PARTIALLY TRANSMITTED LIGHTNING SIGNALS RECORDED BY PIONEER VENUS ORBITER

R. N. Singh,* C. T. Russell* and F. L. Scarf+

*Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA, +TRW Defense and Space Systems Group, Redondo Beach, CA 90278, USA.

ABSTRACT

Impulsive electric fields appearing on all four frequency channels of the Pioneer Venus electric field detector in the night ionosphere of Venus are characteristic of lightning generated signals. Based on our knowledge of the electron density and magnetic field in the Venus ionosphere, we suggest that lightning waves could be partially transmitted upwards into the ionosphere. The leakage of these lightning waves into the ionosphere on encountering electron density holes may be treated as reradiation into the ionosphere from the hole. Since this radiation pattern is frequency dependent, we should not expect to see all frequency components for every lightning stroke observed.

INTRODUCTION

The electric field measurements on Pioneer Venus Orbiter electric field detector (OEFD) in the night ionosphere of Venus and on Venera 11, 12 landers, in the extended frequency range of 100 Hz to 80 kHz, have been interpreted in terms of Venus lightning /1-3/. Lightning discharges appear to be one of the most predominant sources of electromagnetic noise and their typical impulsive signatures are seen on all the frequency channels of OEFD. The lower frequency signals $\omega < \omega_c$ can escape into the ionosphere in the whistler mode and be recorded by the OEFD. However, the higher frequency signals $\omega > \omega_c$ are thought to be shielded by the nightside Venus ionosphere. In absence of an escape mechanism, the higher frequency signals have been interpreted as non-lightning waves generated by current-driven instability mechanisms /4,5/. In this paper, we examine the basic problem of escape of lightning generated signals from the nightside Venus ionosphere. We briefly compare and contrast basic features of the two types of wave generation mechanisms in the light of some of the observed details of OEFD signals.

The nightside Venus ionosphere with its electron density peak around 150 km together with the Venus surface can be considered to form a system of two conducting infinite parallel planes. The Venus clouds lying in the altitude range of 50-70 km provide the occasional lightning signals which propagate between the parallel planes by the process of multiple reflections. When the periapsis altitude of the Pioneer Venus spacecraft is close to the lower boundary of the ionosphere, and when PVO is close to periapsis it can detect any signals that leak through the ionosphere. The presence of electron density inhomogeneities permit the partial transmission of the lightning signals /6/. The largest density inhomogeneities are the electron density depletions know as 'holes' /7,8/. These can provide a means of escape into the ionosphere for any lightning generated signals that may be propagating by multiple reflections between the ionosphere and the Venus surface. Electron density holes in the upper boundary surface if deep enough behave like dipole radiators effectively reradiating the signals which illuminate these holes from below. The proposed mechanism can produce the simultaneous occurrence of lightning events on all the four frequency channels or the occurrence only on some of them. The OEFD data for nightside PVO passage supports the proposed mechanism.

ELECTROSTATIC VERSUS ELECTROMAGNETIC WAVES

The electric field detector, OEFD, onboard Pioneer Venus Orbiter measured only the electric component of the wave at different discrete frequencies. In absence of the correlating magnetic field, it is not possible to ascertain whether these waves are electrostatic or electromagnetic. The issue of wave mode, therefore, has to be settled on the basis of indirect observational and theoretical support. The highly impulsive nature of these signals has been interpreted to arise from Venus lightning /1-3/. The lightning discharges generate broadband electromagnetic waves peaking in the range of 5-10 kHz and falling in intensity at lower as well as higher frequencies /9/. The lower frequency waves 100 and 730 Hz satisfying $\omega < \omega_c$ propagate out of Venus ionosphere in whistler mode. The higher frequency lightning signals 5.4 and 30 kHz for which $\omega > \omega_c$ are shielded by the Venus ionosphere and cannot propagate out. Therefore, the OEFD recorded electric field measurements above 100 Hz have been interpreted as non-lightning waves locally generated by current-driven instabilities /4,5/.

