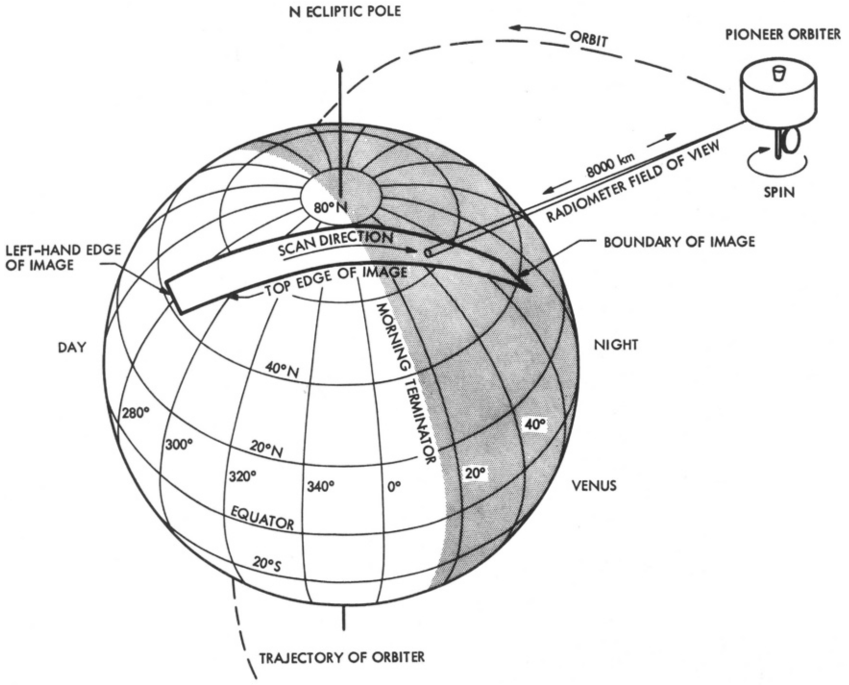

Fig. 2 Diagram showing the geometry of the observations, and the boundaries of the high-resolution image.

observations of spiral bands of cloud and a poleward component of cloud motion "are compelling suggestions that at least during the 7 days of the Mariner 10 flyby in 1974 the stratospheric circulation was composed of two giant vortices more or less centred on each pole with meridional inflow from low latitudes towards each pole. The vortex . . . would be characterised by a region of mass sink in the polar regions in the upper atmosphere and a mass source at lower latitudes, essentially a hemispheric Hadley circulation cell strongly organised by the vertical zonal flow".

The 'single cell' model for the Venus stratosphere is attractive, not least because it provides an intuitive explanation for the ubiquitous and uniform cloud cover outside the polar domains. It is easy to imagine that the atmosphere may be slowly rising over most of the area of the planet, thus sustaining dynamically the observed cloud deck. This mass flow would then be balanced by relatively rapid descent within the polar vortices. There are difficulties with this, however. First, it is difficult to explain why the 'eye' of the vortex is not centred on the rotational pole. The low resolution data alluded to earlier show clearly that its centre is 5°–10° from the pole itself. Second, the presence of the thick, high polar collar cloud (segments of which can be seen in Fig. 3) is not explained by a simple vortex circulation and may, in fact, preclude it. Third, the downwelling in the polar region must be explained in terms of a circulation mechanism which produces a poleward meridional flow[8], but against the gradient of increasing temperature from equator to pole[4]. Such a situation is not consistent with a classical 'Hadley' type circulation driven by solar heating. The stratospheric dynamics on Venus require some more complex mechanism, perhaps involving motions driven from below.

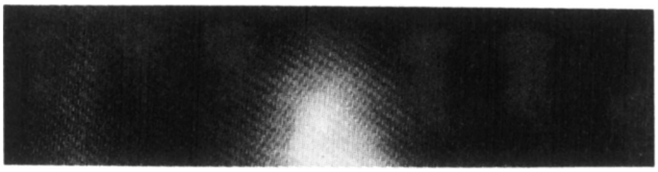

Fig. 3 An 11.5-μm image of thermal emission from the region near the north pole of Venus delineated in Fig. 2. The data were obtained from the Pioneer orbiter on 15 December 1978. The brightest area is emitting more intensely, and hence is warmer, than its surroundings. The dark (cold) circumpolar collar appears either side of the hot region, and some of its detailed structure can be seen. The limb of the planet is visible at either edge of the frame.

