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Turbulence in the near-Venusian space: Venus Express observations

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Key Points:

- First global characterization of kinetic turbulence in the near-Venusian space is shown
- MHD turbulence is present at the boundary layer between Venusian magnetosheath and the wake, while kinetic turbulence extensively occurs in the magnetosheath and the induced magnetosphere
- The kinetic effects on magnetic energy dissipation are common in the near-Venusian space

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Abstract: With Venus Express magnetic field measurements at 32 Hz from 2006 to 2012, we investigate statistically the magnetic fluctuations in the near-Venusian space. The global spatial distribution of their spectral scaling features is presented in MHD and kinetic regimes. It can be observed that turbulence is a common phenomenon in the solar wind in both regimes. The solar wind MHD turbulence is modified at the Venusian bow shock; MHD turbulence is absent in the Venusian magnetosheath but present at the magnetosheath boundary layer. Pre-existing kinetic turbulence from the far upstream solar wind is modified in the near solar wind region, while kinetic turbulence can be extensively observed throughout the Venusian magnetosheath and in some regions of the induced magnetosphere. Our results reveal that, in the near-Venusian space, energy cascade can be developed at the boundary between magnetosheath and wake, and the turbulence-related dissipation of magnetic energy occurs extensively in the magnetosheath and the induced magnetosphere.

Keywords: turbulence; near-Venusian space; kinetic effects; Venus Express

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1. Introduction

Although Venus does not have an intrinsic magnetic field, a so-called induced magnetosphere, consisting of a magnetic barrier at the dayside and a magnetotail at the nightside, is created through its interaction with the solar wind (e.g., Phillips and McComas, 1991; Zhang TL et al., 2007, 2008). As an obstacle planet in the solar wind flow, Venus can also create a bow shock upstream of the planet (e.g., Luhmann, 1986), where the solar wind is decelerated from supersonic speed to subsonic speed. The Venusian solar wind interaction region contains intense magnetic fluctuations, which can be locally generated or convected from the upstream foreshock region (e.g., Luhmann et al., 1983; Du J et al., 2010; Xiao SD et al., 2017). In the near-Venusian space, magnetic field fluctuations play an important role in the transformation of momentum and energy. The power of these fluctuations generally exhibits power law relationships with the frequency, in the form of $P \propto 1/f^{\alpha}$, where the spectral index α is the slope of the power spectral density (PSD). The spectral indices generally have different values for different scales. In terms of second-order statistics, the spectral index α is considered an indicator of the nature of the fluctuations, which is informative about the physics, such as energy injection, cascade, and dissipation, operating in each particular frequency range. The spectral index values α ~5/3 or 3/2 are expected for hydrodynamic or MHD inertial range turbulence. Energy cascade occurs in this regime, where the energy is transferred from lower frequencies to higher frequencies. Turbulence is also believed to have an essential influence on plasma heating and particle acceleration in the space plasma environment. The kinetic turbulence has its spectral index near 2.8, in which regime the magnetic energy dissipates into plasma. Spectral indices have been used extensively in space plasma turbulence analysis (e.g., Bruno and Carbone, 2005; Vörös et al., 2004, 2008a, b; Ruhunusiri et al., 2017; Xiao SD et al., 2018).

The goal of investigations of turbulence in space plasma is to better understand how the energy injected into fluids and plasmas at large spatial or temporal scales is converted to small-scale fluctuations and ultimately to plasma. Venus is a terrestrial planet, but its magnetosphere is considerably smaller than the Earth's because Venus lacks a global intrinsic magnetic field. Vörös et al. (2008a, b) studied spectral scaling feature variations of magnetic

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field fluctuations in the Venusian magnetosheath and in the wake along the Venus Express trajectory. 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 may indicate that the driving mechanisms of these fluctuations are generated not by turbulent cascade but by independent and uncorrelated physical processes in the dayside magnetosheath (Vörös et al., 2008a, b). Guicking et al. (2010) focused on waves and spectral properties of the low-frequency magnetic field fluctuations in Venus' solar wind interaction region, observed by Venus Express, and found that the spectral indices vary between $\alpha = 1.7$ and 2 in the magnetosheath regions and that the spectral power decreases more rapidly in the mantle and tail regions. However, the spectral index data set from Guicking et al. (2010) shows a relatively high sample standard deviation (~0.5), which indicates that strong nonstationarities are present in the Venusian solar wind interaction region. Xiao SD et al. (2018) also examined the spectra of magnetic fluctuations in the dayside Venusian magnetosheath and concluded that, although the thin dayside magnetosheath is not spatially large enough to support full development of turbulence, the solar wind turbulence can penetrate into the Venusian magnetosheath preferentially through the quasi-parallel bow shock, which suggests that the geometry of the bow shock has an effect on the nature of downstream magnetic fluctuations.

