured values of the IMF in the analyzed orbit. The comparison made between MAG data and the simulated magnetic field shown in Fig. 2 suggests that several of the observed features in the data can be understood as signatures of the magnetic field line draping around the planet depicted in Fig. 3.

The Venusian magnetosheath can be a highly fluctuating area resulting from, for example, downstream convection of foreshock waves (Luhmann et al., 1983). At Venus and Mars, fluctuations have been observed to decrease near the planet and the decrease observed on PVO was suggested to result from the spacecraft moving from the magnetosheath to the region connected to the magnetotail lobes (see Saunders and Russell, 1986; Bertucci et al., 2005). Although the detailed analysis of the properties of the MPB is beyond the scope of this initial study, it is worth noting that one possible reason for the quiet magnetic barrier region is that much of the noise in the sheath is slow mode and Alfvénic modes that travel mainly along the magnetic field, and that the high fast-mode speed in the magnetic barrier means that there the waves have small amplitudes for equal Poynting flux. That situation may be the case in the orbit analyzed here, where the global model suggests VEX moved from the region that is magnetically connected to the fluctuating magnetosheath field to the less fluctuating region which is magnetically connected to the induced magnetotail lobes.

References

Barabash, S., et al., 2007. The Analyzer of Space Plasmas and Energetic Atoms (ASPERA-4) for the Venus Express Mission. Planet. Space Sci. 55 (12), 1772–1792.

Bertucci, C., Mazelle, C., Acuña, M.H., Russell, C.T., Slavin, J.A., 2005. Structure of the magnetic pileup boundary at Mars and Venus. J. Geophys. Res. 110.

Kallio, E., Jarvinen, R., Janhunen, P., 2006. Venus–solar wind interaction: asymmetries and the escape of O^+ ions. Planet. Space Sci. 54 (13–14), 1472–1481.

Luhmann, J.G., Tatrallyay, M., Russell, C.T., Winterhalter, D., 1983. Magnetic field fluctuations in the Venus magnetosheath. Geophys. Res. Lett. 10, 655–658.

Saunders, M.A., Russell, C.T., 1986. Average dimensions and magnetic structure of the distant Venus magnetotail. J. Geophys. Res. 91, 5589–5604.

Zhang, T.L., et al., 2006. Magnetic field investigation of the Venus plasma environment: expected new results from Venus Express. Planet. Space Sci. 54, 13–14.