

## PLASMA WAVES OBSERVED AT LOW ALTITUDES IN THE TENUOUS VENUS NIGHTSIDE IONOSPHERE

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*Abstract.* The Pioneer Venus Orbiter Electric Field Detector (OEFD) measured many plasma wave bursts throughout the low altitude ionosphere during the final entry phase of the spacecraft. Apart from 100 Hz bursts observed at very low altitudes ( $\sim 130$  km), the bursts fall into two classes. The first of these is a wideband signal that is observed in regions of low magnetic field, but average densities, in comparison to the prevailing ionospheric condition. This wideband signal is not observed in the 30 kHz channel of the OEFD, but is restricted to the 5.4 kHz channel and lower. Since these bursts are observed with roughly constant burst rate above 160 km altitude, we attribute them to ion acoustic mode waves generated by precipitating solar wind electrons. The second type of signal is restricted to 100 Hz only, and is observed in regions of low electron beta, consistent with whistler-mode waves. These waves could be generated by lightning in the Venus atmosphere if the vertical component of the magnetic field  $> 3.6$  nT. Unfortunately, the spacecraft spin axis is mainly horizontal, and only that component of magnetic field can be measured. Alternatively, the 100 Hz bursts could be generated locally through gradient drift instabilities, provided the ambient magnetic field is horizontal. Because the ionosphere is very different during the entry phase, compared to the ionosphere as observed early in the Pioneer Venus mission, any conclusions regarding the source of the plasma waves detected during entry phase cannot be applied directly to the earlier observations.

## Introduction

The last periapsis data before atmospheric entry of the Pioneer Venus Orbiter were acquired on October 7, 1992. Immediately prior to this, there were some 50 passes of the nightside ionosphere of Venus with periapsis altitude  $< 200$  km. At this time solar activity was waning, while solar activity was high early in the mission (1979 – 1980), when the spacecraft initially sampled the low altitude nightside ionosphere. The entry phase period therefore provided an opportunity to compare observations at solar intermediate levels with solar maximum. The density of the nightside ionosphere was lower during the entry phase [Theis and Brace, 1993], and the ionosphere was a moderate beta plasma, as

opposed to high beta at solar maximum [Russell et al., 1993] (beta is the ratio of thermal to magnetic pressure).

As expected, the nightside ionosphere of Venus was quite different during entry phase from that observed early in the Pioneer Venus mission. In this letter we will describe some of the plasma waves observed during the entry phase. Many of the observations are reminiscent of the plasma waves previously reported as being due to atmospheric lightning (see the reviews of Russell [1991] and Strangeway [1991] for a more complete discussion of the early mission plasma wave observations). However, the ionosphere during entry phase is sufficiently dissimilar from the ionosphere at solar maximum that conclusions based on the entry phase observations cannot be applied directly to the earlier observations. In particular, while higher frequency bursts detected during entry phase are almost certainly locally generated, similar (but not identical) bursts observed early in the mission are more likely due to atmospheric lightning.

100 Hz bursts are also observed during entry phase. Very intense bursts are detected at lowest altitudes ( $\sim 130$  km), and these could be the direct measurement of radiation from atmospheric discharges [Strangeway et al., 1993]. 100 Hz bursts are also detected at higher altitudes. While a lightning source might explain these bursts, they are observed in regions of low electron density, and could be generated by the vertical density gradient in the topside ionosphere.

## Data Examples

Plasma wave data from orbit 5047 (September 29, 1992) are shown in Figure 1. The top four panels give the plasma wave intensity as measured by the four OEFD channels, in descending order, 30 kHz, 5.4 kHz, 730 Hz and 100 Hz. Wave bursts, identified using the technique described by Ho et al. [1991, 1992], are indicated by plus symbols below each wave intensity trace. The spin-axis component of the magnetic field is given below this. In this panel we have drawn a baseline of  $-26$  nT, which is the median magnetic field offset [Russell et al., 1993]. The high resolution electron density, as measured by the Langmuir probe, is shown in the bottom panel as open circles. However, these data have a different temporal resolution than the plasma wave and magnetic field data. In determining the dependence of the wave bursts on the electron measurements we have quadratically interpolated the electron data. The resultant interpolated data are given by the solid line passing through the circles.

