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OBSERVATION OF INTENSE WAVE BURSTS AT VERY LOW ALTITUDES WITHIN THE VENUS NIGHTSIDE IONOSPHERE

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Abstract. Intense ELF (100 Hz) bursts were detected by the Pioneer Venus Orbiter plasma wave instrument during the final operations of the spacecraft prior to atmospheric entry. These bursts were detected at ~ 130 km altitude around 0400 local time. The wave activity lasted for several tens of seconds. Furthermore the bursts were not symmetric about periapsis, unlike instrument noise caused by neutral impacts on the spacecraft. The bursts had a vertical attenuation scale height of the order 1 km, consistent with that expected for whistler-mode waves propagating through a collisional ionosphere. Since the decay of the signals appears to be due to attenuation, the source must persist for several tens of seconds. The wave bursts could therefore be the signature of electromagnetic radiation entering the bottomside ionosphere from several distant sources, as would be expected if lightning were a relatively persistent phenomenon within the Venus atmosphere.

Introduction

The Pioneer Venus Orbiter was allowed to descend to extremely low altitudes (< 140 km) during the final series of nightside periapsis passes prior to final atmospheric entry. This sequence of orbits provided an opportunity to measure plasma waves at altitudes not previously encountered by the spacecraft. One of the goals of the entry phase was to determine if the plasma wave signals previously attributed to lightning (see, for example, the review by Russell [1991]) were detected at these low altitudes. In particular, it may be possible to measure directly the electromagnetic radiation from an atmospheric discharge if the spacecraft were to descend below the ionospheric density peak. Such an observation would provide strong confirmation for the lightning hypothesis. However, it should be noted that local plasma instabilities have also been suggested as a possible explanation for the wave bursts. Recently, Huba [1992] has invoked the lower hybrid drift instability as an alternative hypothesis, but this instability can be quenched through collisions. The collision frequency is usually larger than the lower hybrid frequency at altitudes < 140 km.

The spacecraft and instruments were not designed for flight through a fairly dense neutral atmosphere at a velocity around 10 kms^{-1}, and many of the particle detector data were contaminated by effects due to neutral impacts at the lowest altitudes. Furthermore, the plasma wave instrument was also affected by neutral impacts. However, as we shall argue here, the effects of neutral impacts on the plasma wave instrument (referred to as the Orbiter Electric Field Detector or OEFD) are at least partially understood, sufficient for us to discriminate between naturally occurring signals and those due to spacecraft interactions.

In this letter we will present data from the lowest periapsis passes of the Pioneer Venus Orbiter, where intense bursts of 100 Hz waves were detected. We will briefly discuss the properties of the interference due to spacecraft – atmosphere interactions, showing why the 100 Hz waves are likely to be naturally occurring signals. We will further show that the altitude dependence of the wave intensity is consistent with attenuation due to collisions. The 100 Hz bursts therefore have the properties we expect for signals entering the bottomside of the ionosphere, thus providing evidence for direct observation of electromagnetic radiation due to atmospheric discharges, such as lightning.

Low Altitude Data

Figure 1 shows the last periapsis pass of plasma wave data, acquired on Orbit 5055. Periapsis for this orbit occurred around 0420 local time. Four minutes of data are shown, centered on periapsis indicated by the vertical line in the middle of the plot. The wave intensities as measured by the four OEFD channels are given at the top of the figure. The symbols below each trace mark wave bursts as determined using the identification technique discussed by Ho et al. [1991, 1992]. The spin-axis aligned component of the magnetic field is given in the bottom panel. Only this component of the magnetic field was measured during the entry phase, and furthermore, there appeared to be a large magne-

