has moved 68 km. However, part of this motion may be along the axis of the rope. We obtained a minimum estimate of the diameter of the rope by assuming that it is horizontal and using the altitude variation of the spacecraft; this lower limit is 1.3 km. A better estimate awaits the determination of the relative orientation of the axis of these flux ropes and the satellite trajectory.

The existence of flux ropes in the Venus ionosphere is thus far the major surprise of the magnetic field investigation. At present we can only speculate on the source of these ropes; they could come from either above or below the ionosphere. Perhaps the tension in the field lines draped over the ionopause pulls a flux bundle down deep into the ionosphere. But if so, why are they found so deep in the ionosphere near the terminator region? Perhaps tubes of flux of an intrinsic planetary field are bubbling through the ionosphere on the dayside and being swept back by the ionospheric flow to form a planetary magnetotail. Shears in the flow would twist these tubes into ropes. We note that the flux ropes are a ubiquitous feature of the dayside ionosphere, occurring on every orbit down to the lowest altitudes.

C. T. RUSSELL
R. C. ELPHIC, J. A. SLAVIN
Institute of Geophysics and Planetary Physics, University of California, Los Angeles 90024

References and Notes

1. H. S. Bridge, A. J. Lazarus, C. W. Snyder, E. F. Smith, L. Davis, Jr., P. J. Coleman, Jr., D. E. Jones, *Science* **158**, 1669 (1967); N. F. Ness, K. W. Behannon, R. P. Lepping, Y. C. Whang, K. H. Schatten, *ibid.* **183**, 1301 (1974); Sh. Sh. Dolginov, Ye. G. Yeroshenko, L. Davis, *Kosm. Issled*, **7**, 747 (1969); Sh. Sh. Dilginov, Ye. G. Yeroshenko, L. N. Zhuzgov, V. B. Buzin, V. A. Sharova, *Pisma Astron. Zh* **2**, 8 (1976); K. I. Gringauz, V. V. Bezrukikh, G. I. Volkov, L. S. Musatov, T. K. Breus, *Kosm. Issled.* **8**, 431 (1970).
2. M. I. Verigin, K. I. Gringauz, T. Gombosi, T. K. Breus, V. V. Bezrukikh, A. P. Remizov, G. I. Volkov, *J. Geophys. Res.* **83**, 3721 (1978).
3. C. T. Russell, *ibid.* **82**, 625 (1977).
4. Sh. Sh. Dolginov, L. N. Zhuzgov, V. A. Sharova, V. B. Buzin, Ye. G. Yeroshenko, *Lunar Planet. Sci.* **9**, 256 (1978); C. T. Russell, *Geophys. Res. Lett.* **3**, 125 (1976); *ibid.*, p. 413; *ibid.*, p. 589.
5. For further details on the instrumentation, see R. C. Snare and J. D. Means, *IEEE Trans. Magn.* **MAG-13**, 1107 (1977).
6. J. H. Wolfe, H. Collard, J. D. Mihalov, and D. Intriligator provided solar wind measurements obtained with their plasma analyzer.
7. A. Nagy and L. Brace, personal communication.
8. E. W. Greenstadt, C. T. Russell, V. Formisano, P. C. Hedgecock, F. L. Scarf, M. Neugebauer, R. E. Holzer, *J. Geophys. Res.* **82**, 651 (1977).
9. We thank the entire Pioneer Venus team at Ames Research Center, Hughes Aircraft Company, and Westinghouse Corporation for successful fabrication, testing, and flight of the spacecraft and our instrument. At UCLA we are particularly indebted to R. C. Snare and J. D. Means for instrument design and testing and to N. Cline, M. Emig, and B. Litt for data analysis support. Supported by NASA contracts NAS 2-8088 and NAS 2-9491.

