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15 May 1979

Absorption of Whistler Mode Waves in the Ionosphere of Venus

Abstract. *It is shown that whistler mode waves from the ionosheath of Venus are absorbed by Landau damping at the dayside ionosphere boundary. This process heats the ionospheric electrons and it may provide an important energy input into the dayside ionosphere. Cyclotron damping of the waves does not occur in the same region. However, Landau damping of ionosheath waves is apparently not an important energy source in the nightside ionosphere. Impulsive events in the nightside ionosphere seem to fall into two classes: (i) lightning signals (near periapsis) and (ii) noise, which may be caused by gradient or current instabilities.*

The Pioneer Venus mission was designed to provide definitive answers to a number of important questions about Venus, including those having to do with the mechanism of energy transfer from the solar wind to the ionosphere and upper atmosphere. In reviewing plans for the mission it was noted that the studies of simple static pressure balance would have to be combined with an analysis of dynamical dissipation processes at the ionosphere boundary (*1*), and several of the initial reports on data from the Pioneer Venus orbiter made reference to this problem. It was shown that the dayside ionopause is characterized by an approximate pressure balance relationship (*2*–*4*), and it was also shown that during quiet times, the density and temperature profiles in the upper ionosphere are consistent with a topside energy deposition on the order of (3 to 7) × 10^{-2} erg/cm^2-sec (*3, 4*). The initial analysis of the wave observations suggested that damping of 100-Hz waves (assumed to be whistler mode turbulence) at the ionopause could provide an average of 5 × 10^{-2} erg/cm^2-sec as a local energy source of ionospheric and atmospheric processes (*5*).

In this report we examine critically the concept of damping of whistler mode waves by ionospheric electrons. We use simultaneous, high-time-resolution orbiter measurements of the electron density and temperature, the magnetic field magnitude, and the 100-Hz wave amplitude, and we demonstrate that the Landau damping picture has quantitative validity at the dayside ionopause. We also discuss briefly cyclotron damping and the nightside low-altitude observations, which are characterized by the detection of undamped whistler mode signals apparently associated with atmospheric lightning.

The initial discussion of wave damping by ionospheric electrons was based on data averaged over a number of spin periods from orbit 4 (*5*). We have selected orbit 3 in order to present the quantitative analysis, and Fig. 1 shows details. Figure 1a contains averages (over one spin period) of the 100-Hz power levels (more precisely, values of the electric field spectral density) from the electric field detector. The electron temperature and density data were averaged over a single spin period, as were the magnetic field data. The outbound ionopause was crossed between 1437 and 1438 (spacecraft event time), and we explore here the associated change of the spectral density in terms of wave damping and energy transfer to the ionospheric electrons.

At the start, it is necessary to consider again the previous tentative identification of these 100-Hz waves as whistler mode oscillations. The orbiter wave investigation has limited frequency coverage; it measures only electric fields; and the sun-oriented sheath modulation makes it difficult to carry out a precise polarization analysis. Nevertheless, we have analyzed the wave polarization with respect to the magnetic field direction in the ionosheath (after 1448, for instance), and we find no evidence that these waves have polarization characteristic of electrostatic waves. Some additional guidance comes from a comparison of observations in Earth's magnetosheath with these Venus ionosheath observations. For example, at Earth, simultaneous high-time-resolution electric and magnetic field measurements from the International Sun-Earth Explorer ISEE 1 show that for frequencies $f \leq 56$ Hz the dominant magnetosheath waves have essentially identical amplitude variations (*6*). Thus these magnetosheath waves with $f << f_c$, the electron cyclotron frequency, are certainly electromagnetic whistler mode waves, although the higher frequency turbulence in the same region (including some waves with $f < f_c$) is likely to be electrostatic (*7*). However, since the interplanetary magnetic field at Venus is nominally about 1.8 times as high as that value at 1 AU, the corresponding wave and cyclotron frequencies must be scaled upward by that factor. This scaling suggests that in the Venus ionosheath the 100-Hz channel corresponds to the 56-Hz channel in Earth's magnetosheath, and this extrapolation then indicates that the whistler mode identification is correct for our 100-Hz measurements.