Wideband bursts are often detected during the entry phase interval, and have many of the characteristics of the data shown in Figure 1. Another example is given in Figure

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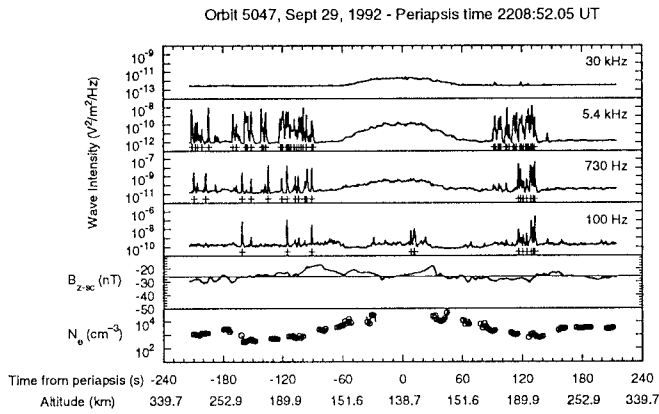


Fig. 1. Plasma wave data acquired on orbit 5047. Eight minutes of data are shown, centered on periapsis. The top four panels show the plasma wave intensity, together with a burst identifier, indicated by the plus symbols. The spin-axis component of the magnetic field is shown below the plasma wave data. The electron data are given in the bottom panel.

2 for orbit 5048 (September 30, 1992). The wideband bursts are observed both inbound and outbound, close to but not at periapsis. Additionally, no bursts occur at 30 kHz, unlike the wideband bursts observed near periapsis during the early Pioneer Venus mission [Ho et al., 1991].

Figure 3 shows an example of 100 Hz bursts observed on orbit 5051 (October 3, 1992) which are in some respects similar to the bursts shown in Figures 1 and 2, in that the bursts are observed both inbound and outbound, but not at periapsis. In this case, however, no bursts occur at higher frequencies. In addition, the spin-axis magnetic field is stronger when the isolated 100 Hz bursts occur.

One common feature in Figures 1 – 3 is the presence of a density trough at altitudes around 200 km, also discussed by Theis and Brace [1993]. There is some indication that the higher frequency waves occur within this trough.

### Altitude Profiles

We have investigated the wave burst dependence on the ambient plasma parameters as a function of spacecraft altitude, as shown in Figure 4, where the data are binned in 10 km altitude bins. In panel a) the 100 Hz burst rate and 5.4 kHz burst rates are shown. The wideband signals are well

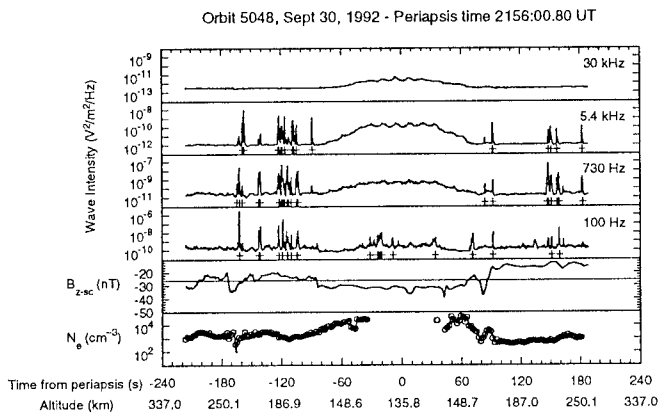


Fig. 2. Plasma wave data acquired on orbit 5048. Similar to Figure 1.