16 January 1979

Plasma Waves Near Venus: Initial Observations

Abstract. *The Pioneer Venus electric field detector observes significant effects of the interaction of the solar wind with the ionosphere of Venus all along the orbiter trajectory. Information is obtained on plasma oscillations emitted by suprathermal electrons beyond the bow shock, on sharp and diffuse shock structures, and on wave-particle interaction phenomena that are important near the boundary of the dayside ionosphere.*

Initial measurements by the electric field detector on the Pioneer Venus orbiter show that the solar wind interaction with the Venus ionosphere is strong and highly variable. Bursts of electron plasma oscillations are generally detected everywhere beyond the bow shock, indicating that suprathermal electrons are generated at the shock surface. In most cases the shocks themselves are well defined in terms of local generation of intense ion acoustic turbulence and whistler mode turbulence. The largest-amplitude plasma waves are frequently detected at very low altitudes in the neighborhood of the ionospheric boundary. In this region, a characteristic feature is the sharp onset of attenuation of the strong 100-Hz waves as the orbiter penetrates the dayside ionosphere. If this 100-Hz plasma wave turbulence represents whistler mode noise, damping of the waves by the ionospheric electrons can be an important interaction mechanism that transfers solar wind energy directly to the ionosphere.

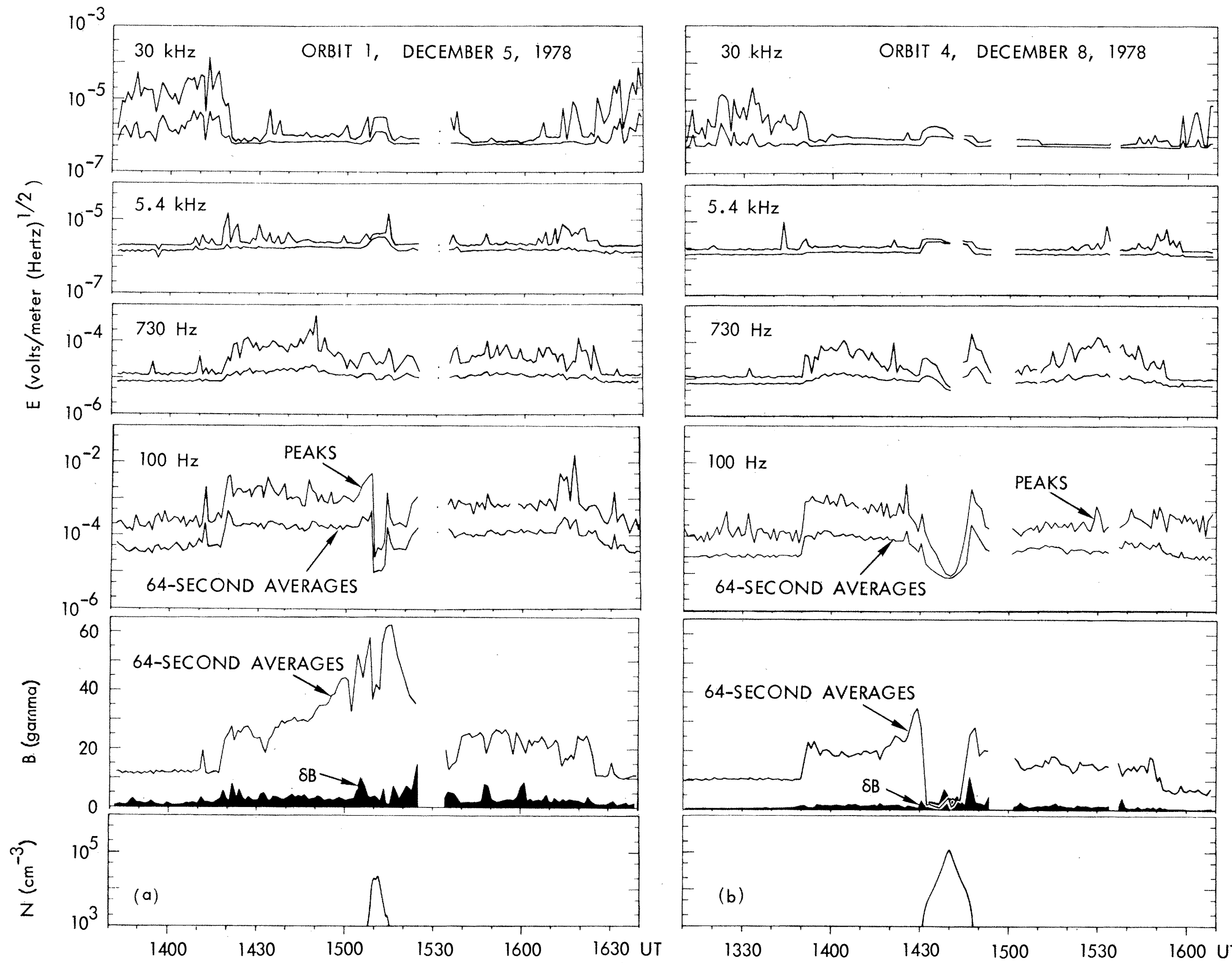
The measurements of plasma wave activity near Venus are made by using a vee-type body-mounted electric dipole with an effective length of 0.7 m. This short antenna detects electric components of the waves in the spin plane, and the signals are processed in four independent bandpass channels having center frequencies at 100, 730, 5400, and 30,000 Hz. In each channel the bandwidth is 30 percent of the center frequency and the wave amplitude is continuously measured with an amplifier with automatic gain control. At the nominal spacecraft rate of 1024 bits per second, a four-channel spectral scan is transmitted every 1/2 second. This instrument was designed to provide exploratory information on all aspects of the solar wind interaction with Venus, and measurements are made throughout the orbit. The conclusions reported here are based on an analysis of quick-look data that include the 3-hour periods centered around periapsis for orbits 1 through 20; short samples of observations from all other parts of the orbits have also been examined.

