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Key Points:

- We observe the transmission of ULF waves from upstream to downstream
- The waves have the similar characteristics in both the upstream and downstream
- They have a large compressibility we conclude that these are magnetosonic waves

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Transmission of large-amplitude ULF waves through a quasi-parallel shock at Venus

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Abstract There exist large-amplitude ultralow frequency (ULF) waves in the upstream region of a quasi-parallel shock, which are excited due to the reflected ions by the shock. These waves are then brought back to the shock by the solar wind, and at last they coalesce and merge with the shock. In this paper, with the magnetic field measurements from Venus Express, for the first time we observe the transmission of large-amplitude ULF waves from the upstream region to the downstream under quasi-parallel shock conditions. These waves exist in both the upstream and downstream regions of the Venusian bow shock, which have the similar characteristics: their peak frequencies are 0.04–0.05 Hz in the spacecraft frame, their propagation angles do not change greatly, they have left-hand polarization with respect to the mean magnetic field in the spacecraft frame, and they also have a large compressibility. We conclude that they are magnetosonic waves. The generation mechanism of such waves at the Venusian bow shock is also discussed in the paper.

1. Introduction

A planetary bow shock is formed due to the interaction between the high-speed solar wind and the magnetosphere/ionosphere of a planet. A fast magnetosonic bow shock and its foreshock are significant features of a planet to the high-speed solar wind flow. The shock is an irreversible energy dissipation process, during which waves play an important role [*Leroy et al*., 1982; *Sckopke et al*., 1983; *Burgess et al*., 1989; *Wilson et al*., 2007; *Su et al*., 2012].

Due to the lack of an intrinsic planetary magnetic field, the interactions between the solar wind and the Venusian ionosphere have some special characteristics [*Lu et al*., 2013]. Although the radius of Venus is similar to the Earth, the size of the Venusian bow shock is less than 1/10 of the Earth's bow shock [*Slavin et al*., 1979]. The observations of Pioneer Venus Orbiter showed that the altitude of the subsolar bow shock is about 0.3 R_V (1 R_V = 6051 km, is the radius of Venus) [*Zhang et al*., 1990] while it is about 14 R_E at the Earth. At the same time, in consideration of the small distance in dimension between the Venusian bow shock and the ionopause or induced magnetosphere, the neutral particles are easily leaked from the ionosphere and then ionized [*Luhmann et al*., 1987]. Therefore, both the foreshock and magnetosheath of the Venusian bow shock have different characteristics from those of the Earth.

Numerous studies have revealed an abundance of wave activities or structures in the vicinity of the Venusian bow shock. *Hoppe and Russell* [1981] observed 1 Hz wave packets in the upstream region of the Venusian bow shock, and such waves were also identified in the upstream regions of the bow shocks at other solar system bodies [*Fairfield*, 1974; *Orlowski et al*., 1990, 1992; *Brain et al*., 2002; *Le et al*., 2013]. Another wave phenomena detected at the upstream region of the Venusian bow shock is proton cyclotron waves [*Delva et al*., 2008]. The waves propagate nearly (anti)parallel to the background magnetic field at a frequency just below the local proton cyclotron frequency, which are considered to be excited by the newly ionized particles escaped from the Venusian exosphere. A ring beam distribution is assumed to be formed for these pickup ions, and proton cyclotron waves are excited by the free energy associated with such a distribution [*Wu and Davidson*, 1972; *Lu and Wang*, 2006]. Proton cyclotron waves have also been observed at the upstream region of the Martian bow shock [*Russell et al*., 1990; *Brain et al*., 2002; *Mazelle et al*., 2004; *Wei et al*., 2011], and the ring beam distribution of pickup protons in the extended hydrogen corona of Mars has been verified by *Barabash et al*. [1991] with Phobos observations. On the basis of observations from Venus Express (VEX), *Collinson et al*. [2012] reported short large-amplitude magnetic structures (SLAMS) in the foreshock of the Venusian bow shock, which are ~1.5–11 s in duration and have magnetic compression ratios between ~3 and 6. SLAMS were believed to steepen out of the large-amplitude ultralow frequency (ULF) waves in the upstream region of a quasi-parallel shock after they interact with diffuse ions, which had been observed at Earth, Jupiter, and comet Giacobini-Zinner [*Schwartz et al*., 1992; *Tsurutani et al*., 1990, 1993]. The ULF waves are suggested to be commonly associated with backstreaming ion distributions in the foreshock of a quasi-parallel shock [*Paschmann et al*., 1979; *Hoppe et al*., 1981; *Thomsen et al*., 1985]. They attempt to propagate upstream; however, they are convected back toward the bow shock by the high-speed solar wind. Then, SLAMS grow out of these ULF waves when they are approaching the shock [*Schwartz et al*., 1992; *Scholer and Burgess*, 1992; *Tsubouchi and Lembège*, 2004; *Wilson et al*., 2009; *Su et al*., 2012]. The nonlinear quadratic and cubic processes were found to play an important role during the evolution of SLAMS [*Coca et al*., 2001; *Zhu et al*., 2008].

