EVIDENCE FOR LANGMUIR OSCILLATIONS AND A LOW DENSITY CAVITY IN THE VENUS MAGNETOTAIL

C. M. Ho\textsuperscript{1}, R. J. Strangeway, and C. T. Russell

Institute of Geophysics and Planetary Physics, University of California at Los Angeles

Abstract. We report the discovery of Langmuir oscillations in a very low plasma density region in the Venus magnetotail. These waves are observed more often at 30 kHz, but also at 5.4 kHz indicating densities as low as 0.3 cm\textsuperscript{-3} in the central tail lobe. The Langmuir probe on board the Pioneer Venus Orbiter cannot resolve such a low plasma density. We use the magnetic field strength and the assumption of total pressure balance to infer the electron temperature as a test of the Langmuir wave identification. By investigating the spatial distribution of this wave activity we find that the plasma cavity is ordered in a coordinate system defined by the interplanetary magnetic field and is found at either side of the central tail current sheet.

Introduction

Langmuir waves are observed at the leading edge of the electron foreshock of Venus [Crawford et al., 1990; Strangeway, 1991; Gurnett et al., 1991] and the Earth [Gurnett et al., 1979]. Strong Langmuir oscillations such as those seen at the electron foreshock are thought to require the presence of a strong flux of energetic backstreaming electrons, stimulating the bump-on-tail instability. While thermal noise in a plasma is also stimulated near the electron plasma frequency, this noise is far too weak to be seen by the short electric dipole antenna of the Pioneer Venus Orbiter (PVO) wave instrument. Thus we would not expect to see Langmuir oscillations over most of the region around Venus except in the foreshock and certainly not in the tail because of the expected dearth of electron beams in these regions.

Nevertheless, despite our expectations, Langmuir waves appear to be present in the magnetotail of Venus. Venus has a long magnetotail stretching to beyond 12 Venus radii (R\textsubscript{V}) [Russell and Vaisberg, 1983]. This tail is at least partially anchored in the night ionosphere that conducts from the dayside ionosphere into the nightside. The solar wind electrons are expected to remain in contact with the night ionosphere by transport from the magnetosheath along the magnetic field [Russell and Vaisberg, 1983; Brace et al., 1987]. The Venus tail is thought to possess plasma and magnetic field regions similar to the terrestrial magnetotail, the main difference being that the orientation of the current sheet separating two magnetic lobes of opposite polarity is controlled by the interplanetary magnetic field (IMF). The current sheet is perpendicular to the plane defined by the IMF and the direction of the solar wind flow. Inside the tail lobes the field strength is enhanced over magnetosheath values and field lines are aligned approximately with the solar wind direction [McComas et al., 1986].

In this study, we report observation of Langmuir waves in the very low density region of the Venus magnetotail at frequencies as low as 5.4 kHz. The inferred electron density is too low (< 2 cm\textsuperscript{-3}) to be resolved by the Langmuir probe. From pressure balance arguments we use the observed magnetic field strength to deduce plasma temperatures consistent with that inferred from the Langmuir wave identification.

Wave Mode Identification

Plasma waves discussed herein were recorded with the Pioneer Venus Orbiter Electric Field Detector [Scarf et al., 1980] (OEFD). The OEFD has four narrow band frequency channels at 100 Hz, 730 Hz, 5.4 kHz and 30 kHz with ±15% bandwidth. In the solar wind around Venus the electron density (n\textsubscript{e}) is about 10 cm\textsuperscript{-3}, and Langmuir oscillations in the foreshock are therefore observed in the 30 kHz channel.

Since the electron plasma frequency f\textsubscript{pe} ∝ √n\textsubscript{e}, the filter bandwidth corresponds to a ±30% variation in density. The magnetic field and the electron density are measured respectively by the Orbiter Magnetometer [Russell et al., 1980] (OMAG) and the Langmuir probe, known as the Orbiter Electron Temperature Probe [Krehbiel et al., 1980] (OETP).

The electron data come from the Unified Abstract Data System (UADS).

In this study we use the first 16 nightside seasons of PVO data (1979 – 1987) to investigate the magnetotail of Venus. The density in the magnetotail generally decreases to about 10 cm\textsuperscript{-3} at an altitude of 2000 ~ 2400 km. We often see wave activity in the 30 kHz channel at these low density...

