Venusian bow shock

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Abstract

We statistically investigate the spectral scalings of magnetic fluctuations at the upstream and downstream regions near the Venusian bow shock and perform a differentiation by shock geometry. Based on the Venus Express data, 115 quasi-parallel ($Q_{\parallel}$) bow shock crossings and 303 quasi-perpendicular ($Q_{\perp}$) bow shock crossings are selected. The statistical results suggest that the bow shock tends to modify the upstream spectra flatter to 1/f noise in the magnetohydrodynamics (MHD) regime and steeper to turbulence in the kinetic regime after the magnetic fluctuations crossing the bow shock, and this modification for the $Q_{\parallel}$ and $Q_{\perp}$ bow shock is basically consistent. While the upstream spectral scalings are associated with the shock geometry. The changes of the spectral scalings of magnetic fluctuations near the $Q_{\parallel}$ bow shocks are not as significant as near the $Q_{\perp}$ bow shock crossings. That might result from the fluctuations generated by the backstreaming ions which can escape across the $Q_{\parallel}$ bow shock into the foreshock. Our results suggest that the energy cascade and dissipation near Venus can be modified by the Venusian bow shock, and the $Q_{\parallel}$ bow shock plays an important role on the energy injection and dissipation in the solar wind interaction with Venus.

Keywords: Magnetic fluctuations, Turbulence, Venusian bow shock, Spectral scalings, Shock geometry, Venus Express

1. Introduction

As a typical unmagnetized planet, Venus has no global intrinsic magnetic field. An induced magnetosphere is created by the solar wind (SW) interaction with Venus (e.g., Zhang et al., 2008a), consisting of the magnetic barrier (e.g., Zhang et al., 1991, 2008b; Xiao and Zhang, 2018) and the magnetotail (e.g., Rong et al., 2014; Xiao et al., 2016). The Venusian induced magnetosphere can deflect the upstream SW, and a bow shock and a magnetosheath are formed above (e.g., Zhang et al. 2008c, Phillips and McComas, 1991). The near-Venusian space environment is a natural laboratory to investigate the SW interaction with unmagnetized planetary bodies (e.g., Luhmann, 1986). In the near-Venusian space, magnetic field fluctuations play an important role in the transformation of momentum and energy, and their properties are widely reported (e.g., Luhmann et al., 1983; Guicking et al., 2010; Du et al., 2010; Xiao et al., 2017). The power of these fluctuations generally exhibits a power-law behavior with the frequency as $P \propto 1/f^{\alpha}$ (where P is the power spectral density (PSD), f is the frequency, and α is the spectral scaling index). The index α is considered as an indicator of the nature of fluctuations, and it generally has different values for the frequency ranges above and below the local proton gyrofrequency (f_p). In the magnetohydrodynamics (MHD) frequency range, a value of α ~ 1.5 is expected for turbulence. Energy cascade occurs in this regime, where the energy is transferred from lower to higher frequencies. In the kinetic frequency range, the turbulence has a larger value of α ~ 2.8, in which regime the magnetic energy dissipates into plasma. The spectral scaling indices have been extensively used to analyze the magnetic field fluctuations and turbulence in the planetary space environments near Mars (e.g., Ruhunusiri et al., 2017), Earth (e.g., Vörös et al., 2004), and Venus (e.g., Vörös et al., 2008a, 2008b; Dwivedi et al., 2015; Xiao et al., 2018, 2020a, 2020b).

