Planetary and Space Science 146 (2017) 55–65

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Ultra low frequency waves at Venus: Observations by the Venus Express spacecraft

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ARTICLE INFO

Keywords:
Solar wind-Venus interaction
Planetary magnetosheaths
Plasma waves
Induced magnetospheres

ABSTRACT

The generation of waves with low frequencies (below 100 mHz) has been observed in the environment of most bodies in the solar system and well studied at Earth. These waves can be generated either upstream of the body in the solar wind by ionization of planetary exospheres or ions reflected from a bow shock or in the magnetosheath closer to the magnetic barrier. For Mars and Venus the waves may have special importance since they can contribute to the erosion of the ionopause and by that enhance atmospheric escape. While over the past years many case studies on wave phenomena observed at Venus have been published most statistical studies have been based on magnetic observations only. On the other hand the generation mechanisms and transport of these waves through the magnetosphere can only be quantified using both magnetic and particle observations. We use the long time observations of Venus Express (2006–2014) to determine the predominant processes and transport parameters. First we demonstrate the analysis methods in four case studies, then we present a statistical analysis by determining transport ratios from the complete Venus Express dataset. We find that Alfvenic waves are very dominant (>80%) in the solar wind and in the core magnetosheath. Fast waves are observed mainly at the bow shock (around 40%) but also at the magnetic barrier where they may be most important for the energy transfer into the ionosphere. Their occurrence in the magnetotail may be an artifact of the detection of individual plasma jets in this region. Slow mode waves are rarely dominating but occur with probability of about 10% at the bow shock and in the pile-up-region. Mirror mode waves have probability <20% in the magnetosheath slightly increasing towards the pile-up-boundary.

1. Introduction

A planetary magnetosheath is the region of space around a planetary body filled by the shocked (compressed, heated, decelerated and deflected) solar wind plasma. The planetary body constitutes an obstacle to the solar wind flow. Thus the plasma flow lines and the interplanetary magnetic field (IMF) lines diverge around the planetary obstacle. At the internal boundary of this region, where the magnetosheath plasma encounters the magnetic barrier, energy is transferred from the solar wind to the magnetosphere (Spreiter et al. (1966); Russell (1991, 2001)).

Venus currently does not have an intrinsic magnetic field. However, an induced magnetosphere is formed through solar wind interaction with its upper atmosphere (Luhmann (1995a,b); Luhmann et al. (2004); Luhmann and Russell (1997)). In this case, currents induced in the upper ionosphere deflect the solar wind magnetic field such that a magnetic barrier is formed above the ionosphere which has many similarities to the magnetopause of magnetized planets (Zhang et al. (1991)). The relative motion between the induced obstacle and the supersonic solar wind creates a bow shock upstream of un-magnetized planets (Venus and Mars). The shocked solar wind then fills the planetary magnetosheaths of the un-magnetized planets as it does for the magnetized planets (Luhmann (1995a,b); Luhmann et al. (2004); Luhmann and Russell (1997); Russell (1991, 2001)).

Planetary magnetosheaths are permeated by a variety of wave modes. The principal modes are the mirror mode and ion cyclotron waves (Hasegawa (1969); Fairfield (1976); Tsurutani et al. (1982); Gary

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http://dx.doi.org/10.1016/j.pss.2017.08.011
Received 24 May 2017; Received in revised form 21 July 2017; Accepted 24 August 2017
Available online 4 September 2017

(1992)). Wave activity has been observed and modeled in Venus magnetosheath as reviewed in the following section. The occurrence of ultra low frequency waves (ULF) in the Venus magnetosheath was first observed by Mariner-10 (Greenstadt (1970); Lepping and Behannon (1980)).

Downstream of the bow shock, in the magnetosheath, ULF waves are most intensive. Since the wave activity in the sheath is supplied by several sources, namely, by convection of upstream waves, by wave generation at the bow shock and by local instabilities, it is very difficult to identify wave modes, mechanisms of their generation and to separate regions dominated by the specific wave modes (Dubinin and Fraenz (2016)).

The ion temperature anisotropy ($T_{perp} / T_{par} > 1$) usually observed downstream of the bow shock might be a source of other wave modes: mirror mode and ion cyclotron waves (Gary (1992)). Mirror waves are characterized by large-amplitude out-of-phase variations in the magnetic field and the plasma density while the ion cyclotron waves are Alfvenic transverse polarized oscillations. Temperature anisotropy is expected to occur either close to the quasi perpendicular bow shock or close to the boundary of the induced magnetosphere where the magnetic field is piled-up. Generally, both instabilities grow in competition with a higher growth rate of the ion cyclotron instability. However, the addition of a relatively small amount of heavier ions significantly reduces the growth rate of the ion cyclotron instability (Gary (1992); Dubinin and Fraenz (2016)). For a discussion on several mechanisms causing magnetosheath oscillations, see the review by Tsurutani et al. (2010).