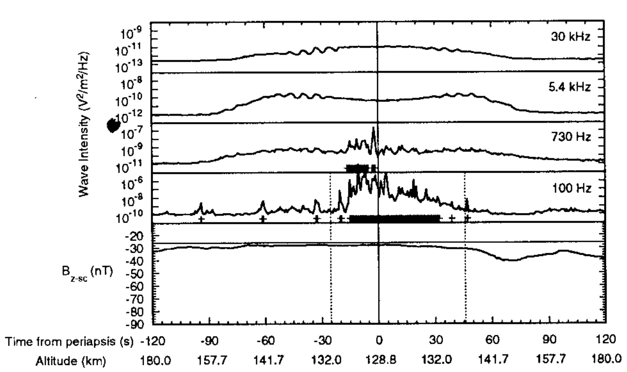

Fig. 1. Plasma wave data acquired during the last periapsis pass received from the Pioneer Venus Orbiter (orbit 5055, Oct. 7, 1992). Four minutes of plasma wave and magnetic field data are shown, centered on periapsis.

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tometer offset of –26 nT [Russell et al., 1993], indicated by the baseline for the magnetic field data. To give an estimate of the uncertainty in this offset, we binned the magnetic field data from orbits 5011 – 5055 in 10 km altitude bins for altitudes < 300 km. The median magnetic field per 10 km bin was on the average –26.07 ± 1.39 nT. The median value tended to be slightly more negative at the lowest altitudes.

The most striking feature in the plasma wave data is the intense burst of 100 Hz waves around periapsis. As we discuss below, this burst may be due to atmospheric discharges measured by the Pioneer Venus Orbiter below the ionospheric density peak. The vertical dashed lines show the time interval we will use later to determine the scale height of the wave burst. The burst occurs in a region of relatively weak magnetic field, but whistler mode propagation can occur at 100 Hz provided the ambient magnetic field ≥ 3.6 nT. We also note the presence of weak 730 Hz bursts correlated with the most intense 100 Hz bursts. These signals are probably above the gyro-frequency, and hence likely to be strongly attenuated. The other feature in the wave data is the relatively uniform enhancement in wave noise in the three higher frequency channels. The enhancement is most clearly observed in the 5.4 kHz channel. This noise has previously been attributed to ionization of the neutral atmosphere on impacting the spacecraft with a relative speed of 10 kms^{-1}, corresponding to an impact energy of 23 eV for CO_2. Electrons and ions created through impact have a relative drift, and so create plasma waves [Curtis et al., 1985]. The figure shows that this signal due to the spacecraft interaction with the ambient atmosphere is symmetric about periapsis, unlike the 100 Hz bursts.

Both the impulsive 100 Hz signals and the periapsis interference signals are also observed on the previous orbit (5054) as shown in Figure 2. Periapsis altitude was 2 km higher for this orbit than for orbit 5055. Figure 2 also shows 100 Hz bursts at higher altitudes (> 150 km inbound, > 140 km outbound). These bursts are generally observed in regions of enhanced magnetic field, and hence low electron beta, $\beta_e = 2\mu_0 n_e k_b T_e / B^2$, where μ_0 is the permeability of free space, n_e is the electron density, k_b is the Boltzmann constant, T_e is the electron temperature and B is the ambient magnetic field strength. The 100 Hz waves observed earlier in the Pioneer Venus mission also tended to occur in regions of low β_e [Strangeway, 1992], and the higher altitude bursts in Figure 2 may be whistler mode waves escaping from the atmosphere. However, in a companion paper, Strangeway et al. [1993] note that these bursts would probably have had to propagate some large horizontal distance in the ionosphere if they were lightning generated. This requires a vertical magnetic field component > 3.6 nT all along the ray path, and Strangeway et al. [1993] suggest that the 100 Hz and higher frequency bursts observed above ~ 160 km altitude during the entry phase are probably not lightning generated.