Fig. 1. Venus tail passage (orbit 2093) showing plasma waves in the two high frequency channels. The magnetic field and electron density data also are shown. The plasma wave and magnetometer data are high resolution data, while the electron data have 12-s resolution.
ties in this region. Figure 1 gives an example of these 30 kHz signals on orbit 2093 in the nightside upper ionosphere (periapsis altitude: 2074 km, SZA: 175.4°). The 30 kHz signals appear around a density of 10 cm⁻³, as shown in the bottom panel. The 30 kHz signals have maximum occurrence rate and strongest wave intensity when the plasma density approaches 10 cm⁻³ [Ho, 1993], and we interpret them to be Langmuir waves observed when the plasma frequency is close to 30 kHz.

Later on this orbit, following the observation of 30 kHz signals, similar signals appear in the 5.4 kHz channel. At the same time, the Langmuir probe's measurement of the electron density has decreased to a very low level (~2.0 cm⁻³), and there is a data gap in the electron data when the 5.4 kHz signals appear. The magnetic field is very steady, perhaps slightly increasing, so the waves are probably not due to a gradient or current driven instability. Figure 2 shows another example of 5.4 kHz signal activity on orbit 2531 in the nightside near tail region (periapsis altitude: 2268 km, SZA: 160.2°). Here strong burst signals appear only in this frequency channel. At the same time, there is a large data gap in the electron density observations, presumably due to the low density of the ambient plasma. Thus, we cannot use electron density data to identify these waves as we did for the 30 kHz signals.

The electron density data gaps may be caused by two conditions, either instrument mode changes (telemetry dropouts), or densities below the Langmuir probe threshold (unmeasurable densities). However, neither condition is indicated by a flagged data record in the UADS data files used in this study, there is simply a data gap. Nevertheless, as we discuss here, low densities appear to cause the data gaps, rather than changes in instrument mode. From Figure 1, we see that the electron density gradually decreases below 10 cm⁻³, and except for the interval where 5.4 kHz bursts appear, the sampling is usually at 12-s intervals (the resolution of the UADS data). The OETP appears to be operating continuously throughout this interval. An interruption of the density measurements due to mode changes should not be correlated with 5.4 kHz signals. In Figure 2 the density data are more sporadic, and the density is lower than that in Figure 1. The 5.4 kHz signals also occur when no electron density data are available in the UADS files. Missing data intervals consequently appear to be due to densities below the instrument threshold (2 cm⁻³ in optical shadow), rather

<table>
<thead>
<tr>
<th>Data Interval</th>
<th>With OETP</th>
<th>Without OETP</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 kHz Burst</td>
<td>14 (13%)</td>
<td>90 (87%)</td>
</tr>
<tr>
<td>30 kHz Burst</td>
<td>110 (59%)</td>
<td>77 (41%)</td>
</tr>
<tr>
<td>All Intervals</td>
<td>1657 (52%)</td>
<td>1518 (48%)</td>
</tr>
</tbody>
</table>

Table 1. Number of 30-s electric field data intervals with or without Langmuir probe (OETP) data.

The waves at 5.4 kHz seen on these two orbits may be Langmuir waves generated in the very low density plasma or possibly ion acoustic waves. If these 5.4 kHz waves are Langmuir waves, their corresponding electron density should be around 0.3 cm⁻³. This is far below the usual measurement range of the Langmuir probe, and also far below any other densities measured to date in the Venus environment. On the other hand, ion acoustic waves are usually wideband, and have a cutoff at the ion plasma frequency. Although Doppler-shift may increase the observed frequency above the ion plasma frequency, the ion density should be around 400 cm⁻³ for H⁺ or 6.4 x 10³ cm⁻³ for O⁺ if the waves at 5.4 kHz are ion waves. These high densities are highly unlikely to occur in the tail region above 2000 km. Thus the narrowband 5.4 kHz waves are not ion acoustic waves.