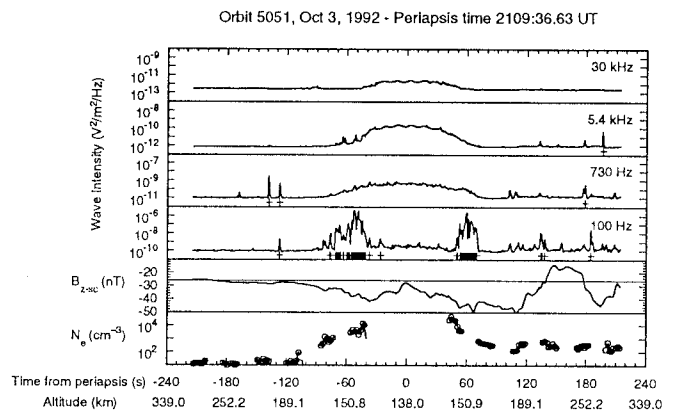


Fig. 3. Plasma wave data acquired on orbit 5051. Similar to Figure 1.

characterized by the 5.4 kHz channel. In calculating the burst rate we have taken into account the different data resolutions used during entry phase. We use an average burst rate at each altitude given by  $\sum n_j(1+\Delta t_j/\Delta t_1)/2\sum N_j\Delta t_j$ , where  $n_j$  is the number of bursts at a particular data resolution,  $N_j$  is the total number of samples,  $\Delta t_j$  is the temporal resolution of the data, and  $\Delta t_1$  is the shortest sampling interval. This rate is the average of two limiting cases, one that assumes all bursts are isolated, the other that assumes bursts are continuous within a sample. In the latter case we also assume that only one burst occurs per sample at the highest resolution, which was 0.5 s during entry phase, i.e.  $\Delta t_1 = 0.5$  s.

In Figure 4 the 100 Hz burst rate is largest at the lowest altitude. These bursts occurred on the last two orbits of the spacecraft (5054 and 5055) and may be due to atmospheric discharges being detected below the ionospheric density peak [Strangeway et al., 1993]. There is a minimum in the 100 Hz burst rate, and a second maximum in the 150 – 160 km altitude range. These bursts correspond to signals such as those shown in Figure 3. The 5.4 kHz rate increases to a roughly constant rate above 160 km altitude. These bursts correspond to wideband bursts as shown in Figures 1 and 2.

The rectified spin-axis component of the magnetic field is also shown in Figure 4. Prior to rectifying the field we have removed the -26 nT offset. The thick solid line gives the median value of the field for all data samples, while the thin line gives the median value when 100 Hz bursts occur, and the dotted line gives the median when 5.4 kHz bursts occur. Except at the lowest altitudes, the median field is the same for all the data and for 100 Hz bursts. On the other hand, the median field is lower when 5.4 kHz bursts occur.

The electron density is shown in panel c) of Figure 4. As noted previously, we have interpolated the electron data so that they have the same temporal resolution as the plasma wave data. We have compared medians of all the interpolated data, binned in 10 km altitude bins, with the original high resolution data and find the average ratio of the median interpolated data over the median original data =  $0.996 \pm 0.067$ , indicating that the interpolated data are representative of the original data. The electron data do not extend to the lowest altitudes because of possible contamination by ionization due to neutral impacts on the spacecraft.

The electron beta ( $\beta_e$ ) is plotted in panel d) of Figure 4. In calculating  $\beta_e$  we have used the electron temperature from