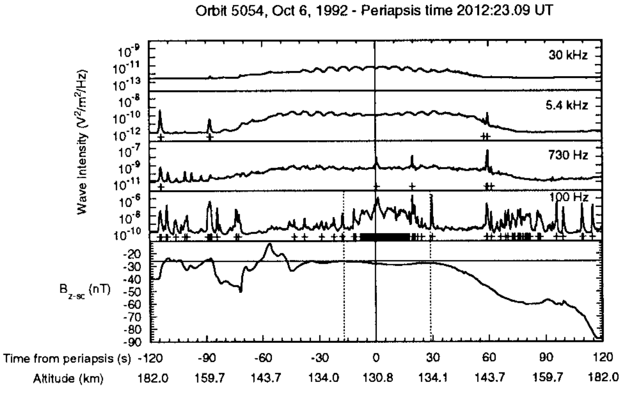

Fig. 2. Plasma wave data acquired on orbit 5054 (Oct. 6, 1992). Similar in format to Figure 1.

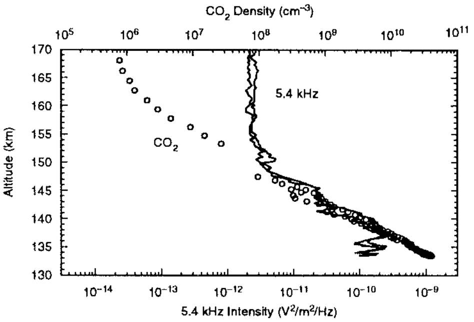

Fig 3. 5.4 kHz wave intensity and neutral CO_2 density plotted as a function of altitude for orbit 5044. The open circles give CO_2 density, while the solid line gives wave intensity. Both have been plotted over a six decade range.

Periapsis altitude on orbits 5054 and 5055 was the lowest of the entire Pioneer Venus mission. Intense 100 Hz activity lasting for tens of seconds was observed around periapsis only for these two orbits, although weaker and more sporadic 100 Hz waves were also detected around periapsis on earlier orbits. It is possible that the wave bursts were caused by signals propagating away from atmospheric discharges (i.e. lightning) in the surface – ionosphere wave guide. Alternatively, the bursts could simply be due to some interaction of the spacecraft with the ambient neutral atmosphere and ionosphere. However, the impact ionization noise, which is thought to be due to interactions with the neutral atmosphere, is clearly symmetric about periapsis. This at least indicates that the 100 Hz bursts around periapsis may be natural signals not caused by some spacecraft interaction. We cannot completely discount other spacecraft effects, such as outgassing due to heating of the spacecraft, but without an associated modification to the impact ionization, it is not clear why there would be a plasma wave response.

To emphasize some of the properties of the impact ionization noise, we plot the 5.4 kHz wave intensity and neutral CO_2 density as a function of altitude in Figure 3. The 5.4 kHz intensity reaches background above 150 km. Below 137 km the wave intensity appears to plateau, although there is some spin modulation of the signal. Curtis et al. [1985] argued that the wave amplitude of the impact ionization noise should be proportional to the square root of the neutral CO_2 density. This appears to be the case above 137 km altitude. However, there is no obvious explanation for the plateau in the wave intensity at lower altitudes. The data in Figures 1 and 2 show, in fact, that the 5.4 kHz noise level actually decreases at the lowest altitudes. On the other hand, the 30 kHz noise level does not show any similar reduction in intensity. Clearly, there is some frequency dependence in the noise, which could either be due shifting to higher frequencies at lower altitudes, or differences in coupling between the antenna and the plasma for different frequencies perhaps due to changes in Debye length. We further note that at these lowest altitudes the orbiter may have passed below the ionospheric density peak (P. A. Cloutier, personal communication, 1993). The plasma wave instrument response to impact ionization noise may consequently be more complicated than as originally discussed by Curtis et al. [1985], and warrants more detailed analysis using the entry phase data.