For plasma waves such as obliquely propagating whistlers, strong wave-particle interactions occur when a significant number of the charged particles in the plasma move with velocities close to the phase velocity of the wave. For a plasma with a thermal (Maxwellian) distribution of particles, strong damping occurs when the wave phase speed is equal to the thermal speed (most probable speed), and this is called Landau damping. This matching of speeds means that in its rest frame the "average" charged particle is acted on by a d-c electric field, and the particle is accelerated, gaining energy at the expense of the wave energy. A related type of resonant damping occurs when waves appear Doppler shifted to the gyrofrequency of the particles. This damping is called cyclotron damping. The energy of the resonant particles parallel to the wave velocity may be computed from the phase velocity. For whistler mode waves and electrons, the Landau resonant energy is

$$E_L \simeq \frac{B^2}{8\pi N_e \cos\theta}\left(\frac{f}{f_c}\right) \qquad (1)$$

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where B is the magnetic field strength, N is the electron density, and θ is the angle between the magnetic field and the wave vector **k**. A similar relation has also been derived for the cyclotron resonance (*8*). This condition is

$$E_c \simeq \frac{B^2}{8\pi N_e \cos\theta}\left(\frac{f_c}{f}\right) \quad (2)$$

[We refer the reader to (*8*) for a discussion of the range of validity of Eqs. 1 and 2.]

Using Eqs. 1 and 2 and the measured values of B and N_e for a few minutes of Pioneer Venus data on 7 December 1978, we calculated the maximum values of E_L and E_c. We then converted these energies to temperatures for comparison with measured electron temperatures (T_e). Figure 1b shows the measured ionospheric electron temperature and the results of the calculations for the outbound dayside ionosphere exit on 7 December 1978. At the point where the measured electron temperature became equal to the calculated resonant Landau temperature (just after 1437:30 at the high-altitude limit of the ionosphere), the electric field spectral density increased, indicating that the 100-Hz whistler mode waves were Landau damped as they traveled inward. Temperatures required for cyclotron damping are about two orders of magnitude too high to represent effects of ionospheric electrons. Similar detailed comparisons between data and calculations have been made for data on 5 and 8 December 1978. These comparisons support the conclusion that the dominant ionospheric damping mechanism for the 100-Hz waves is Landau damping, with little or no contribution from cyclotron damping as was suggested in (*5*). Analysis of the larger set of analyzed data from 5, 7, 8, 12, and 26 December 1978 shows that the energy deposition varies from about 0.01 to 0.2 erg/cm^2-sec at the top of the dayside Venus ionosphere (assuming a spectral bandwidth of 100 Hz) (*9*).

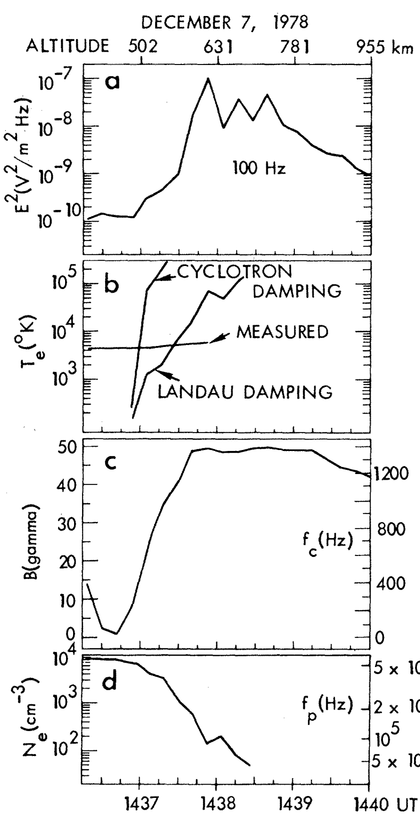

Fig. 1. Spin-averaged data from the outbound part of the Pioneer Venus orbit 3 pass through the dayside ionosphere of Venus. (a) Spectral density of the electric field measured at 100 Hz by the electric field detector. (b) Electron temperature measured with the electron temperature probe (ETP) compared to calculated electron temperatures required to produce damping of 100-Hz whistler mode waves if the Landau and cyclotron mechanisms are active. (c and d) Data required to calculate the temperature, the magnitude of the magnetic field measured by the magnetometer, and the electron density, measured by the ETP. The ETP data reported here are preliminary.

In plasmas with sufficiently nonthermal particle distributions, Landau and cyclotron resonances may also be a source of waves. Physically this requires that there be more particles at energies slightly above the resonant energy than there are at energies slightly below the resonant energy. This condition may exist at times in the ionosheath (the region between the bow shock and the ionosphere) since the Pioneer Venus plasma analyzer measurements indicate the presence of 50- to 100-eV electrons (*10*).