There are also plenty of waves in the downstream region of the Venusian bow shock. Proton cyclotron waves [*Russell et al*., 2006; *Du et al*., 2009, 2010], as well as mirror-mode-like structures [*Volwerk et al*., 2008], have been observed in the Venusian magnetosheath under quasi-perpendicular bow shock conditions. In the downstream region of a quasi-parallel shock, the magnetic fluctuations in the magnetosheath become more intense [*Luhmann et al*., 1986; *Du et al*., 2009, 2010], and the most likely source of these waves comes from the shock itself. Another important magnetic structure in the Venusian magnetosheath is the vortices observed by Venus Express (VEX), which are generated by the Kelvin-Helmholtz instability [*Pope et al*., 2009]. Due to the lack of an intrinsic magnetic field at Venus, there is a direct contact between the fast-flowing solar wind and the Venusian ionosphere, and the velocity shear between the solar wind and the ions of ionopause is easy to be formed. The Kelvin-Helmholz instability then grows in the Venusian magnetosheath [*Pope et al*., 2009; *Walker et al*., 2011], especially near the terminator region [*Biernat et al*., 2007]. VEX has also observed coherent oscillations behind a quasi-perpendicular shock under the conditions with low Mach number and low β [*Balikhin et al*., 2008], which are caused by the spatial pressure variations due to gyrations of the directly transmitted ions downstream of the ramp [*Balikhin et al*., 2008; *Ofman et al*., 2009].

In these previous studies, the wave characteristics at the Venusian bow shock are analyzed at either the upstream or the downstream region. Although *Luhmann et al*. [1986] indicated that the intense magnetic fluctuations in the downstream region of a quasi-parallel shock came from the shock itself, as we have known, the relations of the waves in the downstream and upstream regions have not been directly analyzed. In this paper, based on the measurement of the magnetic field from VEX, for the first time we reveal the existence of large-amplitude ULF waves at a quasi-parallel shock, and these waves can transmit the shock directly while keeping the wave characteristics, such as the frequency, propagating angle, and polarization. We first present two case studies, indicating that the large-amplitude ULF waves can transmit a quasi-parallel shock, and then the generation mechanism of such kind of waves is discussed.

2. Observations

VEX has an elliptical polar orbit with the periapsis 250–300 km altitude. During a 24 h period orbit, the spacecraft encounters the inbound and outbound shock crossings [*Barabash et al*., 2007]. The orbit covers large range of solar zenith angle of the Venusian bow shocks, which make it possible for the studying of subsolar bow shocks from valid measurements. The Venus Express magnetometer (VEX MAG) consists of two fluxgate sensors for a separation of magnetic effects of the spacecraft origin from the ambient space magnetic field [*Zhang et al*., 2006].

2.1. Observations on 8 April 2011

The 15 min magnetic field data accompanied with large-amplitude ULF waves are obtained from VEX on 8 April 2011. In Figure 1, the measurements sampled at 1 Hz are displayed in the Venus Solar Orbital (VSO) coordinates. During the crossing from the upstream to the downstream of the Venusian bow shock, the average magnetic field changes from ~11 nT to ~25 nT. It is clear that VEX begins to encounter the shock at ~03:11:00 UT around (1.31, −0.14, 0.46) R_V which is near the subsolar bow shock. Large-amplitude ULF waves are obviously observed in both the upstream and downstream regions with the peak-to-peak $\delta B/B$ ~0.3–3.1. According to minimum variance analysis (MVA) method [*Sonnerup and Cahill*, 1967], the shock angle θ_{Bn} (the angle between the interplanetary magnetic field and the shock normal) can be calculated with the magnetic field during the interval from 03:10:00 UT to 03:13:00 UT, which is 29°, while it is 18° and 37° when the shock angle is calculated with magnetic coplanarity and the Venusian bow shock model [*Zhang et al*., 2008; *Shan*