Wave Burst Scale Heights

The 100 Hz bursts detected near periapsis are not symmetric about periapsis, unlike the impact ionization noise. We might speculate, for example, that the signal detected on orbit 5055, shown in Figure 1, turns on rapidly around 1946:10 UT and persists for at least a minute, with the slow decay being caused by attenuation of the signal by collisional damping as it propagates to higher altitudes. Huba and Rowland [1993] present a theoretical analysis of the vertical propagation of whistler mode signals through the bottomside of the nightside ionosphere, assuming a vertical magnetic field. In the strong magnetic field limit the wave amplitude attenuation scale $\lambda_0 \approx 2(c/\omega_{pe})[\Omega_e/(\nu_{en}+\nu_{ei})][\Omega_e/\omega]^{1/2}$, where c is the speed of light, ω_{pe} is the electron plasma frequency, Ω_e is the electron gyro-frequency, ν_{en} and ν_{ei} are electron–neutral and –ion collision frequencies and ω is the wave frequency. Vertical propagation is to be expected because of refraction [Sonwalkar et al., 1991; Ho et al., 1992], but Figures 1 and 2 show that the magnetic field can be quite weak at low altitudes, and probably not vertical. Assuming the ambient field makes an angle θ_{br} to the vertical (or radial direction), the quasi-parallel (or quasi-longitudinal) approximation to the Appleton-Hartree dispersion relation including collisions [Clemmow and Dougherty, 1969] gives

$$\lambda_0 \approx 2\frac{c}{\omega_{pe}}\frac{(\Omega_e\cos\theta_{br}-\omega)}{(\nu_{en}+\nu_{in})}\left[\frac{(\Omega_e\cos\theta_{br}-\omega)}{\omega}\right]^{1/2} \qquad (1)$$

Huba and Rowland [1993] show that at altitudes around 130 km the total electron collision frequency is approximately constant, ≈ 100 s^{-1}, which on substitution into (1) gives the attenuation scale heights for 100 Hz waves shown in Table 1. The 730 Hz wave bursts observed near periapsis on orbit 5055 will be attenuated on scales of order the plasma skin depth. They would therefore only be detected in association with the most intense 100 Hz bursts.

In Figures 4 and 5 we plot the altitude profile of the 100 Hz wave intensity for orbits 5055 and 5054 respectively. In these figures we have restricted the data to those time intervals indicated by the vertical dashed lines in Figures 1 and 2. The data ranges were chosen since the signals had essentially decayed to background at the end points. Any data included from higher altitudes, be they background or bursts, would bias the linear regression analysis used to calculate scale heights to longer scales. From the linear regression we have inferred a scale height for amplitude decay for both the inbound and outbound portions of the orbit, labeled λ_0. The correlation coefficient for each fit is given by r. As might be expected from the time series, λ_0 is much shorter for the inbound leg for orbit 5055 (Figure 4). Somewhat surprisingly, this is also true for orbit 5054 (Figure 5). Nevertheless, the range of scale heights for the waves is consistent with Table 1. Implicit in our calculation, however, is the presence of a few nT vertical field, which cannot be resolved by the magnetometer since the spin-axis sensor is aligned nearly horizontally at periapsis. Figures 1 and 2 show that the magnitude of the spin-axis component of the magnetic field increases for the outbound portion of both orbits. An associated change in the vertical component would increase the attenuation scale height.

Table 1. 100 Hz Attenuation Scale Lengths

	λ_0 (km)		
n_e (cm^{-3})	B_r = 5 nT[a]	B_r = 10 nT[a]	c/ω_{pe} (km)[b]
10^3	0.53	5.1	0.17
10^4	0.17	1.6	0.05

[a] $B_r = B\cos\theta_{br}$, $B_r > 3.6$ nT for vertical whistler-mode propagation at 100 Hz.

[b] plasma skin depth, attenuation scale for $\omega > \Omega_e\cos\theta_{br}$.