Although Venus has a similar size to Earth, the Venusian bow shock and magnetosheath are much smaller, with a scale ratio of ~1/10 (e.g., Slavin et al., 1979). This might result in some differences between their space plasma environments. Vörös et al. (2008a, 2008b) reported a survey of the spectral scalings of magnetic fluctuations in the Venusian magnetosheath and wake. They observed 1/f noise in the dayside magnetosheath, wavy structures near the terminator, and MHD turbulence at the magnetosheath post terminator boundary layer and near the nightside bow shock. The observed 1/f noise in the Venusian magnetosheath may indicate that these fluctuations are generated not by turbulent cascade but by independent and uncorrelated physical processes. Xiao et al. (2018) further examined the magnetic fluctuations in the dayside Venusian magnetosheath and found a clear difference of the turbulence distributions between downstream of the quasi-parallel ($Q_{\parallel}$) and the quasi-perpendicular ($Q_{\perp}$) shocks. It is speculated that turbulence can be rapidly developed along the streamlines or penetrate into the Venusian magnetosheath downstream of the $Q_{\parallel}$ bow shock. It suggests that the shock geometry has an effect on the spectral scalings of downstream magnetic fluctuations, and the bow shock plays a role on the turbulence distribution in the near-Venusian space. Xiao et al. (2020a) presented a description of the spectral scalings of magnetic fluctuations at the Venusian bow shock crossings. In terms of the spectral scalings, the dayside-nightside shock crossings exhibit a clear asymmetry.

Noisy fluctuations dominate at the dayside shock crossing, and more MHD turbulence is present at the nightside shocks. Moreover, this distribution at the bow shock seems independent on the shock geometry. However, we still rarely know how the bow shock modifies the upstream magnetic fluctuations and turbulence from the SW.

Besides, previous investigations of turbulence near Venus are mainly focused on the MHD regime. It is believed that the spectral scalings of magnetic field fluctuations in the kinetic regime are quite different from those in the MHD regime. A recent research presented the global spatial distribution of the spectral scaling indices of magnetic fluctuations in both of MHD and kinetic regimes, and the global distribution suggests that the kinetic effects on magnetic energy dissipation are common in the near-Venusian space (Xiao et al., 2020b). The SW turbulence can be modified by the Venusian bow shock in both MHD and kinetic regime, and kinetic turbulence extensively occurs in the Venusian magnetosheath and the induced magnetosphere.

In this paper, we aim to the differentiation of the spectral scalings of the magnetic field fluctuations upstream and downstream of the Venusian bow shock and the shock geometry effects. The spectral scaling indices will be examined in both MHD and kinetic regimes. The investigation of the Venusian bow shock modification to turbulence of the can help us to better understand the energy injection, cascade, and dissipation in the SW interaction with Venus.

2. Data and Methods

Venus Express (Svedhem et al., 2007; Titov et al., 2006), as the first ESA's Venus exploration mission, was launched in November 2005 and arrived at Venus in April 2006. Venus Express provides a great opportunity to examine the spectral scalings of the magnetic fluctuations near the Venusian bow shock. In this study, the magnetic field data measured by Venus Express magnetometer (Zhang et al., 2006) at a sampling rate of 32 Hz are used, and the bow shock crossings can be identified by the sudden change in the magnitude of the magnetic field between the SW and the Venusian magnetosheath, as shown in Figure 1a.

Figure 1a shows the total magnetic field time series containing a bow shock crossing on Dec. 30, 2006. To examine the spectral scalings of the upstream and downstream magnetic fluctuations near the Venusian bow shock, the upstream and downstream intervals need to be selected during this shock crossing event. For this inbound case, a 256-s upstream interval is selected before the shock, and a 128-s downstream interval is selected after the shock crossing, as indicated in Figure 1b. Figure 1b shows the magnetic field observations near the bow shock crossing in the aberrated Venus solar orbital (VSO) coordinate system, where the X axis points antiparallel to the average SW flow (with an aberration angle of 5°) from Venus, the Z axis is perpendicular to the ecliptic plane and toward north, and the Y axis completes the right-handed Cartesian coordinate system. Based on these two intervals, the PSDs are calculated via wavelet transforms (Torrence and Compo, 1998):

$$PSD(f) = \frac{2\Delta t}{N}\sum_{j=1}^{N}\left[W_x^2(t_j,f) + W_y^2(t_j,f) + W_z^2(t_j,f)\right],$$

where Δt is the sampling time, N is the length of the time series, and W_x, W_y, and W_z are the wavelet transforms of the x, y, and z components of the magnetic field.

