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VENUS PLANETARY LIGHTNING RATE AS DEDUCED FROM VLF BURSTS

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ABSTRACT

Statistical studies of the VLF bursts detected in the nightside ionosphere of Venus show that the bursts fall into two classes. The first consists of signals detected when vertical propagation within the whistler-mode resonance cone is allowed. The second consists of signals whose burst rate decreases rapidly as a function of increasing altitude, with a scale height of about 20 km. These non-whistler-mode signals also display a strong dependence on local time, with the burst rates being largest in the post-dusk local time sector. Since these signals are not propagating we assume that they correspond to a "near-field" or prompt response to a lightning stroke. As such we can use these signals to estimate the planetary lightning rate, and we find that the rate at Venus is comparable to or greater than the terrestrial planetary rate of 100 flashes/sec.

INTRODUCTION

The speculation that lightning occurred on Venus has lasted over twenty years /1,2,3/. However, detailed analysis was not possible until the Pioneer Venus Orbiter (PVO) was inserted into the nightside ionosphere of Venus. The plasma wave instrument on board on PVO detected many bursts of VLF signals /4,5/. However, some authors have also questioned the lightning interpretation /6/, suggesting instead in situ plasma instabilities as a possible wave source.

Since we do not have any knowledge about Venus lightning, the properties of terrestrial lightning may guide us in interpreting observations at Venus. However, when we try to draw an analogy for Venus lightning, we note that there are some differences between the environments of Earth and Venus. For example, the main constituent of the Venus clouds is sulfuric acid, instead of water. The cloud layer of Venus also is at an altitude of 50 km, much higher than that at Earth. A study of lightning on Venus will help us to understand the differences and similarities between Earth and Venus in the atmospheric environment. It also helps in understanding lightning on Earth by providing examples of lightning in an atmosphere difference in composition. Through this study we may determine if lightning is important for atmospheric chemistry and if the lightning activity has a high enough rate to cause significant electrification and ionization processes. Thus, our purpose is to clarify the wave properties and to define the rate of Venus lightning.

WAVE PROPERTIES

We have performed morphological studies of the burst signals. After surveying all the nightside data, we find that there are essentially two types of VLF signals detected at the lowest altitudes in the nightside Venus ionosphere. One is a 100 Hz narrowband signal which always appears below the electron gyrofrequency f_{ce}, and has all the features expected of a whistler mode wave. These bursts are well correlated with strong, radial magnetic field and electron density depressions. The other is a wideband signal which can appears in all four frequency channels. These are more impulsive and have stronger intensity relative to the background noise in the higher frequency channels. These wideband signals are frequently associated with horizontal magnetic fields. However, both types of signals are more often observed at the spacecraft periapsis altitude. All these features may be found from orbit 531 as shown in Figure 1. The figure gives an example of two typical signals.

We can see that some wideband bursts appear around periapsis (in the middle of the figure). On the left-hand side some burst signals occur only in the 100 Hz channel. We have designated these narrowband signals as whistler signals. Also some interference spikes with 6 second period (half spacecraft spin period) appear in the 100 Hz channel. From the three bottom panels, we can see the correlation of the 100 Hz signals with the magnetic field and electron density.