The existence of a free energy source is a requirement for the generation of waves by an instability. Increasing impact ionization of neutral gas density with the decreasing altitude of the spacecraft seems to provide the required free energy for local generation of the electrostatic waves which peak near periapsis with gradually increasing and decreasing signals during inbound and outbound /5/. Although detailed information on the velocity distribution of plasma particles is not available, it seems unlikely that the free energy sources would preferentially appear in electron density depletions. The detailed study carried out by Kindel and Kennel /10/ has shown that the threshold for the ion-acoustic instability is higher at low densities and this may further increase at lower altitudes in the presence of ion-neutral collisions. Further, the ion-cyclotron instabilities have lower threshold and these waves heat the ions and reduce the ion and electron temperature difference which further adversely affects the ion-acoustic wave generation /11/. Thus the electrostatic sources should be less dominant at lower altitudes where the wave activity is maximum. The lack of adequate plasma and wave diagnostics on the Pioneer Venus spacecraft prevents us from completely ruling out these sources but the hypothesis of lightning generations seems probable to us because of the following characteristics of the waves.

1. The impulsive nature of wave activity at all frequencies.
2. The wave amplitude and rate of occurrence decrease with increasing altitudes.
3. The enhanced activity at lower altitude at which threshold for current-driven instability becomes large.
4. The frequently simultaneous wave activity at all the frequencies. Lightning generates waves over a broad spectral range.
5. Correlation with electron density inhomogeneity and enhanced leakage with decreasing electron density and increasing collision frequencies.

ESCAPE OF LIGHTNING SIGNALS FROM THE IONOSPHERE

The electron density profiles for two PVO passes covering orbits 70-110 and 490-550 are shown in Figs. 1a,b. The electron density peaks around 150 km and shows a significant variation from orbit to orbit. The average electron density variation at lower altitude as deduced from radio occultation studies is shown by the dotted lines /12/. Another important feature of nightside ionosphere is appearance of electron density depletions known as holes /7,8/. These holes have typical north-south extent of 1000 km and an average east-west extent of 1800 km /8/. The appearance of wave activity on all the four frequency channels is more pronounced whenever holes are present as shown in Fig. 2. Although not shown here, the electron density holes occur when the magnetic field is aligned along $\pm B_x$.

The nightside Venus ionosphere can be idealized as a system of two partially conducting, infinite, plane parallel sheets which allow the propagation of lightning signals by multiple reflections. Whenever lightning signals are incident vertically, the leakage and partial transmission is more effective /6/. However, the general picture of a lightning signal in nightside ionosphere is schematically shown in Fig. 3. An aperture in the conducting sheet illuminated by incident lightning signals will behave like a remote dipole radiator with an induced current which reradiates electromagnetic waves in the surrounding space /13/. Using the geometrical details outlined in Fig. 3, the radiated electromagnetic field by an aperture received at a distant point can be written as

$$E_p\,(\theta) = \frac{P_a \operatorname{Cos}\theta}{4\pi\epsilon_o R}\left[\frac{1}{R^2} - \frac{ik}{R} - k^2\right] e^{ikR} \qquad (1)$$

where P_a is the dipole moment of the aperture and $R = (^2+Y^2+Z^2)^{\frac{1}{2}}$ is the distance of point P(X, Y, Z). The three terms show the contribution of induction, transition and radiation effects. In the vicinity of these holes, the electromagnetic fields vary as R^{-3} and at larger distances as R^{-2}. The exact computation of radiation characteristics of arbitrary size apertures is a highly complex problem. Therefore, we considered an idealized square aperture for which an approximate expression of directive gain has been obtained /14/.

$$G = 3\pi\,\sqrt{2}\,(\tfrac{L}{\lambda})^{3/2} \qquad (2)$$

where L is the length of a side of the aperture and λ is the wavelength of the radiated signal. The variation of the radiative gain with frequency for different values of L is shown in Fig. 4. The four OEFD frequency channels are shown by the dotted vertical lines. We find the radiative gain for higher frequency signals could be sufficiently large to overcome the fall of lightning signal spectrum with increasing frequency.