The upstream and downstream PSDs are respectively shown in Figure 1c and d with dashed f_p. An obvious spectral break near the f_p is present in the downstream PSD, while it is not so clear for the upstream. In this study, we refer to the frequency range below $f_p/2$ as the MHD regime and the frequency range above $2f_p$ as the kinetic regime. The value of f_p is typically exhibited as 0.1 Hz in the upstream SW near Venus and 0.3 Hz in the downstream Venusian magnetosheath. The upstream interval is selected longer to cover a lower frequency range. Then the spectral indices in the MHD range (α_m) and the kinetic range (α_k) can be estimated as the slopes of the power-frequency log-log plot of the corresponding PSD in the frequency ranges of concern. Based on the methods described above, a statistical study of the spectral indices is performed at the upstream and downstream regions near the Venusian bow shock in the next section.

3. Statistical Observations

To statistically differentiate the spectral scaling indices for the upstream and downstream regions near the Venusian bow shock and emphasize the shock geometry effects, we examine the Venus Express magnetic field data for ~7 years

(2006.05~2012.08) and identify the bow shock crossings. Firstly, we select the orbits when the interplanetary magnetic field (IMF) is relatively steady; that is, the directional changes of the IMF between inbound and outbound crossings of bow shock (~15-min time interval) are less than 30°. Secondly, the shape of the Venusian bow shock can be estimated based on the positions of these two bow shock crossings and the conic section equation $R = L/(1 + \varepsilon \cos\theta)$ with a focus at (x_0, 0, 0) and a fixed ε of 1.03 during solar minimum (2006-2010) or 1.095 during solar maximum (2011-2012) as reported by Shan et al. (2015), where R is the bow shock distance from the conic focus, L is the conic section semi-latus rectum, and ε is the eccentricity. At last, we find 209 orbits/418 shock crossings with steady IMF and well-determined bow shock geometry.

We calculate the PSDs of the upstream and downstream intervals of these shock crossings, and then the values of α_m and α_k can be estimated in the corresponding frequency ranges. Figure 2 shows the histograms of the scaling indices for the upstream and the downstream intervals of the 418 shock crossings in the MHD and kinetic regimes. We find that, in the MHD regime, the median values of α_m are 1.27 and 1.03 and the mean values are 1.26 and 1.08 with the standard deviations of 1.07 and 1.10 for the upstream and the downstream intervals, respectively. The statistical distributions indicate that these magnetic fluctuations are in a developing and mixed state. From upstream to downstream, the values of α_m show a decreasing trend and the downstream fluctuations tend towards 1/f noise in the MHD regime. In the kinetic regime, the median values of α_k are 2.27 and 2.88 and the mean values are 2.26 and 2.80 with the standard deviations of 0.72 and 0.54 for the upstream and the downstream intervals, respectively. The values of α_k for the downstream tend to be larger and concentrated, and the downstream distribution indicates that the kinetic turbulence dominates behind the bow shock. As reported by previous studies (e.g., Xiao et al., 2020b), well developed turbulence is a common phenomenon in the SW near Venus. However, Figure 2 shows that although some spectral indices indicating the turbulence can still be found, these upstream intervals are rarely turbulence dominant. We infer that the SW fluctuations have been modified before they reach the bow shock.

Some previous studies suggested that the bow shock geometry could affect the fluctuations and turbulence in the near-Venusian space (e.g. Luhmann et al., 1983; Xiao et al., 2018). To further investigate the bow shock modifications to the SW fluctuations and turbulence, we split the bow shock crossings into two categories of $Q_{\parallel}$ (θ_{BN} < 45°) and $Q_{\perp}$ (θ_{BN} > 45°) geometries. The shock normal angle θ_{BN} can be calculated by the average upstream magnetic field and the estimated local bow shock normal. Consequently, 115 $Q_{\parallel}$ events and 303 $Q_{\perp}$ events are obtained, and then we can examine the shock geometry effects on the spectral scalings of fluctuations near the bow shock.