In addition, the observed spectral scaling features are frequency-range dependent. Dwivedi et al. (2015) investigated the spectra of magnetic field fluctuations below and above 0.07 Hz in the Venusian magnetosheath, based on Venus Express observations, and found that the statistical distribution of the spectral indices has a prominent peak close to $\alpha = 1$ over the low frequencies; over the high frequencies, however, there is another peak near $\alpha = 1.5$ in the distribution. This indicates that the fluctuations present in the Venusian magnetosheath can evolve eventually into a more turbulent regime. The study of Dwivedi et al. (2015) is still based on 1 Hz magnetometer data. Previous investigations of Venusian space turbulence have focused on the low frequency fluctuations. It is believed that the spectral scaling features of magnetic field fluctuations in the kinetic regime are quite different from those in the MHD regime.

Based on Mars Atmosphere and Volatile Evolution (MAVEN) observations, Ruhunusiri et al. (2017) presented the first global characterization of turbulence for two different plasma regimes, MHD and kinetic, in the plasma environment of Mars, which, like Venus, is an unmagnetized planet. They found that fully developed MHD turbulence is absent in the Martian magnetosheath but present in the magnetic pileup boundary, and they also observed spectral indices indicating kinetic turbulence in the Martian magnetosheath. Although the interactions of Venus and Mars with the solar wind are similar, a previous study had suggested that the topology of the magnetic field in the day-side Martian magnetosphere is different from that of the Venus magnetosphere, and that an ionopause is not a characteristic feature of the Martian day-side ionosphere (Gringauz, 1981). The major differences between these two planets are generated by the smaller size of Mars and the lower plasma density and magnetic field strength in the solar wind near Mars (Bertucci et al., 2011). Kinetic effects have been shown to be very important at Mars (e.g., Lembège and Savoini, 2002; Ruhunusiri et al., 2017). In this respect, it is an important question to investigate kinetic effects at Venus. We hypothesize that the spectral scaling features in the kinetic regime of magnetic fluctuations near Venus may also represent some important information. A comprehensive investigation of turbulence in the near-Venusian space will give insight into processes common to unmagnetized planets.

In this study, we investigate the spectral scaling features of MHD and kinetic fluctuations in the near-Venusian space. The results enable better understanding of energy injection and dissipation in the Venusian solar wind interaction region. In Section 2, data and methods are introduced. In Section 3, the spectral scaling features of magnetic field fluctuations are examined statistically in the Venusian solar wind interaction region. Section 4 is devoted to discussion and conclusions.

2. Data and Methods

In this paper, we examine the spectral scaling features of magnetic fluctuations near Venus, based on Venus Express magnetic field data. Venus Express (Svedhem et al., 2007; Titov et al., 2006) was ESA's first spacecraft to visit Venus. It was launched in November 2005, arrived at Venus in April 2006, and then began continuous transmission of science data back from its polar orbit around Venus. In this study, we used magnetic field data obtained between May 2006 and August 2012 by the Venus Express magnetometer (Zhang TL et al., 2006) at a sampling rate of 32 Hz.

