Lightning on Venus confirmed by frequent observations of whistler-mode waves

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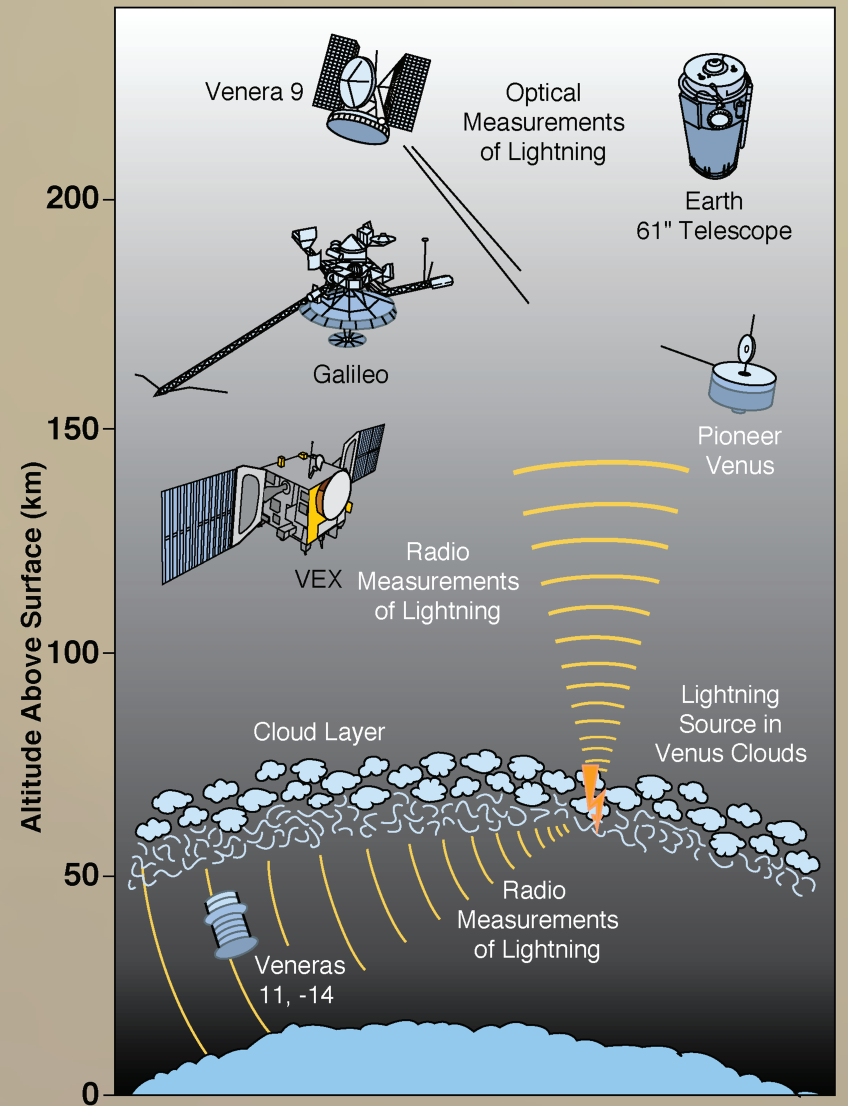
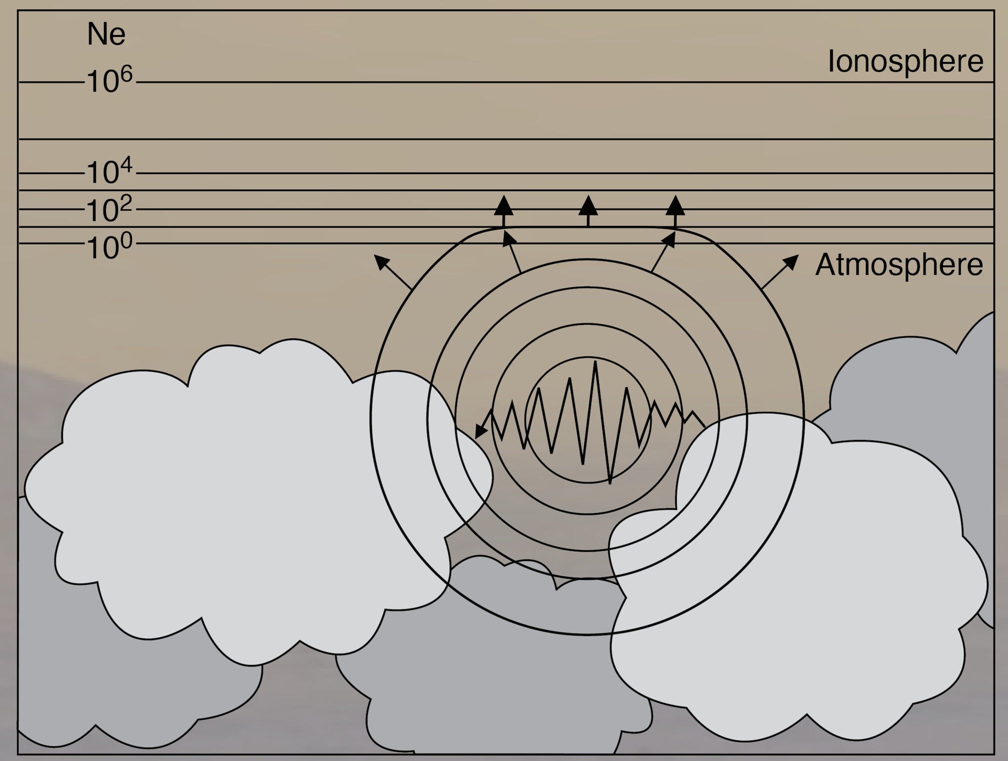