2. Previous studies on waves at Venus

In the following we give a short overview on past results on ULF plasma wave observations at Venus: Luhmann et al. (1983) used a model for the convection pattern of the shocked solar wind flow around Venus, and Pioneer Venus Orbiter (PVO) magnetic field observations in the magnetosheath to study ULF (with periods $\sim$ 10–40 s) magnetic field fluctuations. They traced them along streamlines to the region of the quasi-parallel bow shock. They observed that the periods and polarizations of the sinusoidal fluctuations were similar to those observed upstream of the quasi-parallel bow shock, suggesting that disturbances at the Venus ionopause may be caused by convection of turbulent magnetic fields from the subsolar bow shock when the IMF direction produces a quasi-parallel shock. Phillips et al. (1986) have analyzed PVO magnetometer data to study the configuration of Venus magnetosheath. They have found that the magnetosheath magnetic field magnitude is responsive to solar wind dynamic pressure and that the compression of the upstream field is controlled by the magnetosonic Mach number. Further, they noted that magnetic field fluctuations can dominate the magnetosheath field for periods of low IMF cone angle and mostly for regions near the quasi-parallel bow shock. They also noted that mass loading is a significant process. Winske (1986) has investigated large-amplitude magnetic field fluctuations in the Venus magnetosheath for a quasi-parallel bow shock using numerical simulations. In that work it was found that waves can be generated by two mechanisms: the intrinsic nature of the shock, or by the direct interaction of the solar wind with oxygen ions of planetary origin. The results of that paper showed that the most likely source of the magnetosheath waves is the bow shock itself. Volwerk et al. (2008a, 2008b) presented observations of mirror mode structures in the Venus magnetosheath. They found that these mirror waves have periods between 5 and 15 s and are seen mostly behind the quasi-perpendicular bow shock, and near the magnetic barrier during compression of the magnetosphere due to increased solar wind pressure. Also, they reported that these waves are similar to mirror mode waves found in the Earth magnetosheath, but scaled down in duration and frequency by a factor of $\sim$ 10. In a statistical study Volwerk et al. (2016) found a slightly higher occurrence rate of mirror modes at solar maximum compared to solar minimum. Vörös et al. (2008) studied magnetic field fluctuations in the Venus magnetosheath and wake. They observed different types of spectral scaling in the near-Venus space. Noisy fluctuations were observed in the magnetosheath, wavy structures near the terminator and in the nightside wake. Further, multiscale turbulence was observed at the magnetosheath boundary layer and quasi-parallel bow shock. Pope et al. (2009) reported magnetic field fluctuations in the magnetosheath of Venus that they interpreted as being generated by Kelvin-Helmoltz instability. They observed large amplitude magnetic field oscillations in the Venus Express (VEX) data during the inbound trajectory crossing on 03 June 2006. The oscillations began shortly after the bow shock and continued throughout the magnetosheath and into the magnetic barrier. They interpreted those oscillations as vortices induced by the Kelvin-Helmholtz instability excited by the shear velocity profile at the boundary between the solar wind and the ionospheric plasma. This type of wave observation was later identified by statistical study (Walker et al., 2011) as a rare event. Du et al. (2009, 2010) studied magnetosheath fluctuations at Venus for two orientations of the IMF, i. e., nearly parallel and nearly perpendicular to the solar wind flow. They found that the magnetosheath fluctuations are quite different for both conditions. The magnetic fluctuations behind a quasi-parallel bow shock were strong and turbulent and could be convected upstream waves. The magnetic fluctuations after a quasi-perpendicular shock were less intensive and less monochromatic. The maximum variance direction was more aligned with the magnetic field, indicating a possible local generation mechanism. Du et al. (2010) mention two possible sources for the fluctuations in the magnetosheath: convection from the upstream foreshock and local generation. When the IMF is nearly perpendicular to the solar wind flow, the fluctuations in the magnetosheath are mainly generated locally by ion cyclotron instability due to planetary ion pickup. The wave intensity is relatively low and the transverse component is dominant. The waves were left hand (LH), elliptically polarized and propagating parallel to the mean magnetic field. When the IMF is nearly aligned to the solar wind flow, foreshock waves are convected into the magnetosheath, and the fluctuations are more intense in the magnetosheath. The waves had mixed polarization. The authors assumed that the waves convected from the foreshock are a mixture of multiple wave types and incoherent noise. Guicking et al. (2010) performed a statistical study of the spatial distribution of low-frequency magnetic field oscillations in Venus and its solar wind interaction region. They found that the spatial distribution of Venus waves is similar to the one observed in Mars. They detected an enhancement in the intensity in the dayside magnetosheath and a strong decrease towards the terminator. Shan et al. (2014) have studied the transmission of ULF waves through the Venus bow shock. They have observed that waves in the upstream and downstream regions have similar characteristics, and that they were most likely magnetosonic waves that were transmitted across the quasi-parallel bow shock. In a later study Shan et al. (2016) find that mono-chromatic ULF waves with periods between 20s and 30s are very probably generated by back streaming of protons in the foreshock. Dwivedi et al. (2015) investigated spectral slopes of waves in the Venus magnetosheath and interpreted a softer spectrum in the ULF range as caused by mirror mode and ion cyclotron instabilities. Proton cyclotron waves have been identified upstream of Venus and their generation has been discussed in a series of papers by Delva et al. (2008, 2011a,b, 2015). These can partly be explained by the weak hydrogen corona of Venus and partly by instabilities inherent in the solar wind.

Most plasma wave studies carried out for the Venus plasma environment and cited above are limited in scope by the fact that either