Figure 3 shows the distributions of α_m for the upstream and the downstream intervals of the $Q_{\parallel}$ and $Q_{\perp}$ bow shock crossings. The median values of α_m for the downstream intervals of $Q_{\parallel}$ and $Q_{\perp}$ bow shocks are 0.97 and 1.05, respectively. The similar distributions suggest that, in the MHD regime, the effects of the bow shock on the SW fluctuations and turbulence are independent on the shock geometry. While the values of α_m for the upstream intervals are obviously related to the shock geometry. For the upstream intervals of $Q_{\parallel}$ and $Q_{\perp}$ bow shocks, the median values of α_m are 0.82 and 1.44, respectively. Both distributions upstream and downstream of the $Q_{\parallel}$ bow shocks present two peaks at ~1 and ~1.5. The spectral scalings do not show significant differences between the fluctuations upstream and downstream of the $Q_{\parallel}$ shocks. The MHD fluctuations upstream of the $Q_{\perp}$ bow shocks are also in a mixed state that some fluctuations might be modified or still in developing, but the distribution is more like the SW with pre-existing turbulence. Obvious differences exist between the upstream and downstream intervals of the $Q_{\perp}$ shocks, which could result from the waves excited behind the $Q_{\perp}$ shocks. We infer that the pre-existing MHD turbulence from the SW could be more prone to reaching the $Q_{\perp}$ bow shocks but start to be modified before reaching the $Q_{\parallel}$ bow shocks. The modification might be due to the waves generated near the bow shock.

The distributions of the values of α_k for the upstream and the downstream intervals of the $Q_{\parallel}$ and $Q_{\perp}$ bow shock crossings are shown in Figure 4. The median values of α_k are 2.88 and 2.87 for the downstream intervals of $Q_{\parallel}$ and $Q_{\perp}$ bow shocks, respectively. The distributions indicate that the kinetic turbulence is significantly dominant for the downstream intervals, and it is not shock geometry dependent. The upstream kinetic fluctuations also show a difference between the $Q_{\parallel}$ and $Q_{\perp}$ bow shock crossings. The median values of α_k for the upstream intervals of $Q_{\parallel}$ and $Q_{\perp}$ bow shocks are respectively 2.70 and 2.11. The statistical kinetic spectral scalings of the fluctuations near the $Q_{\parallel}$ bow shocks do not change significantly as near the $Q_{\perp}$

bow shocks, but the values of α_k for the downstream intervals have a much more concentrated distribution. This indicates that the downstream kinetic turbulence is mainly developed behind the bow shock but not penetrate from the upstream. The kinetic turbulence can also be developed upstream of the $Q_{\parallel}$ bow shocks. We infer that the SW kinetic fluctuations could be affected by the Venusian bow shock at the upstream region and the upstream difference of the $Q_{\parallel}$ and $Q_{\perp}$ bow shock might result from the more backstreaming ions upstream of the $Q_{\parallel}$ bow shock.

4. Conclusions

In this paper, we use the magnetic field data of Venus Express from 2006.05 to 2012.08 to investigate the spectral scalings variations of the magnetic field fluctuations near the Venusian bow shock. The spectral indices are calculated in the MHD and kinetic regimes for the upstream and downstream intervals close to the Venusian bow shock. There are 115 $Q_{\parallel}$ and 303 $Q_{\perp}$ shock crossings selected in this study. Based on the statistical results, the shock effects on the spectral scalings near the Venusian bow shocks are examined.