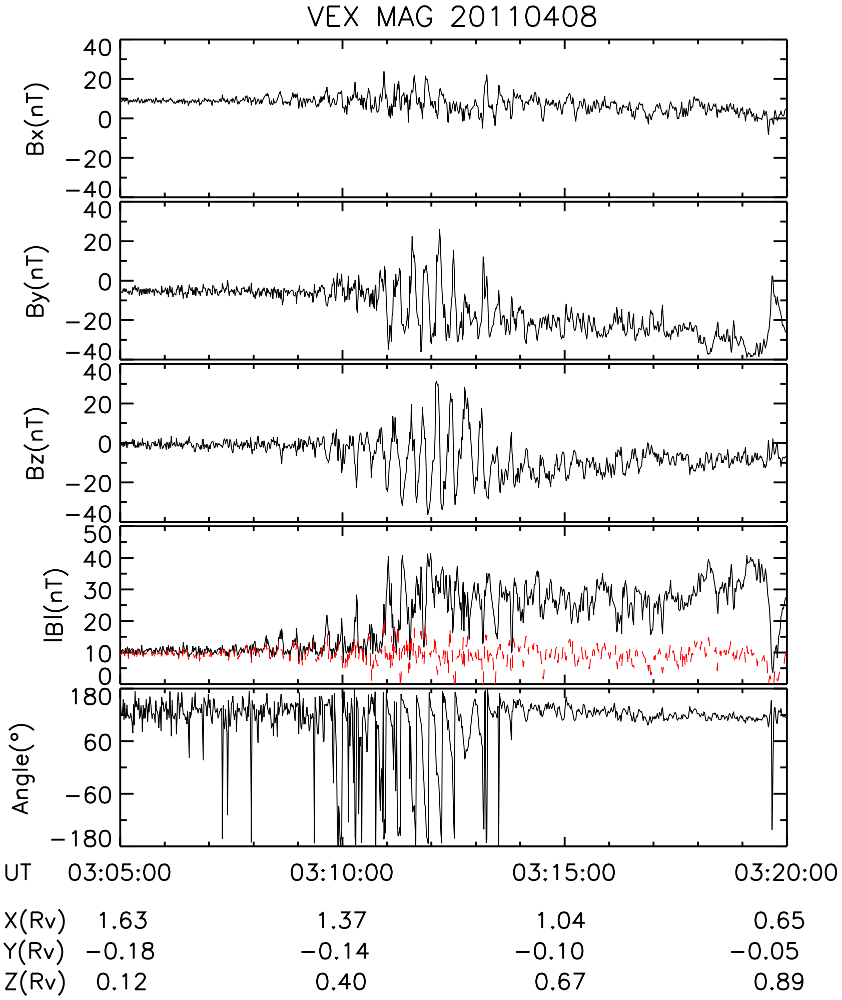

Figure 1. Three components of the magnetic field in VSO coordinates on 8 April 2011. The magnetic field data have 1 Hz time resolution. In the fourth panel, the solid line represents the total magnetic field in VSO coordinates, while the red dashed line is the projection of the magnetic field on the shock normal direction determined with the MVA method. The azimuthal angle of the magnetic field in the plane perpendicular to the minimum variance direction is shown in the fifth panel.

et al., 2013], respectively. Obviously, it is a quasi-parallel shock. A low-pass filter is utilized before we calculate the shock normal. In Figure 1 (fourth panel), we also plot the projection of the magnetic field on the shock normal determined with the MVA method, and values in the upstream are approximately equal to those in the downstream, which validates the identified shock normal. In Figure 1 (fifth panel), we show the azimuthal angle of the magnetic field in the plane perpendicular to the minimum variance direction. Here in order to reduce the disturbance from the shock structure, we select the downstream period from 03:11:50 to 03:13:20 UT to determine the variance reference frame. Then, the data between 03:05:00 and 03:20:00 is transferred into the variance reference frame, and the azimuthal angle is calculated. The ratios of the maximum to intermediate and intermediate to minimum eigenvalues are 1.8 and 15.5, respectively, and it demonstrates that the analysis process is reliable. In Figure 1 (fifth panel), the angle changes from 180° to −180° monotonously, and then a jump is followed, which indicates the elliptical polarization of the waves. It is obvious that the amplitude decreases as the waves propagate to the farther distance from the shock in the magnetosheath. Moreover, the waves disappear at ~03:15:00 UT while the satellite reaches the ionopause at ~03:19:30 UT.