Due to the Venusian orbital motion around the Sun, the solar wind flow is not parallel to the Sun–Venus line but rather has an average aberration angle of 5°. To eliminate the aberration effect (also called the windsock effect), the data were rotated to an aberrated Venus solar orbital (VSO) coordinate system, where the *Z* axis remains perpendicular to the ecliptic plane and toward north, but the *X* axis is antiparallel to the average solar wind flow. Figure 1a shows a typical Venus Express trajectory in cylindrical coordinates. The horizontal axis represents the distance from the center of Venus along the average solar wind flow, and the vertical axis indicates the distance from Venus perpendicular to Sun–Venus line. The black solid line is the trajectory of Venus Express on June 14, 2012, and the nightside shadow region indicates the wake of Venus. The gray dashed line shows the position of a hypothetical bow shock based on the model of Shan LC et al. (2015). Figure 1b presents the time series of the magnetic field components in aberrated VSO coordinate system, and Figure 1c shows the total magnetic field strength. To examine the fluctuations along the trajectory of the spacecraft, the magnetic field data were continuously scanned in a 512 s sliding window with a step of 1 min, and the wavelet transforms were performed to calculate PSDs (Torrence and Compo, 1998). To assume that the observation is in situ, only the central 100 s wavelet spectra were chosen to obtain an average PSD in each window. Because of the existence of data gaps, only parts of the time intervals are available. The spectra time series are shown in Figure 1d.

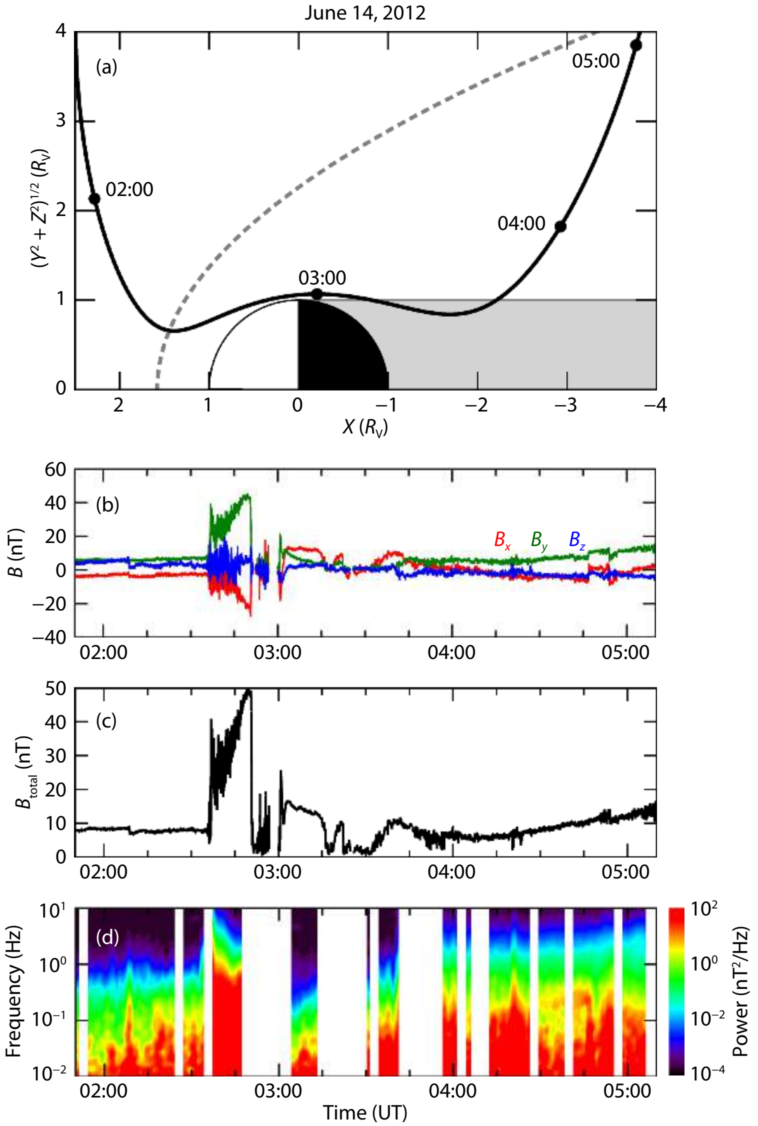

Figure 1. Venus Express trajectory, magnetic fields, and PSDs of magnetic fluctuations on 14 June 2012. (a) The black solid line indicates the spacecraft trajectory, the gray dashed line indicates the bow shock, and the nightside shadow indicates the wake region. (b) Magnetic field time series in aberrated VSO coordinate system. (c) Total magnitude of the magnetic field. (d) PSDs for the magnetic field fluctuations computed using the wavelet transform.