Figure 1 shows summaries of the low-altitude observations for orbits 1 and 4. These measurements are typical for days with low solar activity and relatively high periapsis locations (380 km for orbit 1 and 180 km for orbit 4) on the dayside approaching the western (dusk) terminator. Peaks and averages of the wave spectral densities are shown along with preliminary magnetic field (B) profiles from the UCLA magnetometer and preliminary electron densities derived from the GSFC electron temperature probe. Bow shocks (near 1420 and 1625 on orbit 1) are clearly located by increases of B above the solar wind value; ionosphere boundaries (near 1508 and 1513 on orbit 1) are easily identified by increased electron densities and (generally) decreased B inside the ionosphere.

Since typical solar wind densities near Venus give plasma frequencies near 30 kHz, we identify the 30-kHz wave level enhancements detected beyond the bow shock as electron plasma oscillations generated by suprathermal electrons (*1*). Similar bursts are detected out to apoapsis, and the cutoff at the shock suggests that these electrons are generated at the shock surface. The wave measurements in the upstream solar wind and the observations of high levels of ion acoustic turbulence (5.4-kHz and 730-Hz channels) and whistler mode noise (100-Hz channel) at the inbound shocks on orbits 1 and 4 suggest that strong wave-particle interactions develop there. Mass loading by neutral atoms escaping from Venus into the upstream solar wind (*2*) does not appear important at these shock locations. However, the shocks encountered outbound on the same orbits are quite diffuse, with extensive upstream turbulence, and effects associated with mass loading by ions of atmospheric origin may influence the outbound shocks.

Figure 1 shows that some of the most interesting and novel results are found at very low altitudes. We very frequently observe the strongest wave bursts just outside the dense ionosphere; the 730-Hz peak at 1447 UT on 8 December 1978 (Fig. 1b) is one example. This peak and the rise in the 730-Hz average were detected near the outbound ionopause (*3*) on orbit 4. Strong currents must flow at this type of boundary, which separates the shocked and magnetized solar wind (hydrogen plasma) from the ionospheric heavy-ion plasma, and current-driven plasma instabilities can generate strong ion acoustic waves near the interface. At high time resolution (Fig. 2) a few sporadic higher-frequency (5.4 kHz) bursts were detected near the outbound ionopause on 13 December.

Figures 1 and 2 also show the characteristic and dramatic attenuation in the 100-Hz wave levels near periapsis. By analogy with observations in Earth's magnetosheath and in the solar wind, we assume that 100-Hz turbulence involves whistler mode plasma waves, which propagate only when the wave frequency is less than the local electron cyclotron frequency f_c (=28 B Hz, where B is in gammas). Figure 1 shows a close correlation between the disappearance of the 100-Hz noise and the decrease in the magnetic field strength. However, for orbit 1 the minimum electron cyclotron frequency is 1 kHz; therefore it is not pos-