Figure 2 shows the power spectrum of the ULF waves in the upstream (03:06:30–03:10:40 UT) and downstream (03:12:20–03:16:30 UT) regions on 8 April 2011, separated by the transverse (red) and compressional (black) power, respectively. In Figure 2, the blue dashed lines represent the local proton cyclotron frequency $f_{cp} = qB/(2\pi m_p)$, where B, q, and m_p are the magnetic field, charge, and mass of the proton. The peak frequency of the

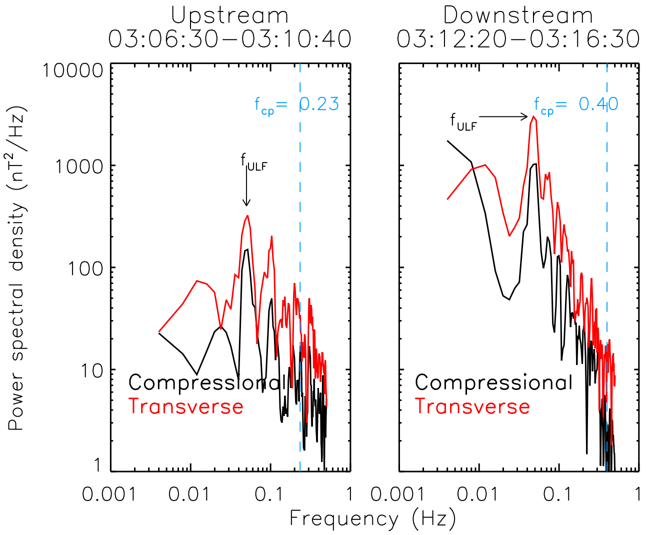

Figure 2. The power spectrum of the ULF waves upstream and downstream of the Venusian bow shock on 8 April 2011, separated in transverse and compressional power, respectively.

ULF waves (the waves have the maximum amplitude at this frequency) is f_{ULF}. Obviously, the transverse component dominates the power spectrum. The peak frequency of the upstream waves is almost the same as that of the downstream waves, which is about 0.05 Hz. In order to investigate the quasi-monochromatic ULF waves in more detail, the principal axis analysis [*Rankin and Kurtz*, 1970; *McPherron et al.*, 1972] is used to determine the characteristics of the ULF waves upstream and downstream of the shock. Figure 3 displays the hodograms of the wave magnetic field in the principal axis coordinates (B_i, B_j, and B_k) during the intervals 03:09:50–03:10:40 (upstream) and 03:13:00–03:13:50 UT (downstream) on 8 April 2011, respectively, where $\boldsymbol{k}$ is the computed propagation direction of the waves, and it may be parallel or antiparallel to the wave vector. In the left boxes, the mean magnetic field points out to the plane; therefore, the waves exhibit left-hand elliptical polarization with respect to the mean magnetic field in the spacecraft frame. The propagation angle θ_{kB} (the angle between $\boldsymbol{k}$ and the mean magnetic field) and ellipticity ε can be calculated with the quadrature power spectral matrix analysis method [*Means*, 1972; *Song and Russell*, 1999]. In the upstream and the downstream regions of the