There is a natural explanation for the fact that at the dayside ionosphere boundary Eq. 1 is roughly satisfied with $E_L \simeq \kappa T_e$ (measured) and $f \simeq 100$ Hz $\simeq$ (0.1 to 0.2) f_c. At the dayside boundary the pressure balance condition is β(total) = β(ion) + β(electron) $\simeq 3\beta$(electron) $\simeq (12\ \pi N_e \kappa T_e/B^2) \simeq 1$ (*3*); β is the ratio of the thermal pressure to the magnetic pressure and κ is Boltzmann's constant. When this condition is inserted into Eq. 1 we find $E_L \simeq [3\ \kappa T_e f/2\ f_c \cos\theta]$, and for $f/f_c \simeq 0.2$, with a range of θ values, E_L should indeed be comparable to κT_e, which leads to strong Landau damping for these unducted whistler waves.

The nightside is different because the inner boundary of shocked solar wind is generally separated from the ionosphere by a wake or rarefaction region (*1*) and thus the $\beta \simeq 1$ condition is not applicable in the same way. More analysis of wave-particle interactions at the inner boundary of shocked solar wind on the nightside is needed to determine whether wave attenuation here is dominated by damping effects or by reflection from the wake boundary. However, we have determined that whistler mode waves apparently associated with atmospheric lightning are commonly detected near the lower boundary of the nightside ionosphere.

Initial evidence of nightside lightning detection from the orbiter was presented elsewhere (*11*). Figure 2 shows low-altitude measurements from 19 February 1979, when the spacecraft passed almost directly over the antisolar point. The 100-Hz panel in Fig. 2 illustrates how the strongest impulsive signals detected on the nightside are generally confined to regions near periapsis where the orbiter skirts the lower boundary of the ionosphere or even goes below it. (The signals attributed to lightning are the in-

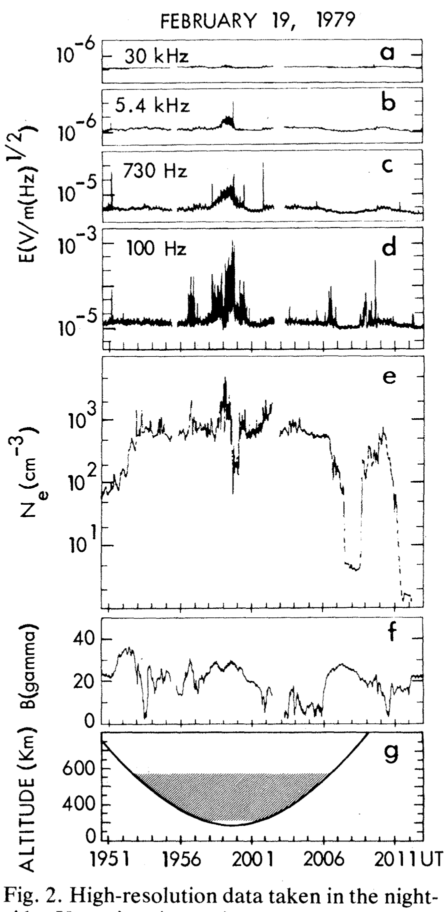

Fig. 2. High-resolution data taken in the nightside Venusian ionosphere on 19 February 1979. (a to d) Electric fields, (e) electron density, (f) magnitude of the magnetic field, and (g) spacecraft altitude. The shaded portion of (g) indicates the approximate extent of the main ionosphere, although detached regions of ionospheric plasma were clearly detected at higher altitudes. Note that the dominant impulsive events occurred when the altitude was low (that is, from about 1958:00 to about 2001:30 U.T.). Others were detected in association with gradients in the density (that is, near 1956:40, 2006:30, and 2008:00 to 2010:00 U.T.). We interpret the low-altitude events as lightning signals. The other events may be instabilities driven by the density gradients or by currents.