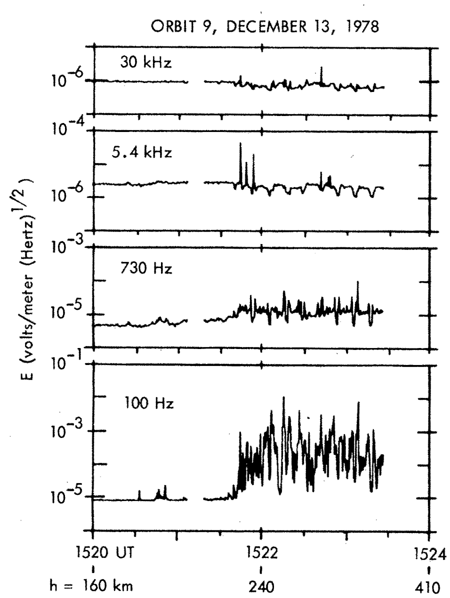


Fig. 1 (above). Peaks and averages of plasma wave electric fields (top four channels), preliminary magnetic field profiles (derived from the UCLA magnetometer), and preliminary ionospheric electron density profiles (derived from the GSFC electron temperature probe) for orbits 1 and 4. The B values are standard deviations (over 64 seconds) of the component of B parallel to the spin axis. The periapsis altitude was 380 km on 5 December (a) and 180 km on 8 December (b). Fig. 2 (right). Unaveraged high-resolution data (two scans per second) near an outbound ionopause crossing on 13 December.

sible to explain the attenuation solely by decreases in the magnetic field. We also considered possible instrumental explanations for the attenuation pattern, but they failed to account for the 100-Hz observations (*4*).

It now appears likely that the complete explanation for the observed 100-Hz amplitude variation also involves energy transfer between the whistler mode waves and ionospheric electrons, as Landau damping and resonant cyclotron damping processes become effective (*5*). Landau damping is usually significant whenever the wave phase speed becomes comparable to the thermal electron speed; however, a suprathermal electron population can also produce strong damping. On orbit 4 the 100-Hz waves started to disappear when B was near 30 γ, with the electron density N rising above 10^3 cm^{-3}. For these conditions the phase speed of a 100-Hz whistler wave is typically 3×10^5 m/sec, which is comparable to the electron thermal speed when the temperature is a few thousand degrees.

When the ionopause is at low altitudes during storms, the higher density leads to small whistler wavelengths; hence absorption, refraction, or reflection can occur on much smaller distance scales. The lowest panel in Fig. 2 shows an amplitude increase of two orders of magnitude as the spacecraft altitude increased by 800 to 1600 m during a 1- to 2-second interval, when the electron density dropped significantly (*3*). Since $N \approx 2 \times 10^4$ cm^{-3}, $B \simeq 20$ to 40 γ, and $f = 100$ Hz gives a whistler wavelength of $\simeq 500$ to 800 m, the high-resolution attenuation profile is consistent with a boundary scale length of one or two whistler wavelengths. Short wavelengths also develop as B falls so that f_c approaches 100 Hz. These unexpected results suggest that whistler mode turbulence generated in the shocked solar wind can be strongly absorbed in the ionosphere of Venus. The maximum energy flux available from the wave damping process is given by the product of the wave energy density and the wave speed. In the case of orbit 4 (outbound) the 100-Hz averages yield a mean whistler mode flux of 0.05 erg/cm^2-sec that could provide a local energy source for ionospheric and atmospheric processes. However, the waves appear to have very large peak amplitudes, with corresponding sporadic enhancements in energy flux up to 5 erg/cm^2-sec (*6*).

F. L. SCARF
W. W. L. TAYLOR, I. M. GREEN
Space Sciences Department, TRW Defense and Space Systems Group, Redondo Beach, California 90278