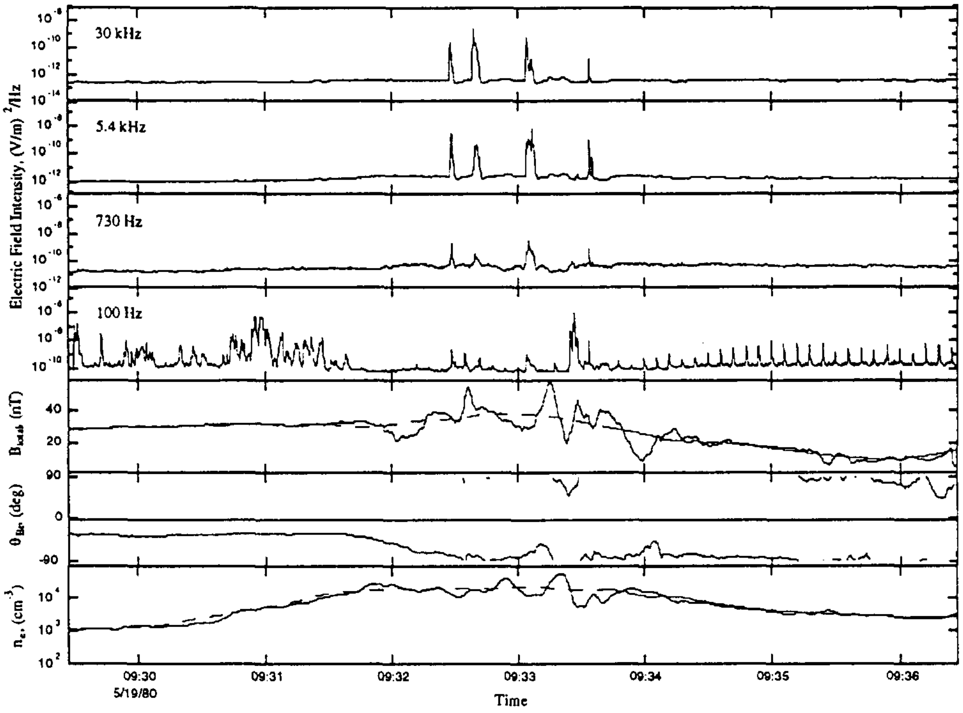

Figure 1. An example which shows two types of signals observed in the nightside ionosphere in orbit 531 in the four frequency channels. In the bottom three panels, the total magnetic field (B), the angle between B and the radial direction, and electron density (n_e) are shown. The dashed lines show the one minute average values of the high resolution data.

We show a quantitative representation of the dependence of the 100Hz burst activity on the variation of the magnetic field and electron density in the Figure 2. We calculate the ratio of the instantaneous electron density n_e (2 sec resolution) to the electron density $<n_e>$ averaged with 60 sec moving window. Then, we plot this ratio on a logarithmic scale as the abscissa in the top panel. If the electron density increases relative to the background average $<n_e>$, then this ratio will be greater than unity, and the log $n_e/<n_e>$ will be a positive number. A density depression corresponds to negative values. Using a similar definition we also plot the ratio of relative variation of the magnetic field in the bottom panel. We can see that these burst signals appearing only in the 100 Hz channel mainly occur when the electron density is depressed and the magnetic field is enhanced. The burst rates (solid line) are also greater for these conditions. When the magnetic field is depressed during most of the intervals (dashed line), burst activity was very low. Thus we infer that the magnetic field variation is a stronger control factor. By comparison, the control of burst activity by plasma density variation is relatively weak, because there is still some activity when density is enhanced. One reason for the magnetic field dependence is that strong magnetic field is usually associated with more radial field, which allows the wave vector to fall more easily within the whistler resonance cone. The other reason may be that both high magnetic field and lower electron density results in a lower β (ratio of thermal pressure to magnetic pressure) plasma, which favors the propagation of whistler wave. A low β region may act as a duct to trap and guide VLF waves. On the other hand, an in situ plasma instability should strongly depend on the plasma density gradient, instead of the relative density variation. We do not find an obvious dependence of these burst signals with density gradients. Thus, the correlation shown in the Figure 2 indicates that this is a wave propagation process, rather than local wave generation.

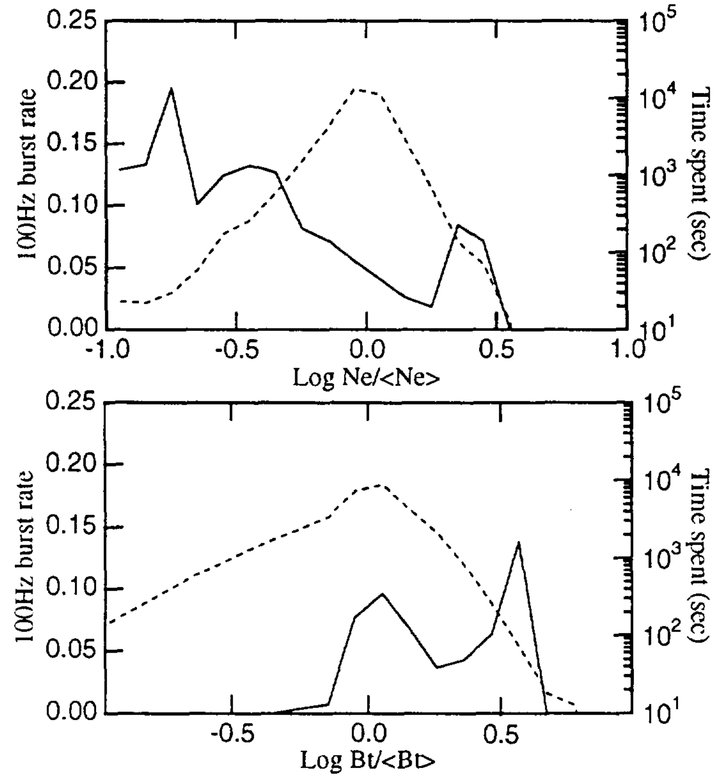

Figure 2. The dependence of the 100 Hz burst activity on relative variations of electron density (top panel) and magnetic field (bottom panel). Time coverage is also shown in both panels (dashed line).