3. Statistical Observations

To obtain the spectral scaling indices of the magnetic field fluctuations in different regions of the near-Venusian space, we binned the data into the spatial regions by $0.2R_V$ (Venus radius is about 6052 km) square grids in the cylindrical coordinates as Figure 1a. Figure 2 shows the spatial distribution of the median magnitude of the magnetic field near Venus. The black curve shows the bow shock model of Shan LC et al. (2015). The magnetosheath and the induced magnetosphere are clearly indicated. In this study, we chose three sample regions to show the features in the regions of solar wind, magnetosheath, and wake, which are marked by white squares in Figure 2. The observed PSDs were normalized by the local proton gyrofrequency (f_{H^+}). Based on these normalized PSDs, we calculated the median PSD in each region, as shown in Figure 3. Then, the spectral index can be estimated as the slope of the power-frequency log-log plot of the corresponding median PSD in the frequency range of concern. In this study, we referred to the lower frequency range ($0.1f_{H^+}$–$0.5f_{H^+}$) as the MHD range and the higher frequency range ($4f_{H^+}$–$10f_{H^+}$) as the kinetic range. The spectral indices in the MHD range (α_m) and the kinetic range (α_k) are labeled on the panels by blue and red colors, respectively. As can be seen in Figure 3, the value of α_m for a PSD is generally different from α_k.

Figure 3 also shows that the spectral indices are different at different locations in the near-Venusian space. In the MHD range, the values of α_m are 1.39, 0.86, and 1.93 in the regions of solar wind, magnetosheath, and wake, respectively. The typical spectral scaling features for MHD turbulence are observed in the solar wind, while the magnetosheath is generally $1/f$ noise, and in the wake region α_m is obviously larger than it is in the magnetosheath, which arises from the dominating coherent wavy structures. These results are according with previous observations by 1 Hz

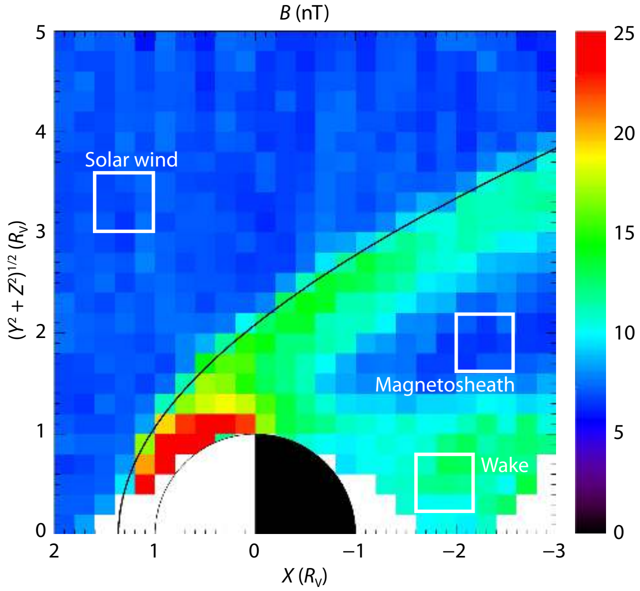

Figure 2. The magnetic field magnitude distributions, in a cylindrical coordinate system, where X is anti-parallel to the average solar wind flow. The bin size is $0.2R_V$. In each bin, the value is the median of the magnetic field observed in this bin. The black line indicates the bow shock of (Shan LC et al., 2015). The typical regions are chosen and marked for the solar wind, the magnetosheath, and the wake.

data (e.g., Vörös et al., 2008b). It can be inferred that the solar wind MHD turbulence rarely penetrates into the magnetosheath, and that the limited spatial scale of the Venusian magnetosheath can't support full development of turbulent cascade. In the kinetic range, the values of α_k are 2.74, 2.88, and 2.56 in the regions of solar wind, magnetosheath, and wake, respectively. The values of α_k are generally larger than α_m. Kinetic turbulence is also generated in the solar wind. In the magnetosheath, the value of α_k indicates that although MHD turbulence is absent, well developed kinetic turbulence is present in this region. In the wake region, the value of α_k is smaller than that in the magnetosheath, and the PSD doesn't show sudden turning between the MHD and kinetic ranges. This indicates that, in the wake region, a prominent spectral break is absent within the frequency range we observed, and the spectral scaling feature variations with frequency are continuous.