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Evidence for lightning on Venus

WHETHER lightning exists in a planetary atmosphere is a fundamental question for the atmospheric physicist. The conditions within a lightning stroke are far different from those within ambient atmosphere, permitting chemical and physical changes in the atmosphere which are not possible in equilibrium conditions. The relative importance of such nonequilibrium processes depends on the frequency and the location of this electrical activity. Discovery of lightning on other planets would also affect other scientific fields, including studies of planetary magnetospheres and of life. Lightning has been predicted or considered on Venus[1] and Jupiter[2,3], and evidence for lightning has been obtained with instrumentation on Venera 11 and 12 descent vehicles[4]. Electric fields characteristic of lightning, and acoustic signals, were detected on the dayside of the planet. We

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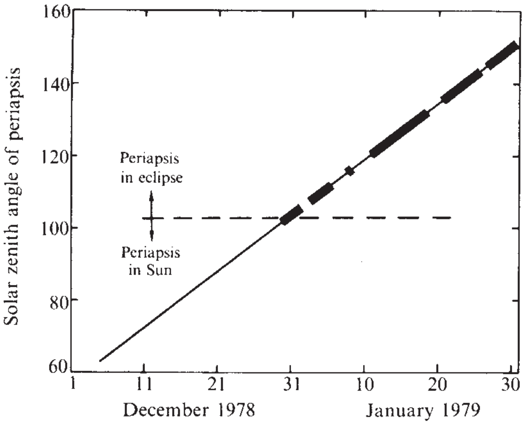

Fig. 1 The solar zenith angle of the periapsis of the Pioneer Venus Orbiter in December 1978 and January 1979 with orbits with impulsive events marked. The events, possibly due to lightning in the atmosphere of Venus, seem to be observed only when the Orbiter is in the shadow of Venus.

present here evidence of lightning on Venus obtained by instruments on the Pioneer Venus Orbiter.

The spacecraft was placed into Venus orbit on 4 December 1978[5]. Results discussed here are derived from observations to 31 January 1979. The periapsis of the Orbiter is well within the Venus ionosphere where electromagnetic waves characteristic of lightning might propagate. Initially periapsis was in sunlight. However, periapsis moved into darkness by the end of December, and at this time the Orbiter electric field detector obtained its first evidence for lightning.

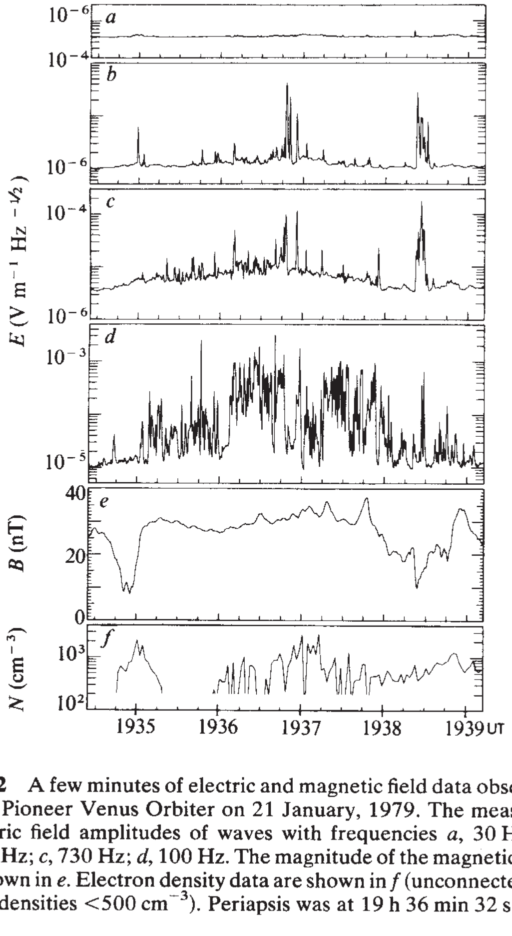

Fig. 2 A few minutes of electric and magnetic field data observed with Pioneer Venus Orbiter on 21 January, 1979. The measured electric field amplitudes of waves with frequencies *a*, 30 Hz; *b*, 5.4 kHz; *c*, 730 Hz; *d*, 100 Hz. The magnitude of the magnetic field is shown in *e*. Electron density data are shown in *f* (unconnected for densities <500 cm^{-3}). Periapsis was at 19 h 36 min 32 s.