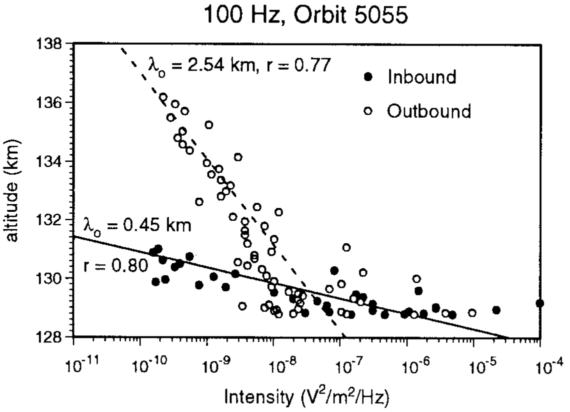

Fig. 4. Altitude profile of the 100 Hz wave intensity for orbit 5055. The solid (dashed) line gives a fit to the inbound (outbound) profile. λ_0 gives the inferred scale height from the fit, with r giving the associated correlation coefficient.

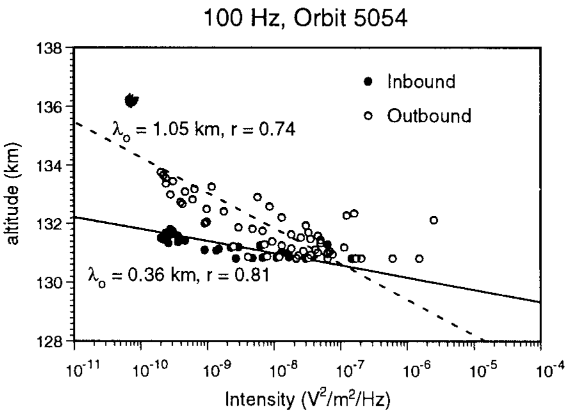

Fig. 5. Altitude profile for orbit 5054. Similar in format to Figure 4.

Conclusions

The entry phase of the Pioneer Venus Orbiter provided an opportunity to measure wave electric fields at altitudes never previously encountered by the spacecraft. Intense 100 Hz bursts were detected around periapsis on the last two periapsis passes. The 100 Hz activity lasted for several tens of seconds, and no similar activity was observed around periapsis on any of the previous passes. These bursts therefore appear to be a low altitude (~ 130 km) phenomenon. Furthermore, the bursts were not symmetric about periapsis, unlike the impact ionization noise. The impact ionization noise depends on neutral CO_2 density, although this dependency breaks down at lowest altitude. The lack of symmetry and long duration of the 100 Hz bursts argues for a naturally occurring phenomenon such as atmospheric lightning, although spacecraft – atmosphere interactions cannot be completely discounted.

In support of this interpretation we calculated scale heights for the bursts, and found that the inferred scale heights were consistent with that predicted by theory for reasonable values of the electron collision frequencies and number density. In calculating the theoretical scale heights, however, it was necessary to assume a few nT vertical magnetic field. In addition, we found a clear asymmetry in scale heights for the inbound and outbound portions of the bursts, with the inbound interval showing a much shorter scale height in both cases. We could attribute the short scale height to the intrinsic rise time of the wave source, rather than attenuation in the ionosphere, but we would not then expect both orbits to display similar behavior. Instead, it appears more likely that the atmospheric signals are relatively constant, and in both cases the ionosphere is more transparent to whistler-mode waves on the outbound portion of the orbit. In support of this we noted that the magnitude of the spin-axis component of the magnetic field is increasing for the outbound leg of each orbit. This could result in larger attenuation scale heights, assuming an associated increase in the radial component of the field.

The entry phase data were acquired in the pre-dawn local time sector, while Russell [1991] has suggested that lightning, if it occurs on Venus, is a dusk-related phenomenon. In reviewing some of the arguments both for and against the lightning hypothesis, Strangeway [1991] noted that the 100 Hz signals may propagate some distance from the source in the surface – ionosphere waveguide. The data presented here could correspond to ambient wave noise caused by lightning occurring at locations quite remote from the point of observation. In conclusion, the intense 100 Hz wave bursts observed near periapsis during the final two periapsis passes may be the direct sub-ionospheric detection of atmospheric discharges by the Pioneer Venus Orbiter.

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