Based on these three samples, it seems that kinetic turbulence is more common in the plasma environment near Venus. To further explore the spatial variation of the spectral indices in different scales and the injection and development of turbulence, the spatial distributions of α_m and α_k were statistically investigated. The PSDs were binned as in Figure 2, and the magnetic field fluctuations in each bin were combined to calculate a median PSD. As shown in Figure 4, the spatial distribution maps display more comprehensive information of spectral scaling features in the near-Venusian space.

The spectral scaling features in the near-Venusian space show wide variations in both the MHD and kinetic ranges. The changing character of physical interactions between the solar wind and the planetary obstacle leads to different types of spectral scaling features in the Venusian space. The MHD range spectral scaling features shown in Figure 4a are in accord with previous studies (e.g., Vörös et al., 2008a, 2008b). In the Venusian magnetosheath, α_m has values around 1. Values of α_m around 1.5 are generally observed in the upstream solar wind, and also at the boundary between the magnetosheath and the wake. Fluctuations with larger α_m ~2 are found in the Venusian induced magnetosphere, including near the terminator and in the nightside wake.

Figure 4b shows an entirely different distribution of spectral indices in the kinetic range. In the kinetic range, the solar wind is in a mixed state. In the region far from the planet, α_k tends to present values between 2.5 and 3. The α_k values then rapidly de-

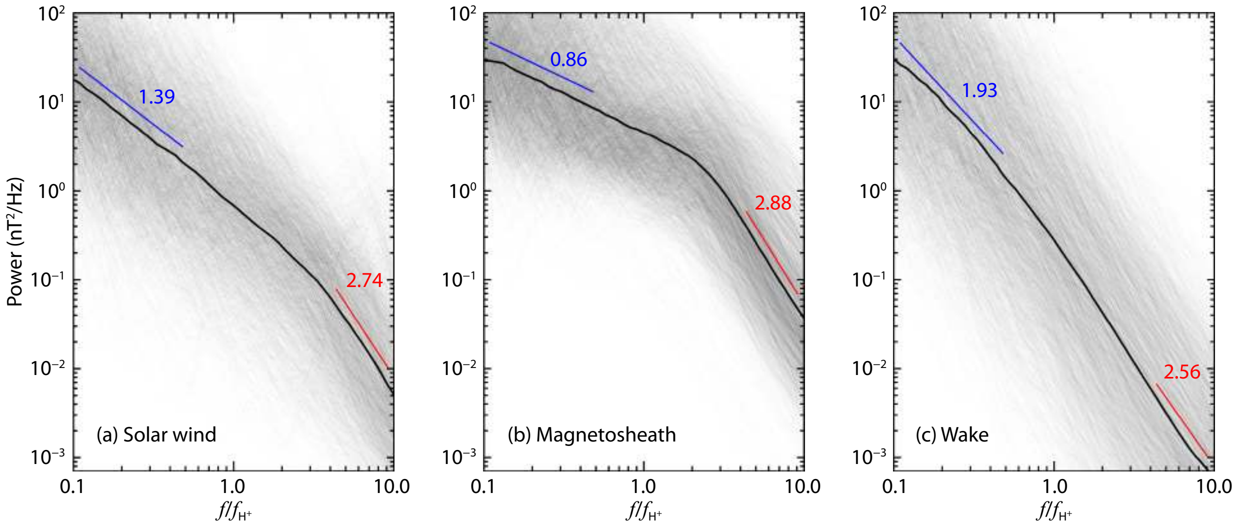

Figure 3. The median normalized PSDs for regions of (a) the solar wind, (b) the magnetosheath, and (c) the wake. The thick black lines indicate the medians of the normalized PSDs (background gray lines). The spectral indices (the slopes) in the MHD and kinetic ranges are labeled in blue and red, respectively.

