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Variations and Effects of the Venusian Bow Shock from VEX Mission

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Abstract. The upper atmosphere of Venus is not shielded by planetary magnetic field from direct interaction with the solar wind. The interaction of shocked solar wind and the ionosphere results in ionopause. Magnetic barrier, the inner region of dayside magnetosheath with the dominated magnetic pressure deflects the solar wind instead of the ionopause at solar maximum. Therefore, the structure and interaction of venusian ionosphere is very complex. Although the Venus Express (VEX) arrived at Venus in April 2006 provides more knowledge on the Venusian ionosphere and plasma environment, compared to Pioneer Venus Orbiter (PVO) with about 14 years of observations, some important details are still unknown (e.g., long Venusian bow shock variations and effects). In this paper, the bow shock positions of Venus are determined and analyzed from magnetometer (MAG) and ASPERA-4 of the Venus Express mission from May 28, 2006 to August 17, 2010. Results show that the altitude of BS was mainly affected by SZA (solar zenith angle) and Venus bow shocks inbound and outbound are asymmetry.

Keywords. Venus, Bow shock, Magnetic field, Venus Express

1. Introduction

Venus has a dense atmosphere without intrinsic magnetic field, so the solar wind interacts directly with its upper atmosphere. A Bow shock is caused by the deflection of the oncoming supersonic solar wind around the planet in the highly conductive ionosphere. The interaction of post-shock solar wind flow and the ionosphere results in a distinct boundary, which is called ionopause. This ionopause separates the thermal plasma of the ionosphere from the hot magnetized plasma of the magnetosheath. The Pioneer Venus Orbiter (PVO) mission (from 1978 to 1992) provided a data set to research the solar wind interaction with Venus over a complete solar cycle (Russell *et al.* 2006).

The bow shock of Venus is originally identified using data from the PVO magnetometer and plasma analyzer. In comparison with the magnetometer (MAG) and the plasma analyzer (ASPERA-4) on board of Venus Express (VEX) spacecraft, however, the resolution of the PVO instruments is lower. Using VEX, the location of Venus bow shock can be accurately retrieved, which also fill the gaps in the PVO observations and extend our knowledge of the plasma environment of Venus. Based on nearly 2000 PVO shock crossings, Russell *et al.* 1988) and Zhang *et al.* 1990) examined the Venus bow shock and found that the Venus bow shock location was influenced by the solar cycle and solar EUV flux, the upstream solar wind parameters and the orientation of the interplanetary magnetic field (IMF) (Phillips & McComas. 1991, Russell *et al.* 2006). Furthermore, a simple conic section was used to model the bow shock focusing the center of the planet based on PVO data. In this study we determined the locations of the Venus bow shock using magnetic and particle measurements obtained by magnetometer (MAG) and electron spectrometer (ELS), and the variations of Venus bow shock are analyzed with a long observations.

2. Observations and results

The data used in this paper were provided by the MAG and ASPERA-4 on board the VEX spacecraft. VEX spacecraft has a polar orbit of 90 inclination, a low periapsis altitude from 250 km to 350 km at 80N and a 24-h period orbit (Titov *et al.* 2006). The magnetometer measures the magnetic field continuously along the orbit in various modes (Zhang *et al.* 2007). The data used in this study are 1 Hz resolution (CODMAC level 3) in Venus Solar Orbital (VSO) coordinates where the x-axis is pointing to the solar direction, i.e. on the line Venus-Sun and positive towards the Sun, the y-axis is perpendicular to the x-axis, but positive in direction of negative orbital velocity of Venus, and the z-axis completes the right hand system (i.e. northward). ASPERA-4 consists of an electron spectrometer, an ion spectrometer and two neutral particle sensors (Barabash *et al.* 2007). Here, we only utilize data from the electron spectrometer. The electron spectrometer (ELS) is a standard top-hat electrostatic analyzer which is located on a scanning platform providing 4π coverage (maximum possible).