History

- Very Low Frequency (VLF) waves detected by Venera landers during their descent.
- Extremely Low Frequency (ELF) signals detected with Pioneer Venus (PVO) electric antenna.
- Flashes of light observed by Venera 9 visible spectrometer.
- Plasma wave instrument on Galileo detected radio signals during its flyby of Venus in 1990.
- Visible observations from 1.5m Earth-based telescope.
- Whistlers observed by Venus Express (VEX) magnetometer (this study).

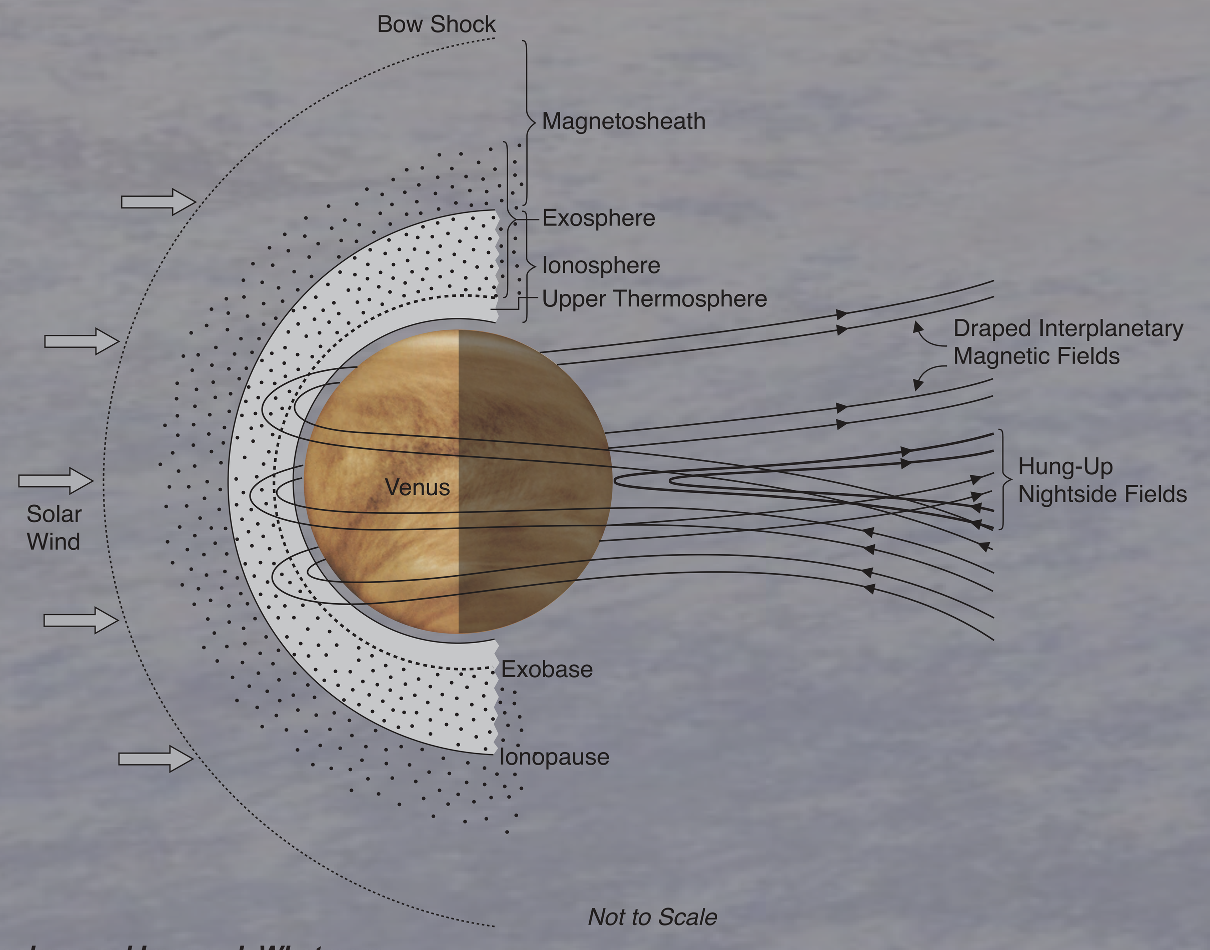
Controversy not settled despite the various types of observations.

Lightning-generated whistler-mode provide the most definitive evidence that lightning occurs in the clouds of Venus.