Since terrestrial lightning has an obvious local time correlation, with activity peaking in the afternoon and evening local time, we have also examined the local time distribution of the two types of signals at Venus. Figure 3 shows signal occurrence rates versus local time for the four channels between 150-180 km in height. We see that there is 100 Hz activity throughout entire nightside. However, the higher frequency signals have a maximum around 20-22 LT and decrease toward dawn and dusk. All wideband signals seem to come from the same source. Post-midnight mainly 100 Hz signals appear.

This local time dependence may be explained as evidence of lightning activity in the atmosphere. There may be a wideband lightning source which occurs around the evening side, similar to the terrestrial lightning distribution. At dusk both high and low frequency signals will be strongly shielded from penetration due to higher ionospheric plasma density, so that they cannot be observed by PVO. At later local times the high frequency waves from this source may directly penetrate the ionosphere by some anomalous transmission mechanism as a "near field". The 100 Hz whistler waves can propagate with little damping in the surface - ionosphere waveguide to post-midnight local times and then pass through the ionosphere as a "far field".

For 100 Hz whistler waves, the resonance cone angle, θ_{res}, is an important parameter in testing whistler mode propagation. At 100 Hz the resonance cone angle is given by $\cos\theta_{res} = f / f_{ce}$, where $f_{ce} = 28B$ (nT), $f = 100$ Hz and the B is the total magnetic field strength. Due to the large refractive index of whistler mode waves in the ionosphere, Snell's law requires that waves entering the ionosphere from below propagate vertically in a horizontally stratified medium. In order to test for the propagation properties of the 100 Hz waves, we have also examined the altitude dependence for bursts both inside and outside the resonance cone as shown in Figure 4. Above 160 km altitude we find that the 100 Hz burst rate inside the resonance cone is much larger and decreases much more slowly than the signal outside the resonance cone. The 100 Hz signals outside the resonance cone, which cannot propagate in the whistler mode, decrease with a scale height of about 20 km. The 730 Hz, 5.4 kHz and 30 kHz signals, which also cannot propagate in the whistler mode, have a similar scale height.

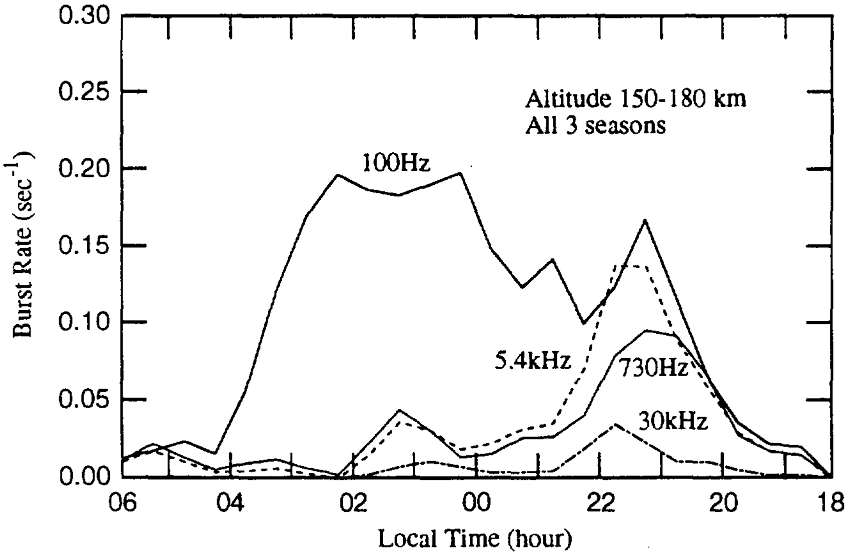

Figure 3. The local time distribution of burst occurrence rates for all four frequency channels between 150 and 180 km in altitude. The 100 Hz signals partially peak before midnight, but the maximum appears after midnight. Higher-frequency signals clearly peak at 20–22 LT.

The clear difference in scale heights shows that there are two different wave populations. When we perform this test, the only assumption is that the wave vector is vertical. The vertical propagation is a consequence of the refraction caused by the high refractive index encountered on entering the ionosphere from below. It is not clear why any in situ instability would also satisfy the assumption of vertically propagating whistler mode waves as a means for classifying the data /10,11/.