In support of the Langmuir wave interpretation, we find that many burst signals appear without corresponding electron measurements as shown in Table 1, where we have restricted the data to inside the optical shadow of the planet and X < -1.3 Rᵥ. Almost all of the 30-s intervals containing 5.4 kHz bursts do not contain any associated electron data in the tail region. For the 30 kHz bursts, on the other hand, the fraction of the intervals that do not have simultaneous electron density measurements is roughly the same as for the total sample. Thus, there is higher coincidence between than telemetry gaps. High resolution "pass plots" have been used to verify that for orbit 2093 (Figure 1) electron data were acquired at the time of the 5.4 kHz bursts (L. H. Brace, personal communication, 1993).

The waves at 5.4 kHz seen on these two orbits may be Langmuir waves generated in the very low density plasma or possibly ion acoustic waves. If these 5.4 kHz waves are Langmuir waves, their corresponding electron density should be around 0.3 cm⁻³. This is far below the usual measurement range of the Langmuir probe, and also far below any other densities measured to date in the Venus environment. On the other hand, ion acoustic waves are usually wideband, and have a cutoff at the ion plasma frequency. Although Doppler-shift may increase the observed frequency above the ion plasma frequency, the ion density should be around 400 cm⁻³ for H⁺ or 6.4 x 10³ cm⁻³ for O⁺ if the waves at 5.4 kHz are ion waves. These high densities are highly unlikely to occur in the tail region above 2000 km. Thus the narrowband 5.4 kHz waves are not ion acoustic waves.

In support of the Langmuir wave interpretation, we find that many burst signals appear without corresponding electron measurements as shown in Table 1, where we have restricted the data to inside the optical shadow of the planet and X < -1.3 Rᵥ. Almost all of the 30-s intervals containing 5.4 kHz bursts do not contain any associated electron data in the tail region. For the 30 kHz bursts, on the other hand, the fraction of the intervals that do not have simultaneous electron density measurements is roughly the same as for the total sample. Thus, there is higher coincidence between

![Fig. 3. Polarization patterns of the 30 kHz waves from Orbit 2093 and the 5.4 kHz waves from orbit 2531. In each panel the wave intensity (indicated by +) is plotted on a logarithmic scale as a function of spin phase, with the center of the circle corresponding to the minimum observed, and the radius of the circle corresponding to the maximum.](image-url)
electron density data gaps and the 5.4 kHz signals than the 30 kHz signals. The high degree of correlation between missing electron data and 5.4 kHz signals suggests that the density is too low to be observed in the tail by the Langmuir probe when the 5.4 kHz bursts occur. If these density data gaps were due to instrument operation, there should be no obvious difference between the two frequency channels.

Although Table 1 alone strongly suggests that the 5.4 kHz bursts are observed at times when the density is below the Langmuir probe threshold, we have verified this using the Langmuir probe periapsis pass plots. There are 36 orbits on which one or more 5.4 kHz burst intervals are present. Of these 36 orbits, pass plots are available from the Planetary Data System Particles and Fields node (supplied to PDS by L. H. Brace) for 31 orbits. Data are acquired by the Langmuir probe when the 5.4 kHz bursts occur for all these orbits, although the observed density may be below the 2 cm\(^{-3}\) threshold set by the experimenters. This has also been verified by L. H. Brace (personal communication, 1993).

We also test the polarization of waves at 30 kHz and 5.4 kHz, as shown in Figure 3. The line labeled B gives the average direction of the magnetic field in the spin plane, with the arrow head giving the fraction of the field in that plane. The line labeled E gives the maximum variance direction of the wave intensity. For a Langmuir wave, we expect that wave intensity is largest when the electric field antenna is aligned with the background magnetic field direction. Figure 3 shows that the maximum intensities of both waves are generally parallel to the ambient magnetic field. Thus, these waves must be longitudinal, electrostatic Langmuir waves. The 5.4 kHz signals are low density plasma oscillations.

Plasma Cavity in Venus Tail

We previously found that the high frequency narrowband waves only appear in the low density tail region (X < -1.3 R\(_v\)) [Ho, 1993]. Because there are no electron data in very low density regions, we can only examine the dependence on the magnetic field strength for waves occurring at 30 kHz and 5.4 kHz in the tail region. Figure 4 shows this dependence for the nightside upper ionosphere and tail. In the upper panel, we see that the 30 kHz signals peak between 16 and 18 nT. The average magnetic field is 17.3 nT. In the lower panel, the 5.4 kHz signals mainly appear between 14 and 26 nT. The average value is 18.6 nT. Thus, we see that the 5.4 kHz signals occur in stronger magnetic fields than the 30 kHz signals.