tense impulsive bursts near 1959, and possibly those associated with the density irregularities at 1956:30 and 1958:30.) Figure 2 also shows that the nominal upper boundary of the ionosphere (at approximately 1952 inbound and 2006 to 2007 outbound) was not marked by an abrupt onset of continuous 100-Hz ionosheath whistler mode turbulence, although the density gradient starting at 2006:30 and the one at 2009 were associated with enhanced turbulence levels. The lack of continuous ionosheath noise is understandable because on 19 February 1977 the top of the ionosphere was not adjacent to shock solar wind plasma (the orbiter plasma probe detected ionosheath plasma before the interval 1942:30 to 1945:08 and after the interval 2013:05 to 2018:59) and the ionosheath whistler mode waves were not in direct contact with the nightside ionosphere (*12*). Thus, if energy deposition is required to explain the structure of the ionosphere at night, a mechanism other than the one described in Fig. 1 must be operating here. In this connection we note that the 5.4-kHz and 730-Hz panels in Fig. 2 show smooth increases in wave intensity near periapsis. Here the electron cyclotron frequency was about 850 Hz, the electron plasma frequency was above 250 kHz, and the 5.4-kHz observations could not represent detection of electromagnetic waves. However, for an O^+ density of (1 to 2) × 10^3 cm^{-3}, electrostatic ion sound waves with 5.4 kHz could be excited (*13*). Further studies of these high-frequency nightside wave observations are in progress.

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Initial Pioneer Venus Magnetic Field Results: Nightside Observations

Abstract. *Initial observations by the Pioneer Venus magnetometer on the nightside of Venus frequently reveal moderately strong fields from 20 to 30 nanoteslas. However, there is little evidence that these fields arise from an internal dynamo since they are mainly horizontal and vary from orbit to orbit. Determining a precise upper limit to the intrinsic moment awaits further processing. This limit is expected to be much less than 10^{22} gauss-cubic centimeters.*

Venus is not only Earth's nearest neighbor, but it is also the planet most similar to Earth in size. Thus, we might expect that Venus would be similar in many respects to Earth. One important difference, however, is that Venus rotates much more slowly than Earth: a Venus sidereal day equals 243 Earth days. From dimensional considerations we would expect the magnetic moment of Venus to scale as the frequency of rotation and the fourth power of the radius of the core (*1*). If we assume that the core radius is 0.5 Venus radii (R_V), then the expected moment is about 2 × 10^{23} gauss-cm^3 or 2 × 10^{-3} of that of Earth. Busse's more sophisticated magnetohydrodynamic treatment gives a similar result (*2*). Although much smaller than the terrestrial moment, such a magnetic field should be easily detectable by an orbiting spacecraft at low altitudes, especially in the wake region behind the planet. Thus, one of the prime objectives of the Pioneer Venus orbiter magnetometer investigation is to search for an intrinsic magnetic field.

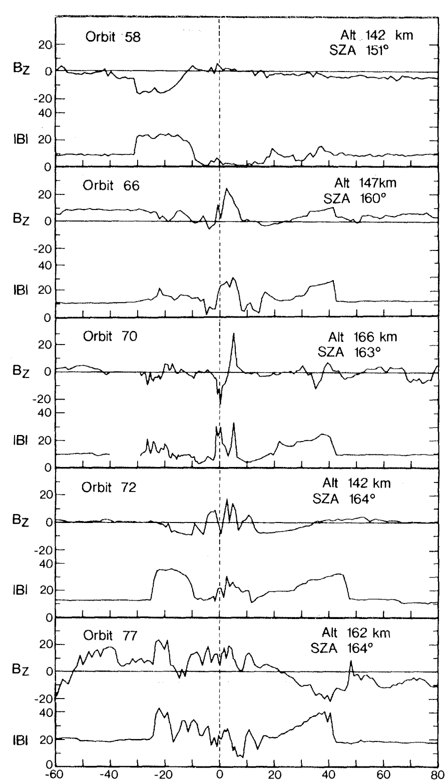

Fig. 1. Average magnetic field strength |*B*| and field parallel to the satellite spin axis B_Z for orbits 58, 66, 70, 72, and 77. Orbit 71 passed closest to the antisolar point. Units are nanoteslas.

This report summarizes our initial observations of the magnetic field on the nightside of Venus where any weak intrinsic field should be confined by the solar wind flow. In an earlier report we discussed our initial dayside observations including the bow shock locations, the ionopause, and ionospheric flux ropes (*3*). As before, the results presented here were obtained from "quick look" data. These data now contain inertial reference information, but timing errors limit the directional accuracy to about 5° to 10° depending on telemetry rate. These errors will not be present in the final processed data (*4*).

The magnetic field of Venus has been measured on Mariner 5, Venera 4, Venera 9, and Venera 10. Mariner 5 passed close to the wake of Venus and saw a steady field directed toward Venus north of the ecliptic plane (*5*). Venera 4 penetrated to about 200 km on the nightside just behind the terminator. Venera 4 detected little change in the field magnitude (*6*), but the variation in the vector components was suggestive of a possible planetary field with a northward moment

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