The bow shock is a shock front which is formed when the supersonic solar wind plasma encounters the obstruction, which engenders strong heating of particles due to the conversion of kinetic to thermal energy. From the results of VEX measurements, there has seen a sudden increase in Magnetic field intensity and electron counts over a large energy range (Fig. 1). The dayside bow shock is clearly visible by the sudden increase in magnetic field amplitude as well as in the electron counts at 03:42. As the solar wind plasma flow, including the electrons, is transported around the planet, the electron count rates gradually decrease as VEX approaches the planet.

The spacecraft enters into the magnetic barrier, which can be recognized in the MAG measurements by the sudden decrease in magneto sheath wave activity (Zhang *et al.* 2008). In Fig 1 the magnetopause is first crossed at 04:13, where the oscillations in the magnetic field amplitude suddenly decrease. The outbound crossing of the magnetopause

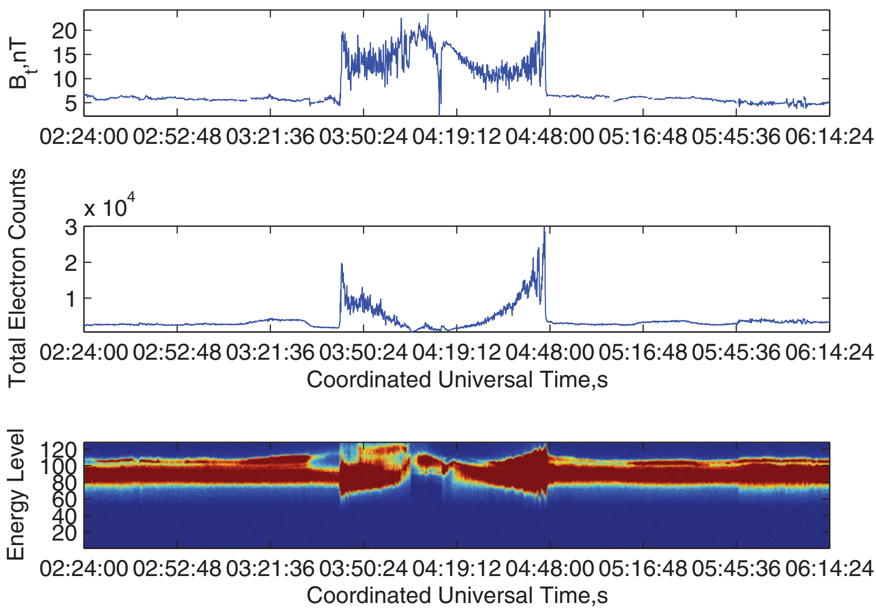

Figure 1. The bow shock locations from MAG total field strength (top panel). ELS total electron counts (middle panel) and ELS electron spectrum (lower panel).

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Table 1. a and b values in each year.

	2006	**2007**	**2008**	**2009**	**2010**
a(incross)	438.05	403.45	353.68	297.15	283.21
b(incross)	0.031	0.0313	0.0313	0.0319	0.0315
a(outcross)	267.95	288.46	315.28	311.51	374.64
b(outcross)	0.0311	0.0309	0.0311	0.0321	0.0311