Assuming pressure balance in the tail [Brace et al., 1987], and ignoring dynamic pressure inside the tail lobes, the plasma parameters at two locations (1 and 2) where 30 kHz signals and 5.4 kHz signals are separately observed can be related through

\[
\frac{(B_1^2 - B_2^2)}{2 \mu_0} = n_1 k_B T_1 (1 - \frac{n_2 T_2}{n_1 T_1})
\]

For 30 kHz waves, \(n_1 = 10 \text{ cm}^{-3}\), \(B_2 = 17.2 \text{ nT}\), and for 5.4 kHz waves, \(n_2 = 0.3 \text{ cm}^{-3}\), \(B_2 = 18.6 \text{ nT}\). Hence, \(n_2/n_1 \approx 0.03\), and assuming \(T_2/T_1 \approx 0(1)\), \(n_2 T_2 \ll n_1 T_1\). We find that the electron temperature in the low density region \((T_1)\) is about 13 eV. Note that \(T_2\) has to be 400 eV for \(n_2 T_2 \approx n_1 T_1\). An electron temperature of 13 eV is reasonable. The OETP does not give reliable electron temperatures for very low density plasma, but we would expect that the temperature in the tail lobes to be less than in the magnetosheath where the electrons usually have temperature around 50 eV.

The Langmuir oscillations in the magnetotail of Venus are probably not caused by a beam instability similar to that of the electron foreshock, where energetic electrons are generated at the bow shock. Instead, we suggest that they may be driven by electron heat flux from the solar wind propagating through a weak cold ionosphere, but without accurate knowledge of the electron distribution function this suggestion can only remain somewhat speculative. It is perhaps surprising that the density in the tail lobes is much less than that of the magnetosheath to which we believe the field lines connect. However, the magnetosheath ions are convected downstream by the solar wind motional electric field. The magnetosheath electrons have thermal velocities much higher than the ion flow speed, but they will be coupled to the ion motion through ambipolar electric fields. Hence, the electrons cannot flow freely along the magnetic field into the near-tail region, and a wake will form behind the planet. Above 2000 km altitude the ionospheric density falls to very low values, and the exclusion of solar-wind/magnetosheath plasma from the wake will result in a very low density cavity.

Through the spatial distribution of the Langmuir wave activity we can attempt to locate regions of low density plasma. In Figure 5, we have used an upstream magnetic coordinate system to order the 30 kHz and the 5.4 kHz plasma wave data. The data are restricted to ±0.2 R\(_v\) in the direction perpendicular to the magnetic equatorial plane defined by the upstream IMF and the solar wind flow. From the distribution of the 5.4 kHz wave occurrence, we see that the plasma cavity is found on both sides of the central current sheet, in the center of two lobes in the magnetic equatorial plane. Inside the current sheet the plasma density should be higher, and we see that some 30 kHz waves appear in this region. Although not shown here, we find no ordering of wave activity in the noon-midnight magnetic meridian plane. Furthermore, in Figure 5, we find that the 30 kHz waves peak in the altitude range of 2000 – 2300 km, rather than the highest altitude region. However, the 5.4 kHz (0.3 cm\(^{-3}\) level) burst activity peaks in the highest region where

\[\text{Fig. 4. Relationship between burst activity and magnetic field for } X < -1.3 \text{ R}_v. \text{ The } 30 \text{ kHz signals (upper panel) often occur in the weaker magnetic field, while the } 5.4 \text{ kHz signals (lower panel) peak in the stronger magnetic field.}\]
Particles and Fields node at UCLA for providing high resolution plots of the OETP data. This work was supported by NASA under grants NAG2–485, NAG2–501, NAGW–3492, and NAGW–3497.

References


C. M. Ho, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

C. T. Russell* and R. J. Strangeway, Institute of Geophysics and Planetary Physics, University of California at Los Angeles, Los Angeles, CA 90024-1567

(Received: July 1, 1993; revised: September 28, 1993; accepted: November 5, 1993)