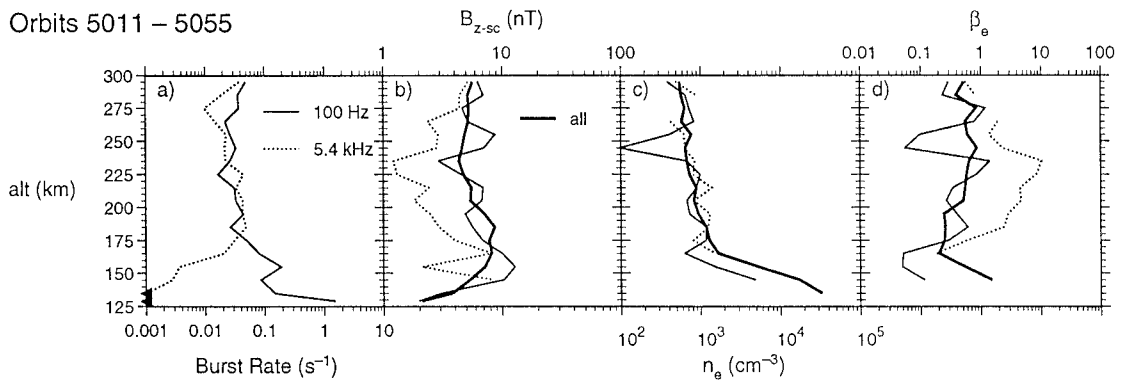


Fig. 4. Altitude profiles of the burst rate and plasma parameters for the entry phase interval (orbits 5011 – 5055). The burst rate for the 100 Hz (solid line) and 5.4 kHz (dotted line) channels are shown in panel a). The arrows mark those altitude bins for which the 5.4 kHz burst rate is  $< 0.001$  bursts/sec. The medians of the rectified spin-axis magnetic field (b), electron density (c), and electron beta (d) are also shown. The medians are calculated for all samples (thicker solid line), samples when 100 Hz bursts occur (thin solid line), and when 5.4 kHz bursts occur (dotted line).

lower (12 s) resolution data. Because these data, referred to as UADS data, are more sparse than the high resolution data we have not interpolated these data. Instead, we have binned the UADS data as a function of altitude and used the same electron temperature profile for all of the  $\beta_e$  calculations. In addition, following the analysis of Russell et al. [1993], we have multiplied the rectified spin-axis component of the magnetic field by 2.5 to obtain the total magnetic field.

Figure 4 shows that the 100 Hz bursts occur in regions of  $\beta_e < 1$ , indicating that these waves are whistler-mode waves, which are weakly damped in a low  $\beta_e$  plasma [Strangeway, 1992]. At lowest altitudes, where  $\beta_e$  is usually larger, the 100 Hz bursts occur in regions of reduced density and enhanced field. By way of contrast, the 5.4 kHz bursts occur in high beta regions, but this is because the spin-axis component of the ambient field is reduced, rather than an enhancement in density. Again, we note that the magnetometer only measures the spin-axis component of the field, and we assume that the total field is proportional to this component.

Plasma waves were detected at low altitudes during the early part of the Pioneer Venus mission, and we include data from Season III (orbits 484 – 560) in Figure 5, using a similar analysis to that used in Figure 4. The main difference in the analysis is that high resolution temperature data are also available, and we have used these data rather than lower resolution UADS data. Considering the 100 Hz bursts first, we see that the 100 Hz burst rate decreases slowly with increas-

ing altitude. The 100 Hz bursts occur in regions of enhanced magnetic field and slightly reduced density. As a consequence, the 100 Hz bursts occur mainly in regions of low  $\beta_e$ , which is required both for whistler-mode propagation from lightning [Strangeway, 1992], and also for generation by the lower hybrid drift instability [Huba, 1992]. In the latter case, however, collisions tend to reduce the instability, suggesting that the lower hybrid drift would be more likely to occur at higher altitudes. The 5.4 kHz bursts, on the other hand, occur mainly at lowest altitude, in regions with somewhat reduced density, but typical magnetic field strengths.

## Conclusions

The nightside ionosphere of Venus is markedly different during the entry phase of the Pioneer Venus mission, in comparison to data acquired earlier in the mission. The plasma beta is of order unity during the entry phase, while the beta was much higher in Season III [Russell et al., 1993].