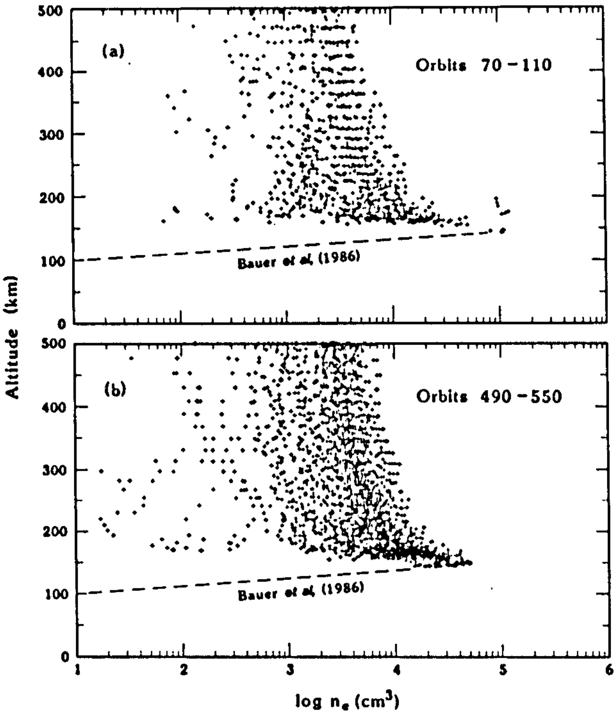

Fig. 1. Plots of Venus nightside electron density profiles for two PVO seasons (a) orbits 70-110, (b) 490-550. Electron density peak appearing around 150 km. The dotted lines show the density profiles obtained using radio occultation technique.

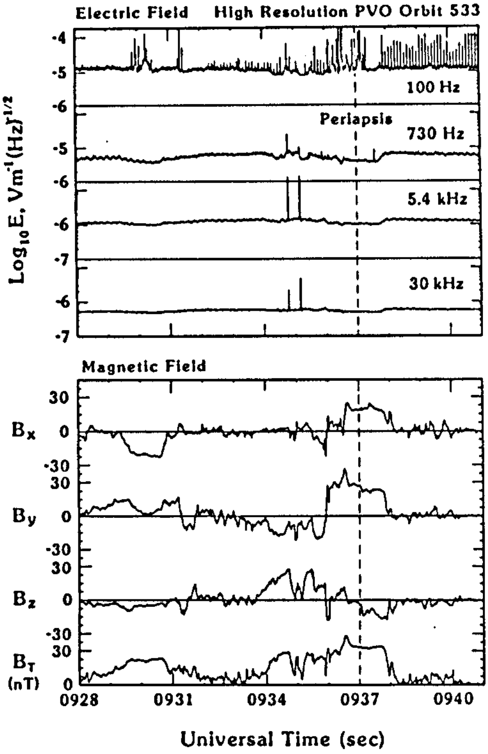

Fig. 2. Examples of electric field events appearing on all the four frequency channels in the presence of electron density holes as indicated by the regions with strong B_X magnetic fields.

RESULTS AND DISCUSSION

The electron density in the Venus ionosphere maximizes around 150 km. The electron density, even around the peak altitude, shows orders of magnitude variations. The magnetic field in the night ionosphere is active in the periapsis region with an average magnitude of 25 nT which corresponds to the electron cyclotron frequency of 700 Hz.

Whenever the lightning signals are incident vertically on the ionospheric layers, as would occur directly above a lightning bolt the skin depth is largest and the leakage of the waves upwards is comparatively more effective /6/. Electron inhomogeneities cause scattering and partial transmission of the waves into the ionosphere. The effect of finite collision frequency at the altitude of wave scattering or wave partial transmission has been accounted for by modifying our earlier computation of reflection coefficient /6/. The partial transmission coefficient increases with increasing ratio, ν/ω, as shown in Fig. 5. In presence of collisions an enhanced scale length of inhomogeneity is required for significant reflection coefficient.