We find the Venusian bow shock tends to flatten the spectra of upstream MHD fluctuations and steepen the kinetic spectra. At the downstream regions, the MHD magnetic fluctuations and turbulence tend to be modified to 1/f noise and the kinetic turbulence can be fully developed behind the shock, which is consistent with the previous studies (e.g., Vörös et al., 2008a; Xiao et al., 2020b). This suggests that the energy cascade and dissipation near Venus can be modified by the Venusian bow shock. The spectral indices for the downstream intervals show this shock modification is independent on the shock geometry. However, we find the upstream spectral scalings are associated with the shock geometry. In the MHD regime, the spectra upstream of $Q_{\parallel}$ bow shocks are flatter than of $Q_{\perp}$ bow shocks. In the kinetic regime, the spectra upstream of $Q_{\parallel}$ bow shocks are steeper than of $Q_{\perp}$ bow shocks.

The bow shock effects on the SW fluctuations could begin at the upstream region, which might result from reflected ions and newborn pickup ions. At the $Q_{\parallel}$ shocks, some ions can escape into the foreshock region, and a variety of large-amplitude waves can be excited by these backstreaming ions (e.g., Delva et al. 2011, Collinson et al., 2012; Shan et al., 2013). These waves generated in the foreshock can be convected to the downstream side across the $Q_{\parallel}$ bow shock (e.g., Luhmann et al., 1983; Du et al., 2010; Shan et al., 2014). That might be a reason of the statistical finding that there are no significant variations of the spectral scalings of magnetic fluctuations near the $Q_{\parallel}$ bow shocks. This suggests that the $Q_{\parallel}$ bow shock is an important channel of the energy injection and dissipation in the interaction of the SW with Venus. More fluctuations and higher energies are injected at $Q_{\parallel}$ rather than $Q_{\perp}$ shocks. At the $Q_{\perp}$ shocks, these ions will generally gyrate back and then excite waves behind the shocks (e.g., Volwerk et al., 2008). These waves could result in the changes of downstream spectral scalings. However, in some cases, the waves upstream of $Q_{\perp}$ shocks can be transmitted into the downstream, and the downstream spectra could also be similar to the upstream except an enhanced amplitude (e.g., Lu et al., 2009). Thereby, the the spectral scalings variations across the bow shock could be controlled by multiple factors. In this study, we find the shock geometry is an important factor. Other possible factors affecting the Venusian bow shock modification to the SW fluctuations will be our future topics.

Declarations

Availability of data and materials

Venus Express magnetic field data are available in the ESA's Planetary Science Archive (ftp://psa.esac.esa.int/pub/mirror/VENUS-EXPRESS/).

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Not applicable.

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Authors' contributions

SDX initiated the investigation and prepared the original manuscript. TLZ supervised the investigation. MYW and GQW participated in the discussions and reviewed the manuscript. YQC and TLZ gave the suggestions of the manuscript. All authors read and approved the final manuscript.

Acknowledgments

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Figure Legends

Figure 1. A Venusian bow shock crossing event observed by Venus Express on 30 Dec. 2006. Panel a presents the time series of the total magnetic field and the shock crossing interval is shown in shadow. Panel b presents the magnetic field observations near the bow shock in the aberrated VSO coordinate system, and the upstream and downstream intervals are indicated. Panel c and d present the PSDs of the magnetic fluctuations for the upstream and downstream intervals.

Figure 2. Histograms of the spectral indices for the upstream and the downstream intervals of the bow shock crossings in the MHD and kinetic regimes. The upper panels show the histograms for the MHD regime, and the lower panels show the histograms for the kinetic regime.

Figure 3. Histograms of the spectral indices in the MHD regime for the upstream and the downstream intervals of the $Q_{\parallel}$ and $Q_{\perp}$ bow shock crossings. The upper panels show the histograms for the $Q_{\parallel}$ bow shock crossings, and the lower panels show the histograms for the $Q_{\perp}$ bow shock crossings.

Figure 4. Histograms of the spectral indices in the kinetic regime for the upstream and the downstream intervals of the $Q_{\parallel}$ and $Q_{\perp}$ bow shock crossings. The upper panels show the histograms for the $Q_{\parallel}$ bow shock crossings, and the lower panels show the histograms for the $Q_{\perp}$ bow shock crossings.