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LETTERS

Lightning on Venus inferred from whistler-mode waves in the ionosphere

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The occurrence of lightning in a planetary atmosphere enables chemical processes to take place that would not occur under standard temperatures and pressures[1–3]. Although much evidence has been reported for lightning on Venus[4–8], some searches have been negative[9–11] and the existence of lightning has remained controversial. A definitive detection would be the confirmation of electromagnetic, whistler-mode waves propagating from the atmosphere to the ionosphere. Here we report observations of Venus' ionosphere that reveal strong, circularly polarized, electromagnetic waves with frequencies near 100 Hz. The waves appear as bursts of radiation lasting 0.25 to 0.5 s, and have the expected properties of whistler-mode signals generated by lightning discharges in Venus' clouds.

We have begun again receiving scientific data from Venus with the arrival in April 2006 of the Venus Express spacecraft, inserted into a high inclination elliptical orbit with periapsis at 73° latitude and an altitude near 250 km. Among its instrumentation, Venus Express carries a magnetometer that can sample at rates as high as 128 Hz (ref. 12). When sampling at this rate, the magnetometer is weakly low-pass-filtered before digitization, permitting some 'aliasing', in which signals enter the telemetry above the highest frequency that can be reconstructed by the digital telemetry. This frequency is half the sampling frequency, or 64 Hz. This mode was specifically designed to capture lightning by taking advantage of the broad natural bandwidth of the magnetometer within the limitation of a fixed number of bits transmitted to ground from the spacecraft. Owing to the large data volume produced, this mode was initially limited to 2 min per orbit, centred on periapsis. Although the amplitudes and durations of the signals are preserved, the folding of the digitally sampled signals around half the sample period (aliasing) can affect the apparent dispersion of the signals and the handedness of the waves.

Here we discuss measurements from 37 initial orbits in May and June 2006, when the interference from the reaction wheels on the body of this spacecraft remained outside our analysis bandwidth of 42–60 Hz. We illustrate the properties of the wave events seen, with examples from day 160 (9 June 2006; Fig. 1). When the transmission began, signals appeared immediately, suggesting that the generation process was already active. The signals stopped after 15 s—probably when the spacecraft moved away from the source, or when the magnetic-field-aligned propagation path became disconnected from the source. The signals on other passes appeared to begin and end during the transmissions, and some continued to at least the end of the pass. All signals resemble those shown here. They are bursty, with rapidly varying amplitudes, and variable interburst spacings and durations. The lower wave amplitude in the *x* direction (see Fig. 1 legend) indicates that the direction of propagation of the wave is roughly parallel or antiparallel to the solar direction.

We can find the minimum variance direction (direction of phase propagation) of these signals quite precisely, and rotate the measurements into the principal axis coordinate system (Fig. 2a). The individual bursts each have slightly different directions. The direction of propagation in the example is aligned within 13° of the background magnetic field, as expected for a whistler-mode wave. This direction is very well determined, as the eigenvalues of the principal axis determination are in the ratio 13 to 10 to 1. The near equality of the two largest eigenvalues indicates that the wave is nearly circularly polarized, again as expected for a whistler-mode wave propagating close to parallel to the magnetic field. The wave components are very nearly 90° out of phase, as expected. A hodogram, in which the tip of the perturbation magnetic field is drawn for successive samples (Fig. 2b), confirms that the wave is nearly circularly polarized and its perturbation confined to a plane. Again, these are the characteristics expected for a whistler-mode wave, the only electromagnetic mode expected to propagate at these frequencies for the observed background magnetic field of 23 nT. Some of the events on the other three passes are more elliptically polarized, as would occur for propagation at an angle to the magnetic field.

These signals are not due to spacecraft interference. There are two magnetometers on board, one on the spacecraft deck and one on a one-metre boom. Spacecraft signals produce different amplitudes on the two sensors, whereas real signals produce the same amplitude.

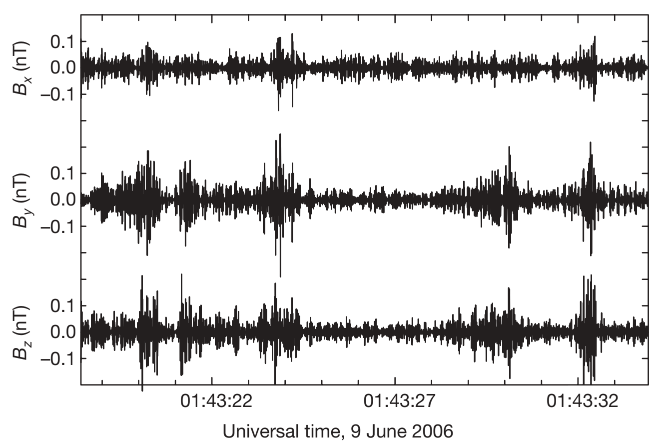

Figure 1 | Examples of the wave events. Signals recorded by the three sensors of the fluxgate magnetometer at an altitude of 305 km at 05:16 local time and a solar zenith angle of 91°. Data sampled at 128 Hz have been rotated into Venus solar orbital (VSO) coordinates (to give B_x, B_y, B_z) and bandpass filtered to display signals from 42 to 60 Hz to reduce spacecraft interference. The coordinate system has its *x* direction pointed towards the Sun, *y* is opposite planetary motion, and *z* is along the orbit pole. Signals appeared to be in progress at the start of the interval (shown here) but ceased after 01:43:32 UT (h:min:s). The spacecraft moves about 100 km in 15 s.