The lightning signals from a distant source may propagate by the process of multiple reflections. The propagating waves on encountering electron density holes can reradiate up into the ionosphere. The directive gain of the reradiated signal depends on the direction of the incoming waves and the actual dimension of the holes. We find that holes reradiate low frequency signals less effectively because L/λ is small as shown in Fig. 4. The lower frequency signals at ∿ 100 Hz can escape through whistler mode propagation whenever $\omega < \omega_c$ is satisfied.

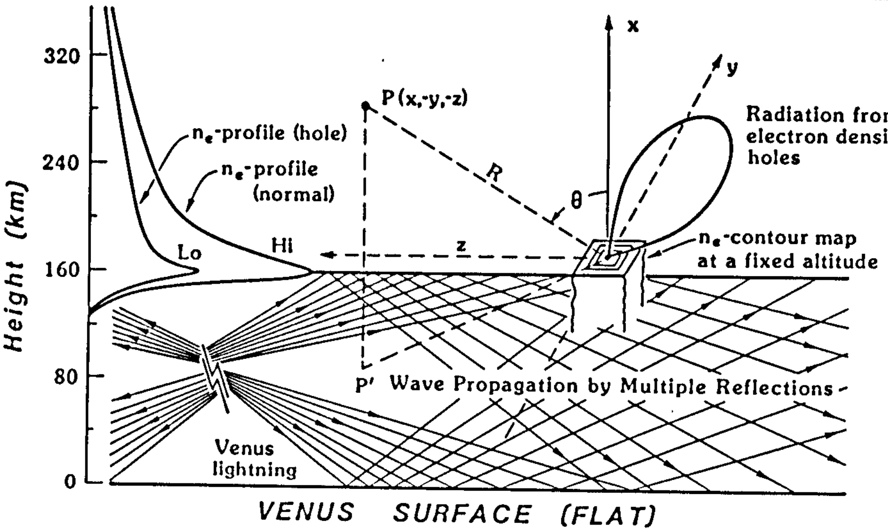

Fig. 3. Schematic diagram showing the propagation of lightning signals between conducting infinite parallel planes formed by the Venus surface and its ionosphere and the reradiation on encountering the electron density holes.

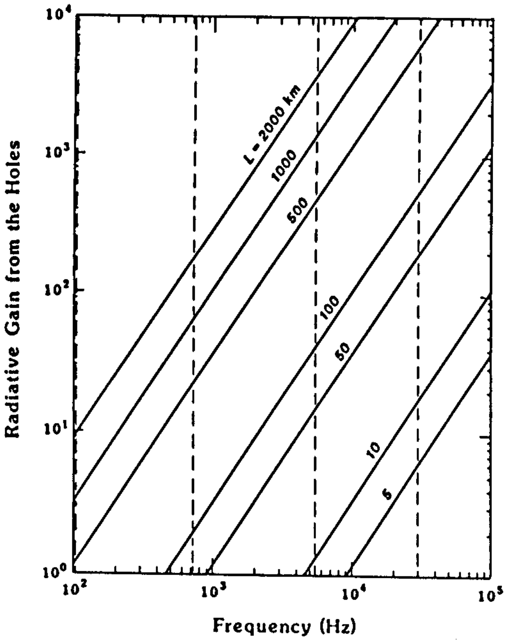

Fig. 4. Variation of directive gain of reradiation from electron density holes with incident frequencies for different hole sizes.

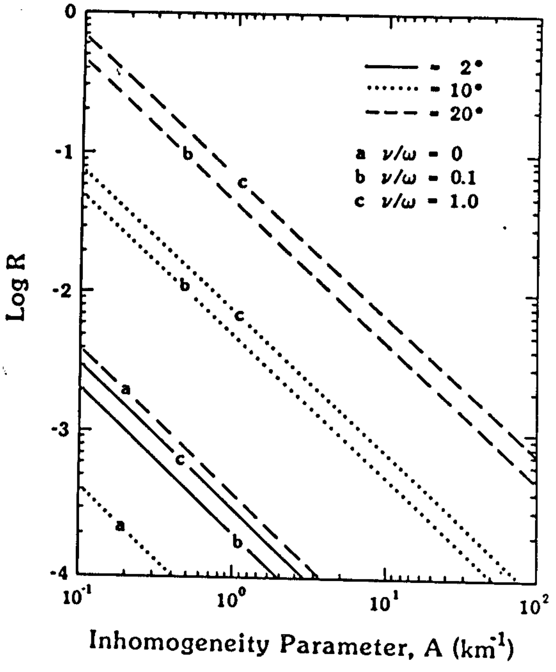

Fig. 5. Effect of collisional parameter ν/ω on the partial transmission coefficien (T=1-R) variation with scale length of electron density inhomogeneities.