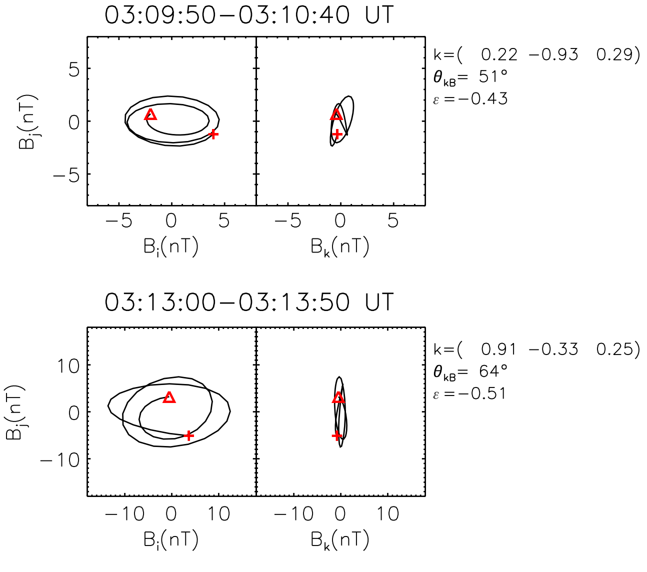

Figure 3. The hodograms of the wave magnetic field in the principal axis coordinates (B_i, B_j, and B_k) during the intervals 03:09:50–03:10:40 (upstream) and 03:13:00–03:13:50 (downstream) on 8 April 2011, respectively, where $\boldsymbol{k}$ is the computed propagation direction of the waves and it may be parallel or antiparallel to the wave vector. In the figure, "plus" and "triangle" are the beginning and end of the interval.

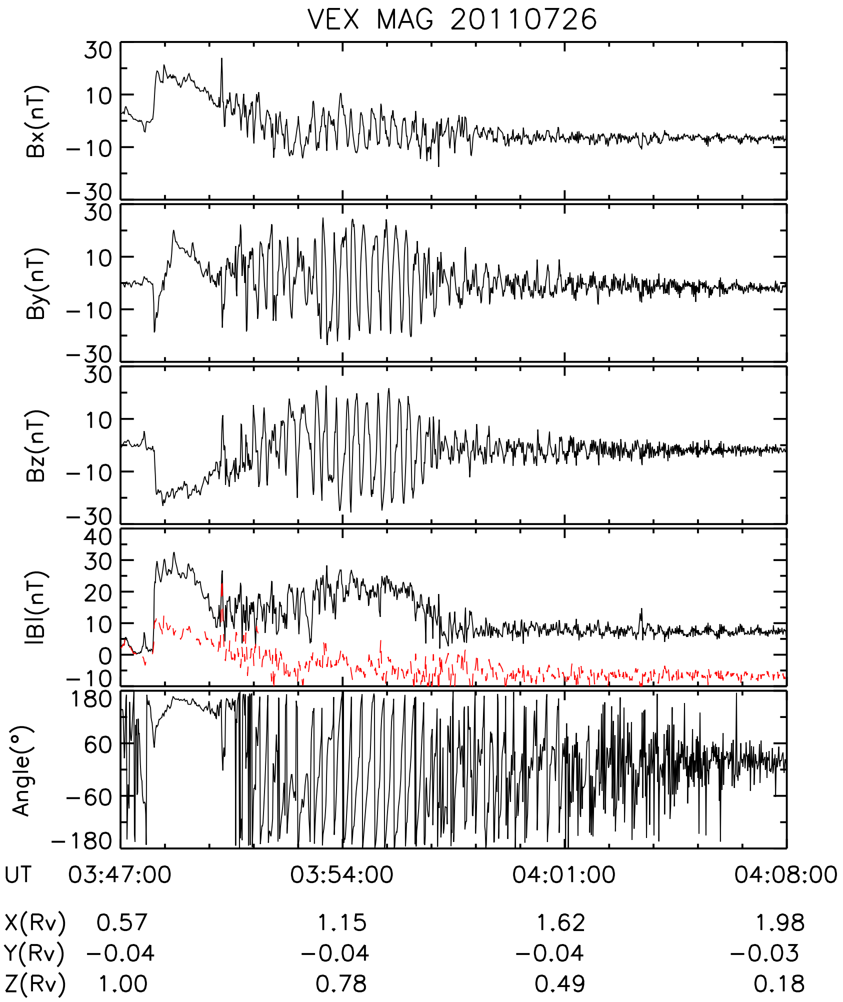

Figure 4. Same as Figure 1 but for observations on 26 July 2011.

shock, θ_{kB} is about 51° and 64°, while ε is -0.43 and -0.51, respectively. The minus sign of ε means that the waves are left-hand polarized with respect to the mean magnetic field, while the plus sign is for right-hand polarization. Therefore, the waves exhibit left-hand polarization with respect to the mean magnetic field in the spacecraft frame. However, these waves are propagating in the high-speed solar wind, and they may have right-hand polarization in the plasma frame due to the Doppler shift [*Hoppe and Russell*, 1983; *Mazelle et al.*, 2003].