Whistler-mode waves

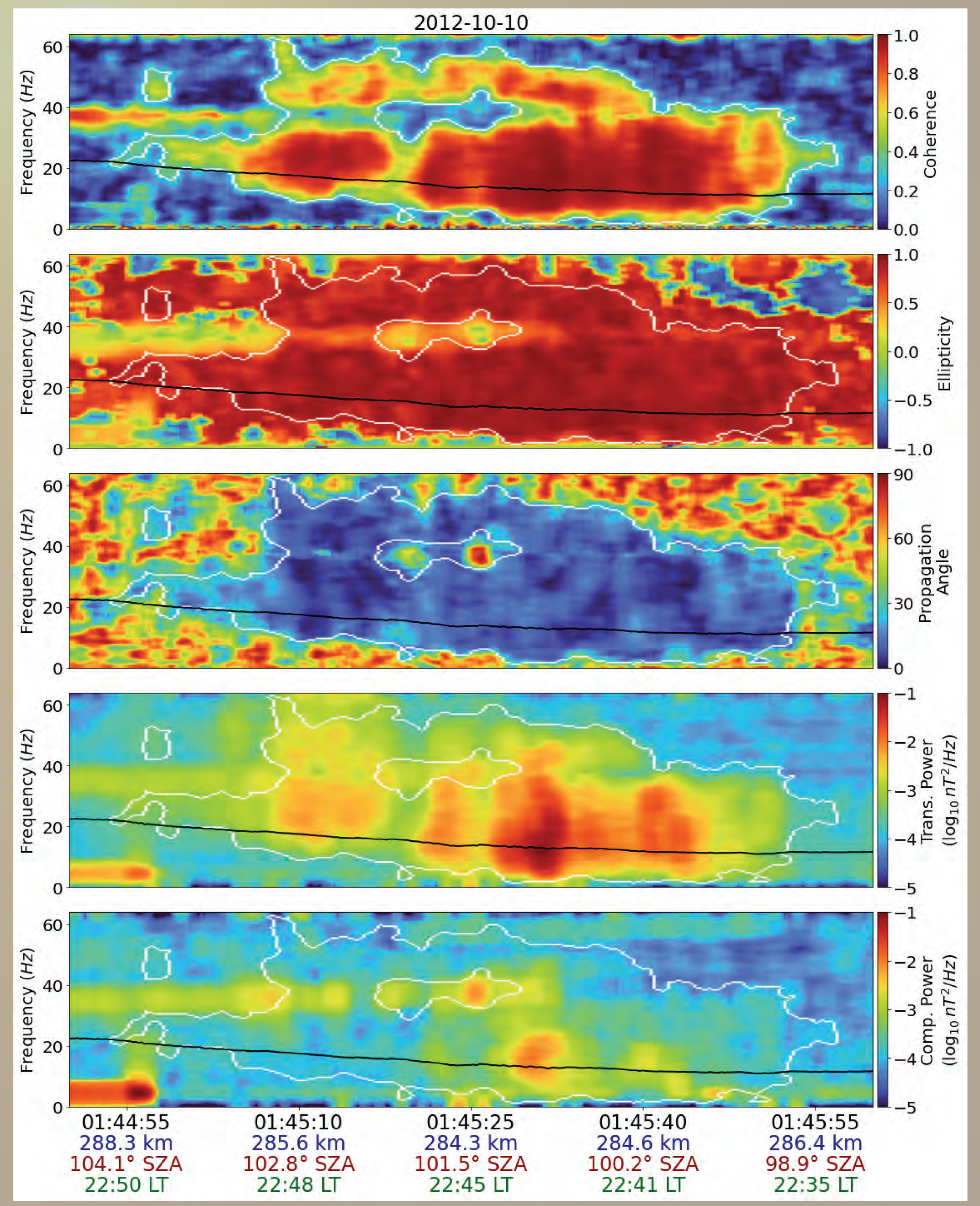
- Lightning produces atmospheric waves (sferics) that propagate up to the ionosphere.
- Some wave energy leaks into the ionosphere and then propagates in the whislter-mode.
- Whistler-mode waves are transverse, right-hand circularly polarized, field-aligned waves.
- The increasing index of refraction causes the wave normal angle to bend vertically.



Venus field structure

- Venus lacks an intrinsic dipole field.
- The interplanetary magnetic field (IMF) produces a comet-like tail.
- The dayside field is mostly parallel to the surface.
- The nightside field is mostly radial.
- Whistler-mode waves propagate along magnetic field lines, so dayside detections require the varying field to dip, creating a radial component.