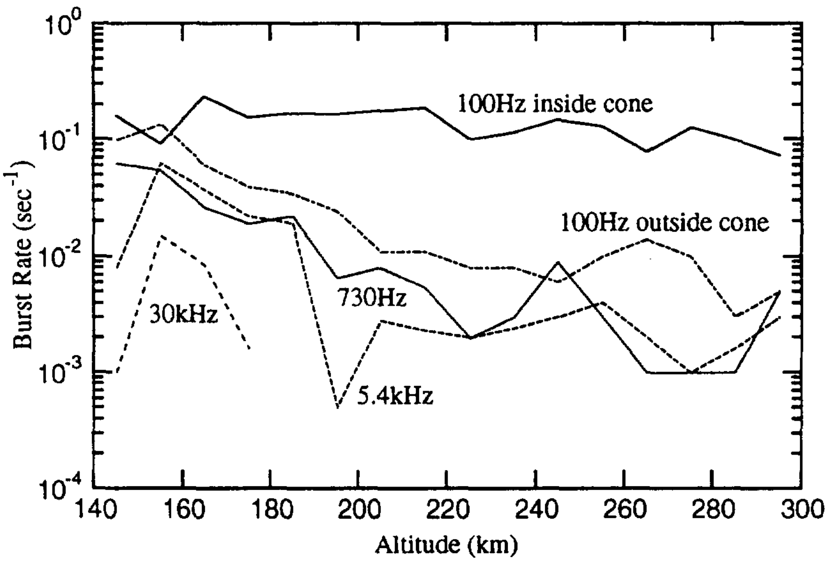

Figure 4. Altitude distribution of the 100 Hz signals inside and outside the resonance cone, and signals at 730 Hz, 5.4 kHz and 30 kHz. The burst rates are plotted on a logarithmic scale.

PLANET-RATE

Since the higher frequency signals such as the 5.4 kHz signal are a non-propagating wave, we assume they are from a "near field", and so probably better reflect local source activity than the 100 Hz waves which may have traveled some distance from the source. Using the burst rate given in the local time distribution we can estimate the planet-wide lightning rate at Venus and compare this with terrestrial lightning.

Because the cloud layer at Venus is as high as 50 km altitude, any lightning on Venus would be expected to be an intra-cloud discharge phenomenon and not cloud to ground. The PVO periapsis is near 150 km, and is consequently at least 100 km distance away from the cloud layer. We assume that the PVO can detect signals as far horizontally as the spacecraft is distant vertically. In addition, we assume that lightning occurs in the range 18-24 LT only and -30° to +30° latitude which corresponds to 1/8 planet surface, or in the range 12-24 LT which corresponds to 1/4 planet surface. We use the maximum burst rate 0.14/s of 5.4 kHz channel as the lightning occurrence rate over the locally active region. This gives a planet-wide burst rate of 250 per second for 1/8 of planet and 500 per second for 1/4 of planet. This is comparable to or greater than the terrestrial rate (about 100/sec) of lightning over all the planet /12/. Our burst rate of 0.14/s over 31,400 km^2 area is equivalent to a local burst rate of 140 bursts/km^2/terrestrial year. This maximum rate is much larger than the 2.7 bursts /km^2/terrestrial year estimated by Scarf and Russell /13/, but less than that obtained from optical data /14/. Estimates from Poynting flux calculations obtained a rate of 80 flashes per second /15/.

SUMMARY

Data from the PVO Electric Field Detector show that there are two types of VLF signals detected at the lowest altitudes in the nightside Venus ionosphere. The first type of signal is observed only in the 100 Hz channel and not in any of the higher frequency channels. This signal is well correlated with strong magnetic field and lower electron density, that is, a low β plasma. The propagation of these 100 Hz signals is clearly restricted by the whistler resonance cone. The occurrence rate decreases slowly as a function altitude. Thus, they have been defined as whistler signals generated by lightning in the Venus atmosphere. The second type of signal is a non-whistler mode wideband signal, which spreads from 100 Hz through the higher frequency channels. The occurrence rate of these signals peaks in the post-dusk local time sector, and decreases for increasing altitude with a scale height of about 20 km. These signals may also come from a lightning, but it is still a mystery how these waves enter the ionosphere.

We use the occurrence rate of 5.4 kHz signals to estimate the planetary lightning rate, because these high frequency signals may be a prompt response to a lightning stroke in the lower ionosphere. We obtain a rate of lightning that may be comparable or greater than that on Earth. However, the estimate of the planet-wide lightning rate from the data is sensitive to both the area of the planet's surface from which VLF signals may reach the spacecraft at any one time and the size of the source region that can not be sensed by Pioneer Venus, i.e. on the dayside and at high latitudes.

ACKNOWLEDGMENTS

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