References and Notes

1. These plasma oscillations are narrow-band electrostatic waves with frequency $f = f_p = 9000 \sqrt{N}$ Hz, where f_p is the electron plasma frequency and N is the electron density (electrons per cubic centimeter). For Earth, the connection between electron plasma oscillations and suprathermal electrons from the bow shock was first established by F. L. Scarf, R. W. Fredericks, L. A. Frank, and M. Neugebauer [*J. Geophys. Res.* **76**, 5162 (1971)].
2. M. K. Wallis, *Cosmic Electrodyn.* **3**, 45 (1972); *Planet. Space Sci.* **21**, 1647 (1973); R. E. Hartle, S. J. Bauer, C. S. Wu, *IAGA (Int. Assoc. Geomagn. Aeron.) Bull.* **34**, 569 (1973); S. J. Bauer *et al.*, *Space Sci. Rev.* **20**, 413 (1977).
3. L. Bruce, personal communication.
4. The only instrumental effects that we have discovered to date involve the regular amplitude ripples that are evident in the high-resolution data of Fig. 2 after 1522. This effect is a measure of the sun-oriented anisotropy of the plasma sheath surrounding the spacecraft, which is not an equipotential. The observed ripple arises because the antenna on the spinning spacecraft is at a different angular position with respect to the sun during each successive sampling.
5. R. M. Thorne, *J. Geophys. Res.* **73**, 4895 (1968); H. B. Liemohn and F. L. Scarf, *ibid.* **69**, 883 (1964); C. Kennel, *Phys. Fluids* **9**, 2190 (1966).
6. This is quite large compared to the energy deposition in Earth's upper atmosphere. For instance, L. A. Frank and K. L. Ackerson [*J. Geophs. Res.* **76**, 3612 (1971)] showed that the energy input to the topside of Earth's auroral region is < 1 erg/cm^2-sec during quiescent periods.
7. We thank P. Virobik, J. Atkinson, and E. Vrem for their invaluable assistance with the design, fabrication, and integration of the orbiter electric field detector; C. Hall and the staff of the Pioneer Venus Project at NASA Ames Research Center and Hughes Aircraft Company for their excellent support; C. Russell and his colleagues for assisting with the data processing; and C. Russell and L. Brace for allowing us to show their preliminary results here. We also acknowledge very helpful suggestions by F. V. Coroniti. This work was carried out under NASA contract NAS2-8809 and NAS2-9842

16 January 1979

Initial Observations of the Pioneer Venus Orbiter Solar Wind Plasma Experiment

Abstract. *Initial results of observations of the solar wind interaction with Venus indicate that Venus has a well-defined, strong, standing bow shock wave. Downstream from the shock, an ionosheath is observed in which the compressed and heated postshock plasma evidently interacts directly with the Venus ionosphere. Plasma ion velocity deflections observed within the ionosheath are consistent with flow around the blunt shape of the ionopause. The ionopause boundary is observed and defined by this experiment as the location where the ionosheath ion flow is first excluded. The positions of the bow shock and ionopause are variable and appear to respond to changes in the external solar wind pressure. Near the terminator the bow shock was observed at altitudes of ~ 4600 to ~ 12,000 kilometers. The ionopause altitude ranged from as low as ~ 450 to ~ 1950 kilometers. Within the Venus ionosphere low-energy ions (energy per unit charge < 30 volts) were detected and have been tentatively identified as nonflowing ionospheric ions incident from a direction along the spacecraft velocity vector.*

The Ames Research Center Pioneer Venus orbiter plasma analyzer instrument is a quadrispherical, curved plate, electrostatic analyzer with five current collectors and electrometer amplifiers. It measures the ambient flux of plasma ions and electrons as a function of energy per unit charge (E/Q) and direction of incidence. Ions are analyzed over two E/Q ranges: low energy from 0 to 250 V and high energy from 50 to 8000 V. Electrons are measured over the energy range 0 to 250 eV. A more complete description of this experiment is given in (*1*).

The results presented here were obtained during the first few weeks of orbital operation of the Pioneer Venus orbiter mission. During this period only real-time and incomplete data have been available, so the results are considered to be very preliminary.

Values of the peak speed of solar wind protons (Fig. 1) were obtained daily at approximately noon universal time (UT); they represent an interplanetary value taken several hours upstream from the bow shock (*2*) on the inbound leg of each orbital pass. After Venus orbit insertion, the solar wind underwent a general decrease in speed until orbit 9. The large increase in solar wind at orbit 9 has been tentatively identified with the arrival at Venus of an interplanetary shock wave associated with a class 2B solar flare observed at 1909 UT on 11 December 1978. After the passage of this shock wave the solar wind convective pressure increased by approximately an order of magnitude; this was presumably responsible for the lowest ionopause altitude observed by this experiment in any orbit for which we have data. The prominent feature with a peak speed of ~ 760 km/sec on orbit 17 is a high-speed solar wind stream and was probably not associated with any specific flare activity.

Figure 2 shows a comparison of an interplanetary solar wind ion spectrum and an ionosheath (*3*) spectrum obtained during relatively quiet conditions. These data were taken on day 344 (10 December) along the outbound trajectory of orbit 6. The interplanetary spectrum, ob-