The OEFD data for nightside PVO pass covering orbits 490-570 have been examined. For these orbits, the OEFD showed electric field events on 34 orbits and 50 percent of these orbits showed simultaneous presence of electric field on all the four frequency channels. The remaining 50 percent of the orbits show the predominance of either 100 or 730 Hz or of 5.4 and 30 kHz signals. This behavior is totally consistent with either leakage of the signals out of the ionosphere aided by scattering via electron density inhomogeneities or the reradiation of the electromagnetic waves in deep electron density holes. The correlation of the occurrence of waves both below and above the local electron cyclotron frequency with ion troughs (i.e., electron density holes) /15/ is expected from either leakage or reradiation. Thus, these correlations support our proposed mechanism for the escape of lightning signals and strengthens the Venus lightning scenario.

REFERENCES

1. W. W. L. Taylor, F. L. Scarf, C. T. Russell and L. H. Brace, Evidence of lightning on Venus, Nature, 279, 614-616, 1979.

2. L. V. Ksanfomality, Discovery of frequent lightning discharges in the clouds on Venus, Nature, 284, 244-246, 1980.

3. F. L. Scarf, W. W. L. Taylor, C. T. Russell and L. H. Brace, Lightning on Venus: Orbiter detection of whistler signals, J. Geophys. Res., 85, 8158-8166, 1980.

4. F. L. Scarf, S. Neumann, L. H. Brace, C. T. Russell, J. G. Luhmann and A. I. F. Stewart, Current-driven plasma instabilities and auroral-type particle acceleration at Venus, Adv. in Space Res., 5, No. 9, 185-191, 1985.

5. S. A. Curtis, L. H. Brace, H. B. Niemann and F. L. Scarf, CO_2 impact ionization-drive plasma instability observed by Pioneer Venus Orbiter at periapsis, J. Geophys. Res., 90, 6631-6636, 1985.

6. R. N. Singh and C. T. Russell, Further evidence of lightning on Venus, Geophys. Res. Lett., in press, 1986.

7. L. H. Brace, R. F. Theis, H. G. Mayr, S. A. Curtis and J. G. Luhmann, Holes in the nightside ionosphere, J. Geophys. Res., 87, 199-211, 1982.

8. L. H. Brace, H. A. Taylor, T. I. Gombosi, A. J. Kliore, W. C. Knudsen and A. F. Nagy. The ionosphere of Venus: Observations and their interpretations, Venus, edited by D. M. Hunten, L. Colin, T. M. Donahue and V. I. Moroz, Univ. of Arizona Press, 779-840, 1983.

9. M. A. Uman, Lightning, Dover, N.Y., 1983.

10. J. M. Kindel and C. F. Kennel, Topside current instabilities, J. Geophys. Res., 76, 3055-3078, 1971.

11. B. B. Kadomtsev, Plasma turbulence, Academic Press, 75, 1965.

12. S. J. Bauer, L. H. Brace, T. K. Breus, A. J. Kliore, W. C. Knudsen, A. F. Nagy, H. A. Taylor, Jr., C. T. Russell and V. A. Savich, The Venus ionosphere: A model for VIRA, Adv. Space Res., submitted, 1986.

13. A. Z. Fradin, Microwave antennas, Pergamon Press, 142, 1961.

14. R. C. Hansen, Microwave scanning antennas, Academic Press, edited by R. C. Hansen, 21, 1964.

15. H. A. Taylor, J. M. Grebowsky and P. A. Cloutier, Reply to a comment by F. L. Scarf, J. Geophys. Res., 91, 4599-4604, 1986.