During the entry phase 100 Hz bursts are found to occur in regions of low electron beta, suggesting that these bursts are whistler-mode. A similar property of the 100 Hz bursts was also found earlier in the mission. It is therefore possible that 100 Hz bursts like those shown in Figure 3 could be generated by lightning, although the symmetry of the bursts with respect to periapsis is puzzling. Perhaps the spacecraft encounters a layer of enhanced magnetic field at higher alti-

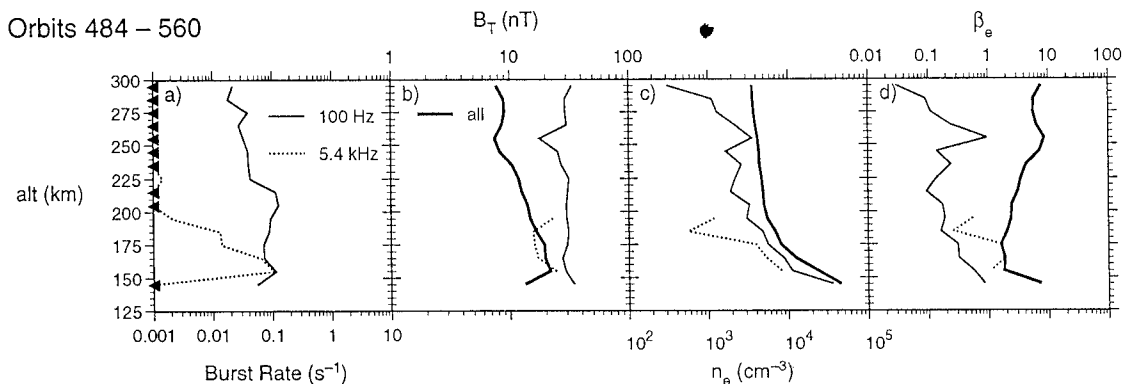


Fig. 5. Altitude profiles of the burst rate and plasma parameters for season III (orbits 484 – 560). Similar to Figure 4.

tudes, which allows whistler-mode waves to escape from the atmosphere. However, without a measurement of the radial field, we can only speculate that the field actually penetrates to lower altitudes. Moreover, this must occur at some distant location since the bursts in Figure 3 are not continuous through periapsis, and the wave ray path is not locally vertical. (It is important to note that while the wave vector will be vertical for escaping whistler-mode waves due to refraction, the ray path is still mainly field-aligned.) The vertical field must be  $> 3.6$  nT all along a ray path for 100 Hz whistler-mode waves to escape and it is by no means clear that this condition will be satisfied. The field is very weak at lowest altitudes, with a spin-axis component of only a few nT.

Alternatively, the field may be horizontal when the 100 Hz bursts occur, and a gradient drift instability [Huba, 1992] could be present since the field is perpendicular to the vertical density gradient. In Season III, however, the 100 Hz bursts are found for much higher densities, where collisions are likely to stabilize the gradient drift instability, and the bursts tend to occur for be vertical fields [Ho et al., 1992], so that the vertical density gradient is field-aligned. While the 100 Hz bursts detected at higher altitudes during the entry phase could be locally generated, this does not preclude the low altitude bursts detected early in the Pioneer Venus mission and at  $\sim 130$  km during entry phase [Strangeway et al., 1993] from being due to atmospheric lightning.

Wideband bursts detected during in entry phase appear to be different than those observed at low altitudes earlier in the mission. First, the bursts tend to occur above 160 km altitude, and the burst rate is constant with altitude  $> 160$  km. Second, the bursts are a low magnetic field phenomenon. Third, no bursts occur in the 30 kHz channel. During Season III the wideband bursts occurred at low altitudes, in slightly reduced density regions, and also occurred at 30 kHz (see, e.g., Ho et al. [1991]). The ion plasma frequency is  $\sim 1.7$  kHz for an oxygen plasma with density  $10^3$  cm $^{-3}$ . Even with Doppler-shift it would be difficult to increase this frequency to 30 kHz. We therefore suggest that the wideband waves detected at higher altitudes during the entry phase are ion acoustic mode waves, perhaps generated by solar wind electrons precipitating into the ionosphere. These electrons are also mainly responsible for maintaining the nightside ionosphere during low solar activity [Gringauz et al., 1979; Knudsen et al., 1987]. In this regard, the wideband bursts detected during entry phase cannot be used to infer a lack of association with lightning for the wideband bursts detected earlier in the Pioneer Venus mission, which occurred at lower altitudes and earlier local times.

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