2.2. Observations on 26 July 2011

The similar large-amplitude waves are also identified on 26 July 2011. The 21 min magnetic field components and the azimuthal angle are displayed in Figure 4. Obviously, VEX is on the outbound crossing of its trajectory, and it detects the ionopause at ~03:48:00 UT and enters the upstream region of the shock at ~03:57:20 UT around (1.38, -0.04, 0.66) R_V. The shock angle θ_{Bn} is 10°, 28°, and 4° determined by MVA (based on the interval from 03:55:00 UT to 03:58:00 UT), magnetic coplanarity, and the Venusian bow shock model, respectively, suggesting that it is a quasi-parallel shock. It is noted that the large-amplitude waves are observed in the upstream region between 03:57:20 and 04:08:00 UT, corresponding to the position from (1.38, -0.04, 0.66) to (1.98, -0.03, 0.18) R_V. The ULF waves have peak-to-peak $\delta B/B$ ~0.2–2.7. The downstream measurements during the period of 03:53:00–03:55:00 UT are selected to determine the azimuthal angle of the magnetic field in the plane perpendicular to the minimum variance direction. The analysis is valid because the ratios of the maximum to intermediate and intermediate to minimum eigenvalues are 1.1 and 30.5, respectively. For the azimuthal angle, we can obviously observe a monotonous change from 180° to $-180°$, and then a jump is followed, which indicates the elliptical polarization of the waves.

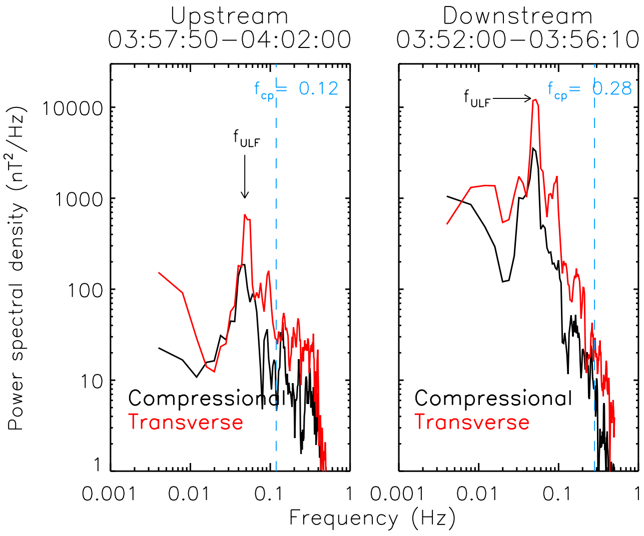

Figure 5. Same as Figure 2 but for observations on 26 July 2011.

Figure 5 shows the power spectrum of the large-amplitude waves on 26 July 2011. The peak frequency of the upstream waves, ~0.05 Hz in the spacecraft frame, is similar to that observed on the downstream side of the shock. Therefore, it is shown that the quasi-monochromatic waves are possible generated at the upstream region of the shock and then convected into downstream by high-speed solar wind. The hodograms of the wave magnetic field upstream (04:00:10–04:01:00 UT) and downstream (03:55:20–03:56:10 UT) of the shock are displayed in Figure 6. The average magnetic field points out to the plane in the left boxes. Hence, the waves exhibit left-hand elliptical polarization with respect to the mean magnetic field in the spacecraft frame. The propagation angle θ_{kB} varies from 31° (upstream) to 41° (downstream), and the ellipticity ε is -0.55 and -0.90, respectively.