Background Image: J. Whatmore

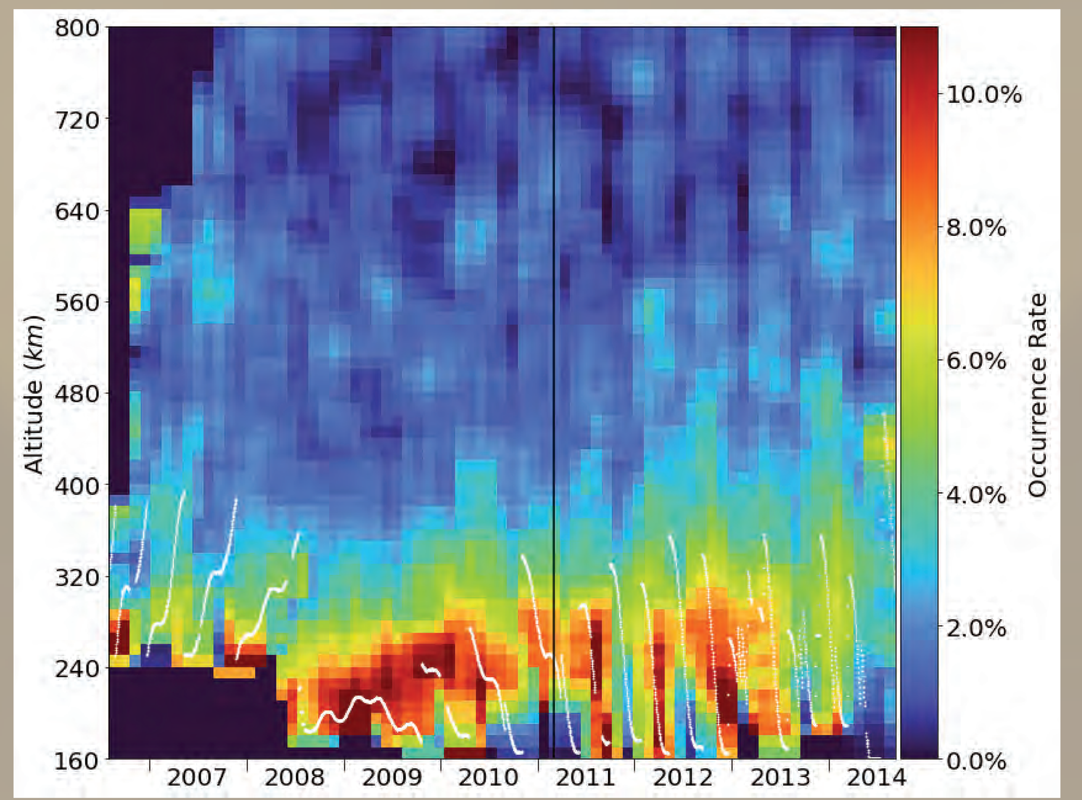


Dynamic spectra

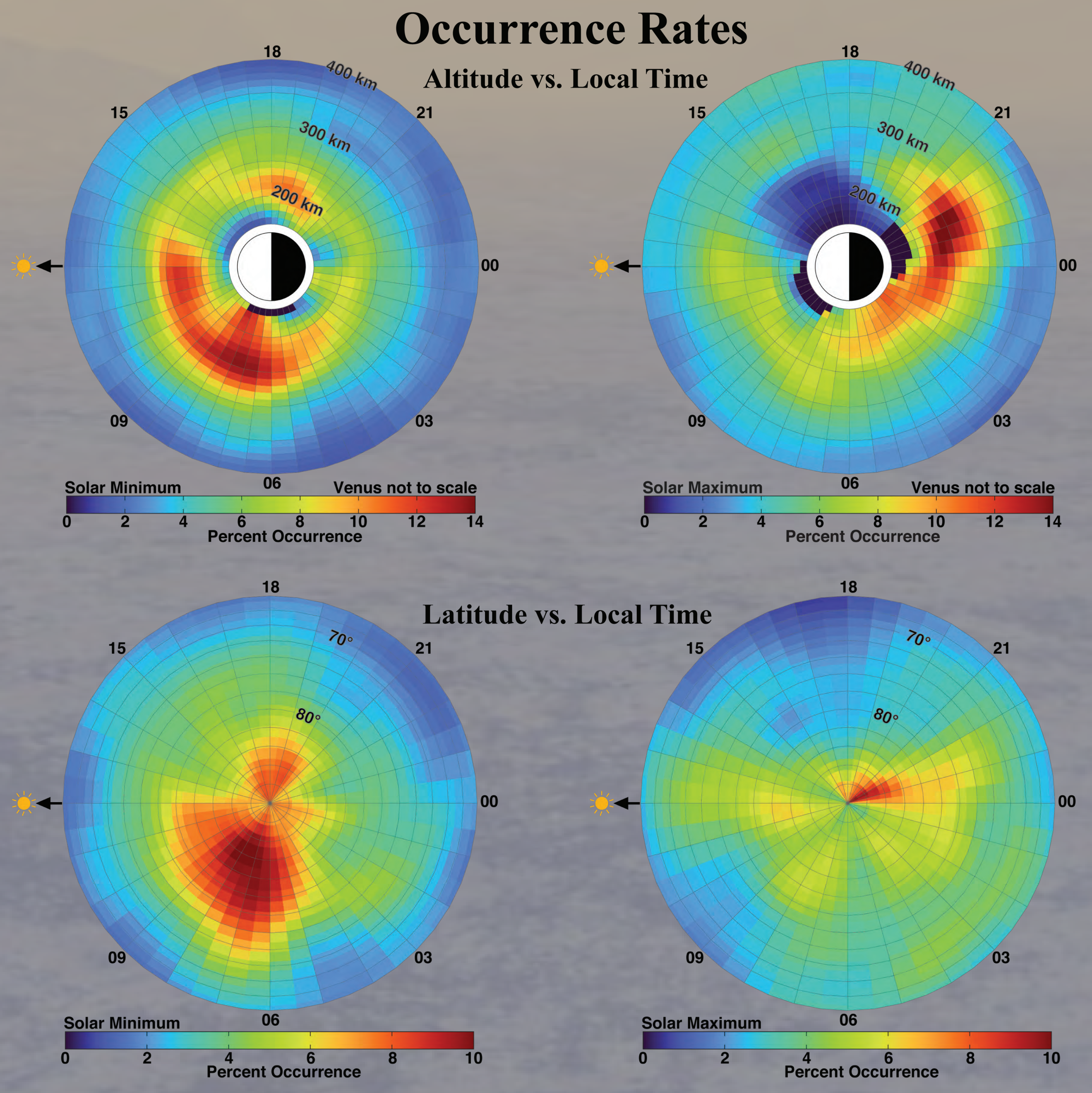
- The Venus Express magnetometer sampled at 128 Hz, allowing for wave observations up to 64 Hz.
- We identified waves using the following criteria:
  - coherence > 0.3
  - ellipticity > 0.5 (RH > 0)
  - propagation angle < 45º
  - $P_{transverse} > P_{compressional}$
- The white contours are identified whistler-mode waves.
- The black line is B_T with nT on the same scale as Hz.
- At these field strengths, the whistler band extends to 280 Hz. We are only observing 30% of the waves.
- Whistler-mode waves typically last milliseconds to seconds. This one-minute long signal is a train of waves that appear continuous because of the resolution.