The electric field detector has sensors which are mounted on the body of the Orbiter spacecraft with an effective antenna length of 0.7 m. The amplitude of the voltage induced on the antenna is measured in four frequency bands centred at 0.100, 0.730, 5.40 and 30.0 kHz, each 30% wide. The amplitudes are telemetered at various rates, commonly a complete spectrum (four measurements) every 0.5 s. The data reported here are from three instruments on Pioneer Venus—the electric field detector[6], the magnetometer[7], and the Langmuir probe[8].

Electric field data from early orbits were carefully inspected for evidence of lightning but none was found. In fact, in the dayside ionosphere, the wave levels were particularly low during these early orbits, especially in the two lower bands. Beginning with periapsis data on 30 December 1978, strong, very impulsive signals were often observed at low altitudes. Figure 1 shows the precession of the solar zenith angle of the periapsis of the orbit with the days of the low altitude impulsive events indicated. Reception of the waves at the satellite appears possible only when the satellite is in or near the shadow of Venus. In principle, this could be due to a source effect (for example, if venusian thunderstorms occur only at night) or to a propagation effect (for example, if the daytime venusian ionosphere is opaque to the waves). A source effect can probably be ruled out since Venera 11 and 12 lightning observations were made at solar angles <25°, and this fact alone suggests that the nightside observations on the Orbiter are associated with changes in the ionosphere.

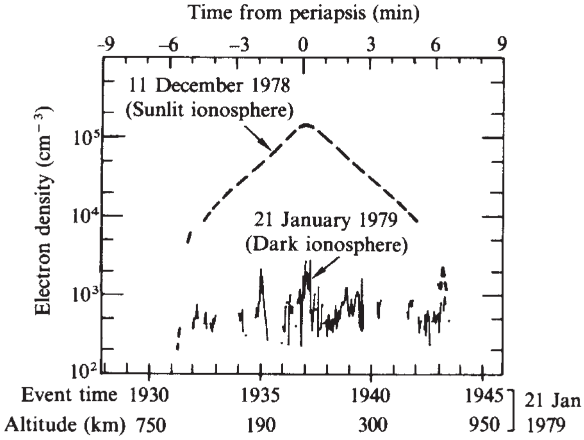

Fig. 3 Onboard measurements of the electron density for a typical dayside and nightside ionosphere (dashed line) and for the nightside ionosphere corresponding to the data shown in Fig. 2 (solid line).

Figure 2 shows a fairly typical example from 21 January 1979 when the altitude of periapsis was 164 km (at 19 h 36 min 32 s). The impulsive wave events were primarily detected at altitudes less than about 250 km, with regions of low electric field activity in the ionosphere above about 250 km. The magnetic field was about 30 nT during most of the time shown in Fig. 2, giving an electron gyrofrequency of about 840 Hz. Within the density 'dropouts' we use $N \simeq 40$ cm^{-3} as an electron density estimate. For a magnetic field of 30 nT and an electron density of 40 cm^{-3}, 100 and 730 Hz waves will propagate in the whistler mode, whereas no cold plasma wave mode will support propagation at 5.4 or 30 kHz. The events are strongest at 100 and 730 Hz although a few events extend to 5.4 kHz as well. The 5.4 kHz data may be due to propagation in other wave modes or may be due to waves leaking out of a nearby region of depleted electron density (common on the nightside of Venus). Figure 3 shows the different character of the ionosphere on the day and night sides of Venus. The dayside is relatively more dense and more regular. The impulsive events occurred at an average rate of about 0.5 s^{-1} between 19 h 35 min and 19 h 39 min. The actual

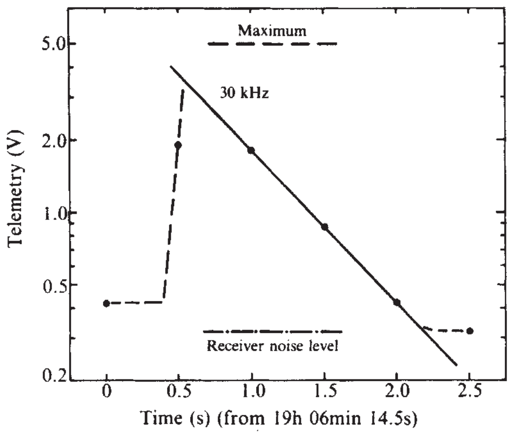

Fig. 4 The decay of the measured amplitude of an impulsive event on 13 January, 1979. The decay is exponential and apparently due entirely to the electronic averaging in the instrument. This indicates that the length of the input signal was very much less than the time constant of 0.70 s.

rate may have been much higher since the time between measurements was 0.5 s during this period. Venera 11 observed a maximum impulse rate of 25 s^{-1} (ref. 1).