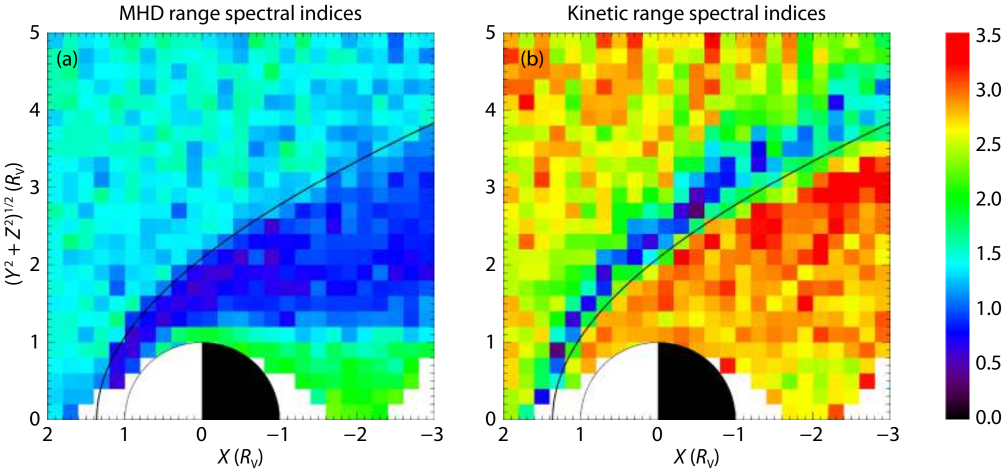

Figure 4. Global spatial distributions of the spectral indices for the magnetic fluctuations in (a) the MHD range and (b) the kinetic range. The format is the same as in Figure 2.

crease when going from far upstream to closer to the bow shock. A clear blue belt, which means very low values of α_k, is displayed at the upstream region close to the bow shock. In the magnetosheath, the values of α_k are obviously high, varying from 2.5 to 3 or higher. In particular, α_k in the wake is lower than it is in the magnetosheath, contrary to the tendency of α_m. In the wake, the values of α_k vary in a range from 2 to 3, and some bins exhibit α_k values approximately equal to α_m.

4. Discussion and Conclusions

In this paper, we used the 32 Hz magnetic field data of Venus Express to investigate the features of magnetic fluctuations in the near-Venusian space. For the first time, the spectral scaling features of magnetic fluctuations in the kinetic regime in the near-Venusian space have been analyzed. Our results show that the values of α_k ~2.5–3, typical for kinetic turbulence, are observed extensively in the far upstream turbulence, in the Venusian magnetosheath, and in some parts of the wake, indicating that kinetic turbulence can play an important role in the dissipation of magnetic energy. On the basis of previous investigations of MHD turbulence (e.g., Vörös et al., 2008a; b; Xiao SD et al., 2018), we can obtain a statistical global map of the spectral features that can supply an essential reference for the spatial development of turbulence and energy cascade in the solar wind interaction with Venus. Our observations are similar to those at Mars, which means that turbulence features are common to the space environments of unmagnetized planets.

In the MHD regime, the observations show that turbulence is common in the solar wind. The pre-existing solar wind MHD turbulence is modified at the Venusian bow shock. Although some MHD turbulence from solar wind can pass through the parallel bow shock (Xiao SD et al., 2018), the locally generated fluctuations are generally dominant, and noisy fluctuations can be observed in the Venusian magnetosheath. At the boundary between the Venusian magnetosheath and the wake, the MHD turbulence can be generated from some shear-driven instabilities (e.g., Möstl et al., 2011). The induced magnetosphere shows larger spectral indices, which might indicate accompanied wavy structures (Vörös et al., 2008b).

Compared with the MHD spectral scaling, the features and distribution of kinetic spectral scaling are quite different. In the kinetic regime, turbulence exists in the far upstream solar wind, and then the far upstream turbulence is rapidly modified in the near solar wind as it gets closer to the bow shock, which might arise from the backstream ions in the foreshock. Different from the MHD regime, well-developed kinetic turbulence can be observed throughout the Venusian magnetosheath and in parts of the induced magnetosphere.

Our results reveal that the energy cascade occurs in the upstream solar wind and the boundary layer between the magnetosheath and the wake, in which the energy is transferred from the larger scales to smaller scale fluctuations; while the turbulence related magnetic energy dissipation extensively occurs in the Venusian magnetosheath and the induced magnetosphere, in which the magnetic energy from the fluctuations dissipates into plasma.

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