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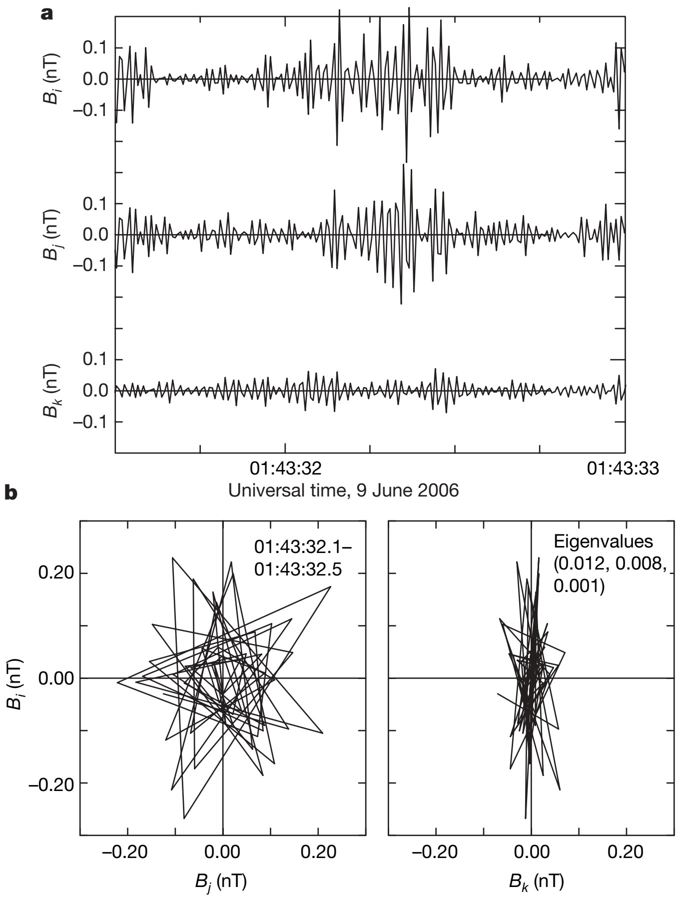

Figure 2 | Propagation of the signals. **a**, Burst of signal at 01:43:32 UT rotated into the principal axis coordinate system, and bandpass filtered as in Fig. 1; B_i, B_j and B_k are the field components in principal axis coordinates, with B_i along the direction of maximum variance and B_k along the direction of minimum variance. **b**, Hodogram of signal burst in the principal axis system. The wave is propagating along the direction (0.918, 0.340, 0.205) in VSO coordinates.

Subtracting the two sensor outputs then will exactly cancel the real signal, leaving noise. This test was performed, and showed that the bursts were registered identically by the two sensors over the entire 15-s period the waves were present.

As the electromagnetic energy flux of these waves diminished with altitude when surveyed by Pioneer Venus[13], these waves must have a source in Venus' atmosphere. We know of no other possible source of natural signals with these properties in Venus' ionosphere other than lightning in the atmosphere. The waveforms indicate an impulsive current source similar to terrestrial lightning. Also, the intermittent appearance of the bursts is like the occurrence pattern expected for a weather-associated phenomenon. As the mission proceeds, we will obtain further data and be able to gather occurrence statistics, including the occurrence rate across the dayside for which we have no information from previous missions. We further note that the night and morning local times at which these results were obtained coincide with the region of lowest expected occurrence rate from previous measurements[14].

On 50% of these passes, there are bursts of noise greater than 0.1 nT peak-to-peak, and on about 10% of the passes, there are bursts with amplitudes of greater than 0.2 nT peak-to-peak. The bursts have durations of about 0.2–0.5 s. If we assume that the magnetometer can detect signals over a footprint that has a radius equal to the spacecraft's altitude, it can see about 0.06% of the planet. If so, the burst rate of 0.03 s^{-1} observed on these orbits corresponds to a planet-wide rate of 50 s^{-1}, about half that at Earth[15]. However, the high-latitude region beneath the spacecraft at periapsis may not be representative of the entire planet.

In short, the initial data resolve the controversy concerning the presence of electromagnetic signals in Venus' ionosphere consistent with generation by atmospheric lightning. These signals are seen extensively, even well away from the regions of expected maximum occurrence based on the Pioneer Venus survey. They are bursty, and occur intermittently as on Earth, but occur at a lower frequency, in part because the ionosphere cannot transmit much higher frequencies. They are sufficiently intense to be well characterized by the fluxgate magnetometer at all local times examined, and the rate of occurrence may be similar to the terrestrial rate.

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