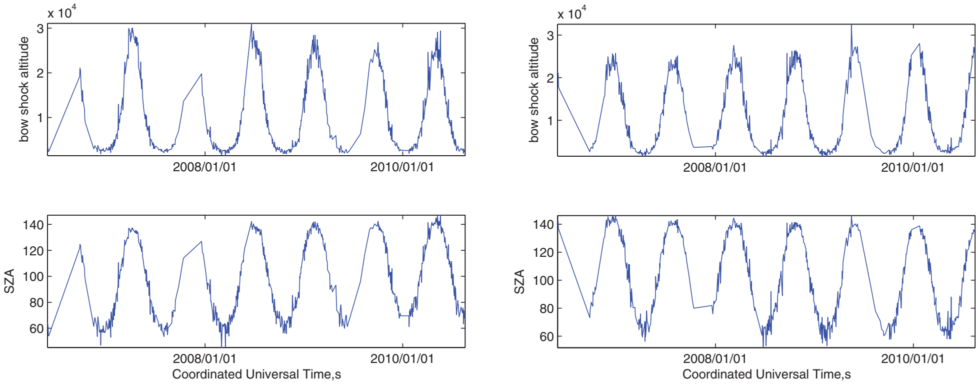

Figure 2. Trends of bow shock altitude and SZA. (left: inbound; right: outbound)

takes place at 04:19, where the higher energy electron counts and the magneto sheath wave activity increased again. The nightside bow shock can be observed around 04:48.

From May 28, 2006 to August 17, 2010, 1375 Venusian bow shock crossings (688 inbound, 687 outbound) were derived from the MAG and ELS data. On some orbits the bow shock is difficult to identify because of disturbance in foreshock. Fig 2 shows the time series of bow shock altitude from 2006 to 2010. As shown in this figure, the altitude of bow shock was mainly affected by SZA (solar zenith angle).

Further analysis indicated that the altitude of bow shock and solar zenith angle meet an exponential relationship. The altitude of bow shock and solar zenith angle can expressed as

$$y = a\, e^{(b * \mathrm{SZA})} \tag{2.1}$$

where y is the observed altitude of Venus bow shock, SZA is solar zenith angle, a is the change of BS altitude, and b is almost constant. The values of a and b for separate years are presented in Table 1.

The analysis of the results shows that bow shock altitude was generally stable, but still had obvious variations in the last time sequence. The contrary trend between inbound and outbound indicated the space asymmetry in Venus bow shock. See the 3D Bow Shock surface fitting (Fig. 3) demonstrating this asymmetry.

3. Discussion and conclusions

The bow shock is mainly determined by the size of the obstructive planet, but also reflecting how the obstacle deflects the solar wind completely. Venus and Earth have similar sizes, but due to the lack of an intrinsic magnetic field on Venus, the interaction

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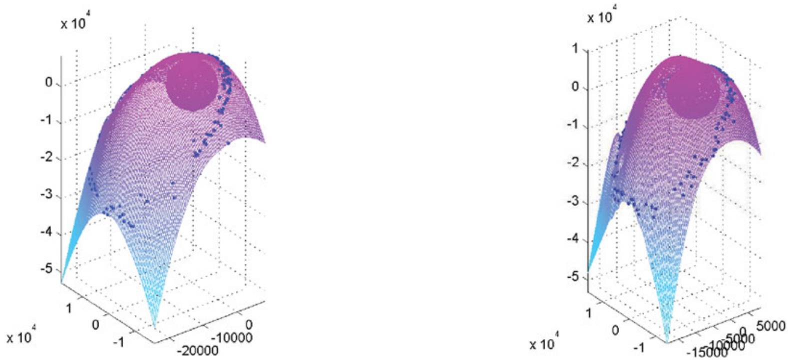

Figure 3. 3D Venus bow shock (Mesh surfaces) fits in 2007. (left: inbound; right: outbound)

of the solar wind with Venus is quite different from the Earth. The Venus bow shock was well studied by PVO over a solar cycle. However, because of the orbital bias of PVO, the subsolar bow shock locations are not well-determined. The orbit of Venus Express is more suitable to study the subsolar bow shock than that of PVO. In this paper we determined the positions of the Venusian bow shock based on MAG and ASPERA-4 observations on board the Venus Express spacecraft. The locations and variations of bow shocks are analyzed and studied from May 28, 2006 to August 17, 2010. It was found that the altitudes of bow shocks were mainly affected by SZA (solar zenith angle) and Venus bow shocks inbound and outbound are asymmetry.

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