Statistics

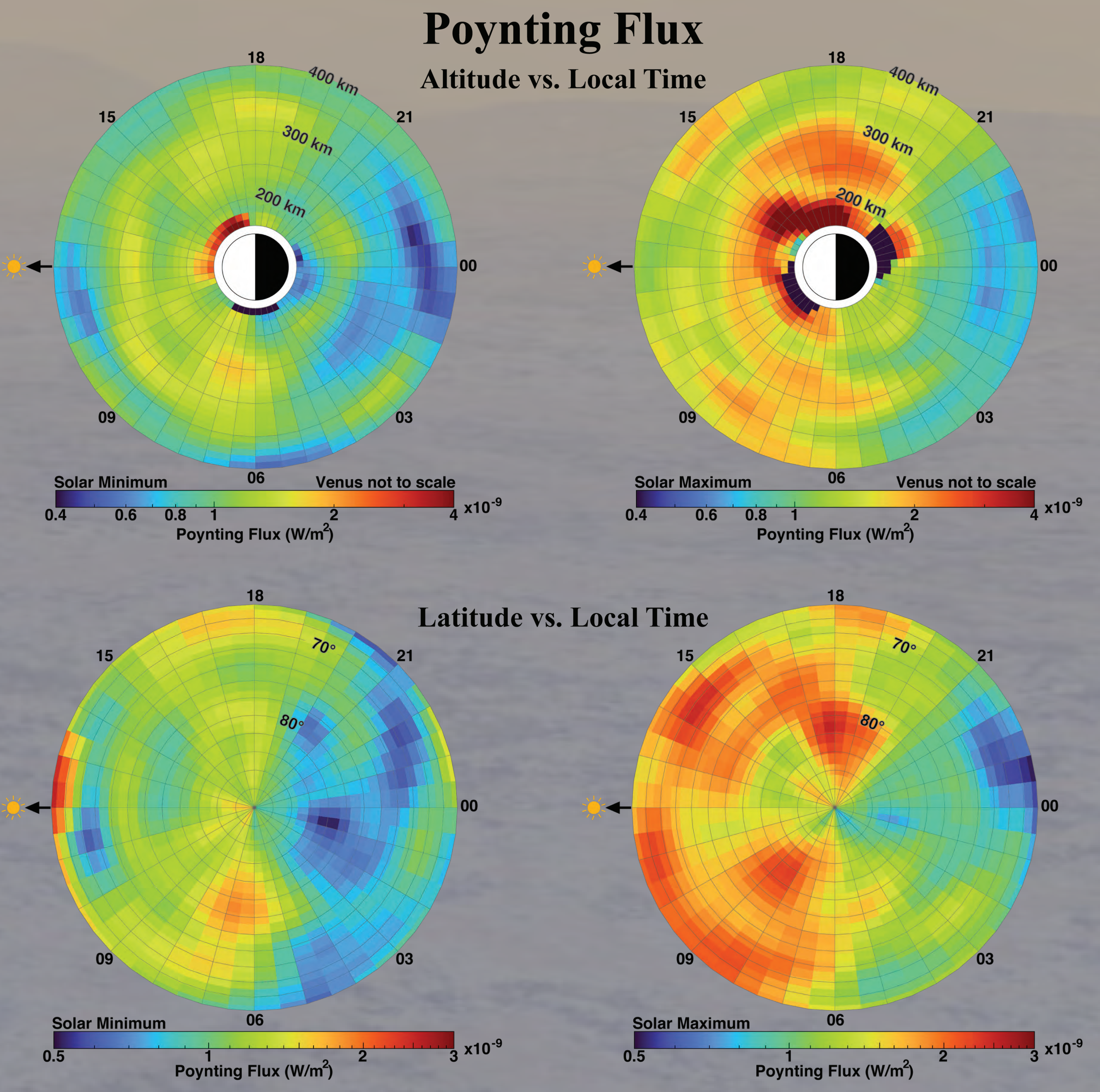
- We analyzed all VEX MAG data under 1000 km.
- 10,516 distinct signals were identified, totalling 62,000 seconds (17 hours) of waves.
- Signals varied in length up to 140 seconds, but only 1.5% were longer than 25 seconds.
- 76% of the waves were below 400 km.



- On average, whistler-mode waves were observed 5.2% of the time.
- At 200 - 300 km altitude, the occurrence rate throughout the mission was 7% on average.
- The periapsis (white lines) did not go below 245 km until mid-2008.
- From mid-2008 through 2009, the periapsis did not exceed 215 km.
- The most abundant observations occurred when Venus Express spent more time at low altitudes, closer to the source below.



- The average occurrence rates were about the same for the solar minimum and maximum periods.
- The detections peaked on the nightside during solar minimum because of the enhanced radial component in the field.
- In solar minimum, the ionosphere is often strongly magnetized, so there is improved field ducting on the dayside.
- In solar maximum, the Poynting flux is greatest at lower altitudes.
- In solar minimum, the improved field ducting distributes the energy more evenly up to 400 km.
- There are no mechanisms that produce whistler-mode waves at low altitudes in the ionosphere of Venus except lightning.
- Following theoretical work by Pérez-Invernón et al. (2017), these signals imply a connection to a storm with up to 1000 flashes per second.
- At 250 km, waves are detected 7% of the time. If they travel no more than 60º around the planet from their sources, then the global flash rate must be at least 320 s^{-1} , ~7x that of Earth.



References

Pérez-Invernón et al. (2017), J. Geophys. Res. Space Phys., 122, 11633–11644.