Lightning on Earth is very impulsive. A test of the impulsiveness of the events is to observe the decay of the receiver output after an isolated impulse. The pulse shape of such an isolated impulse on 13 January 1979 is shown in Fig. 4. The rise time of the pulse is very short but, as expected, the decay is exponential with a time constant of 0.70 s, consistent with the decay time constant of the receiver.

The following evidence leads to the tentative conclusion that the impulsive events were caused by venusian lightning: (1) The signals are intense and highly impulsive; (2) the signals are detected near periapsis, well inside the ionosphere; (3) the spectral characteristics of the signals are generally consistent with whistler wave propagation up through the ionosphere; (4) the signals are often observed during intervals when low and variable electron densities are measured.

When the nightside densities are as high as 10^3 cm^{-3}, the interpretation that the impulsive events were caused by lightning requires that the whistler mode damping that seems to be effective in the dayside ionosphere[6] should be ineffective in the lower density nightside ionosphere. Other interpretations of some of the wave measurements are also conceivable (for example, some observations could represent electrostatic ion acoustic or electrostatic ion cyclotron waves[9,10], or be due to turbulence near zero frequency[11]. However, many of the impulsive events are detected near regions with local electron densities $<10^2$ cm^{-3}, and since the electron energy for Landau damping is proportional to the inverse of the density, the cool electrons near periapsis at night can never provide much damping. Moreover, for densities $<10^2$ cm^{-3} and a magnetic field of 30 nT, a 100-Hz whistler mode wave has a wavelength of 10 km or more, and it is almost certain that the spacecraft is frequently as close as the wavelength from the lower edge of the ionosphere. For these cases, and others where ducts might be present, signals from atmospheric lightning should be able to propagate to the spacecraft without any significant damping.

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Observation of magnetic flux ropes in the Venus ionosphere

MAGNETIC field measurements made by the Pioneer Venus Orbiter spacecraft reveal a very low average field strength within the dayside ionosphere of Venus, typically only a few nanoteslas, in contrast to fields of several tens of nanoteslas just outside the ionosphere[1]. Thus, at least in the range of solar zenith angles (65–90°) initially probed by the orbiter, the compressed interplanetary magnetic field of the shocked solar wind plasma (the magnetosheath) is effectively shielded from the ionosphere by currents flowing on the ionopause, the boundary between the ionosphere and the magnetosheath. In addition, the magnetic field pressure just outside the ionopause approximately balances the ionosphereic thermal plasma pressure[2,3]. However, within this generally low-field region the spacecraft occasionally passes through regions of very large field strength which can sometimes exceed that observed external to the ionosphere. These intense, short-lived enhancements are described here and interpreted to be due to the passage of the spacecraft through 'flux ropes', bundles of twisted magnetic field lines surrounded by ionospheric plasma.

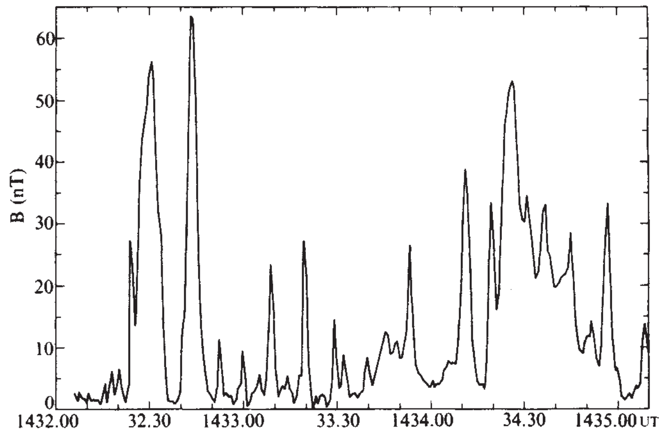

Fig. 1 Magnetic field enhancements observed within the ionosphere shortly after periapsis (at 1431.56) on orbit 3 of Pioneer Venus. Before and after this interval, the characteristic ionospheric field strength is less than 10 nT, while the peak field just outside the ionopause is ~55 nT.