3. Conclusions and Discussion

This paper presents the observations of the transmission of large-amplitude ULF waves from the upstream region into the downstream region under the quasi-parallel shock conditions in the vicinity of the Venusian bow shock. Two events, on 8 April 2011 and 26 July 2011, are analyzed in detail. By examining the magnetic field data

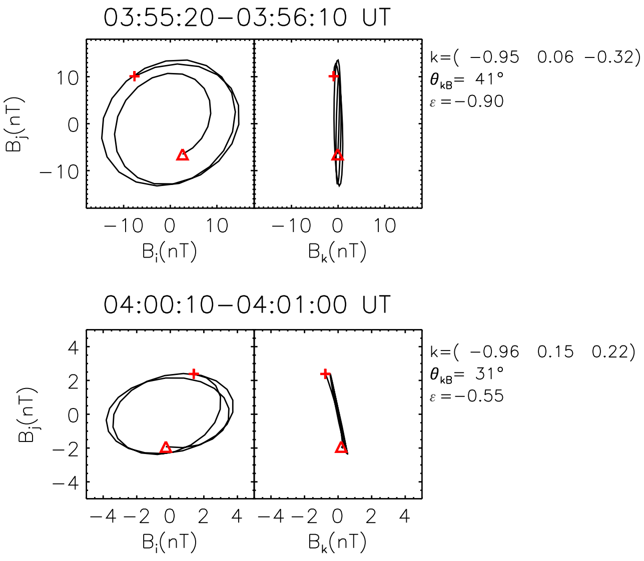

Figure 6. Same as Figure 3 but for observations on 26 July 2011.

Table 1. The Characteristics of the ULF Waves

Time (UT)	θ_{Bn} (deg)	θ_{kB} (deg)		Ellipticity ε		Peak Frequency (Hz)		$\delta B/B$
		Upstream	Downstream	Upstream	Downstream	Upstream	Downstream	
22 Sep 2006 041230–042230	44	42	59	−0.61	−0.46	0.044	0.040	0.5–3.2
27 Nov 2008 090730–091730	18	15	49	−0.75	−0.88	0.042	0.042	0.5–2.4
8 Apr 2011 030630–031630	29	51	64	−0.43	−0.51	0.050	0.050	0.3–3.1
19 May 2011 020000–021000	32	42	41	−0.60	−0.76	0.043	0.047	0.3–2.4
26 July 2011 035200–040200	10	31	41	−0.55	−0.90	0.050	0.054	0.2–2.7

measured by VEX, we find five similar cases, and their characteristics are listed in Table 1. In these cases, the large-amplitude quasi-monochromatic waves exist in both the upstream and the downstream regions of the Venusian bow shock. The characteristics of the downstream waves are similar to that of the upstream waves, except with a larger amplitude, and these characteristics include the following: left-hand polarization with respect to the mean magnetic field in the spacecraft frame, the peak frequency 0.04–0.05 Hz in the spacecraft frame, and the stable propagating angle (except the event on 27 November 2007, the propagating angle changed from 15° in the upstream to 49° in the downstream). We conclude that these waves are magnetosonic waves.

We can rule the vortices and coherent oscillations out of the generation mechanism for these waves. The vortices is formed by Kelvin-Helmholtz instability due to the velocity shear between solar wind and ionospheric ions [*Pope et al*., 2009; *Walker et al*., 2011], and they only exist in the downstream region of the Venusian bow shock. The coherent oscillations are caused by the spatial pressure variations due to gyrations of the directly transmitted ions downstream of the ramp [*Balikhin et al*., 2008; *Ofman et al*., 2009], and they only exist in the downstream region of a quasi-perpendicular shock with low Mach number and low β [*Balikhin et al*., 2008; *Ofman et al*., 2009]. These waves observed in this paper may be excited by the reflected ions by a quasi-parallel shock through electromagnetic ion beam instabilities [*Winske and Gary*, 1986; *Gary*, 1991], and they are then convected toward the shock by the high-speed solar wind. However, these waves will steepen into SLAMS after they interact with diffuse ions. In the paper, we observe large-amplitude ULF waves in both the upstream and downstream regions of the Venusian bow shock under quasi-parallel shock conditions, and they have the similar characteristics. These waves are considered to be able to transmit from the upstream region to the downstream. One possibility is that the size of the Venusian foreshock is much smaller than that of Earth, and the region with diffuse ions is also small. Therefore, the waves do not have enough time to grow into SLAMS when they propagate through the Venusian foreshock.

Luhmann et al. [1983] observed large-amplitude magnetic fluctuations with a period of 10–40 s in the downstream region of a quasi-parallel shock and indicted that the source of these waves was from the upstream region of the shock. Our study shows that the large-amplitude ULF waves in the upstream region can transmit the Venusian bow shock under the quasi-parallel shock conditions, and it gives the direct evidence that the intense downstream waves behind a quasi-parallel shock can be from the upstream region.

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