HIGH RESOLUTION SPECTROSCOPY FOR INVESTIGATION OF PLANETARY ATMOSPHERES

H.-W. Hübers[1,2], H. Richter[1], U. U. Graf [3], Rolf Güsten[4], B. Klein [4,5], J. Stutzki[3] & H. Wiesemeyer[4]

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[4] Max-Planck-Institut für Radioastronomie, Bonn, Germany

[5] University of Applied Sciences Bonn-Rhein-Sieg, Sankt Augustin, Germany

DLR

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Heiko Richter
1973-2023

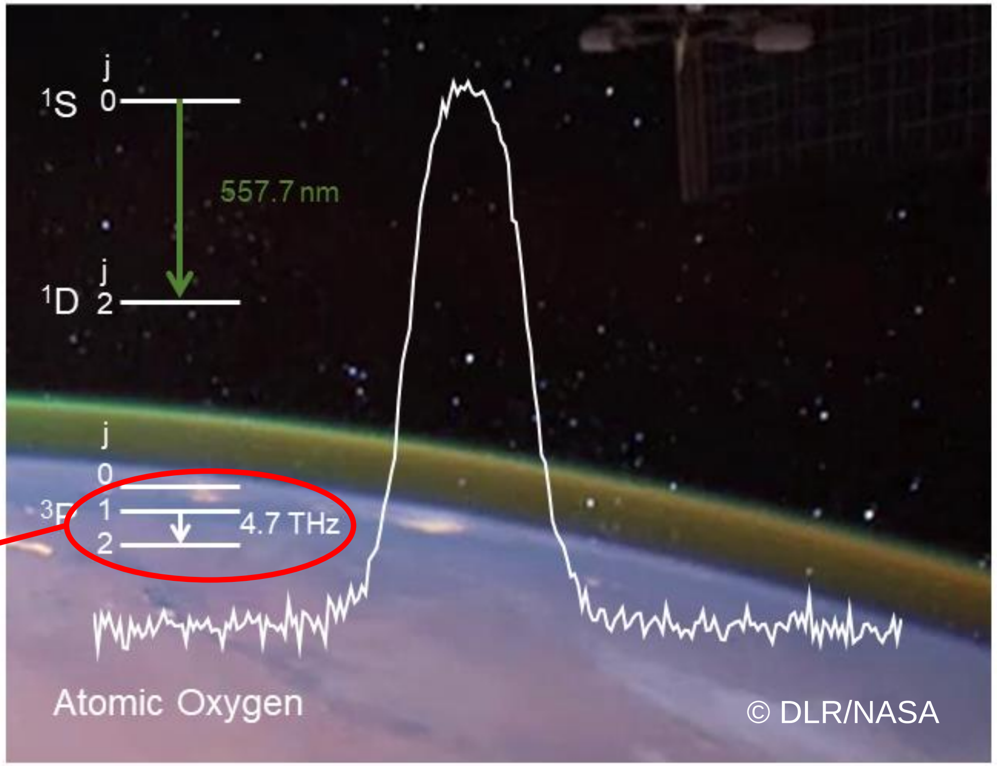
DLR

Atomic oxygen in the mesosphere and lower thermosphere (MLT) of Earth

Atomic oxygen in the MLT (quick facts)

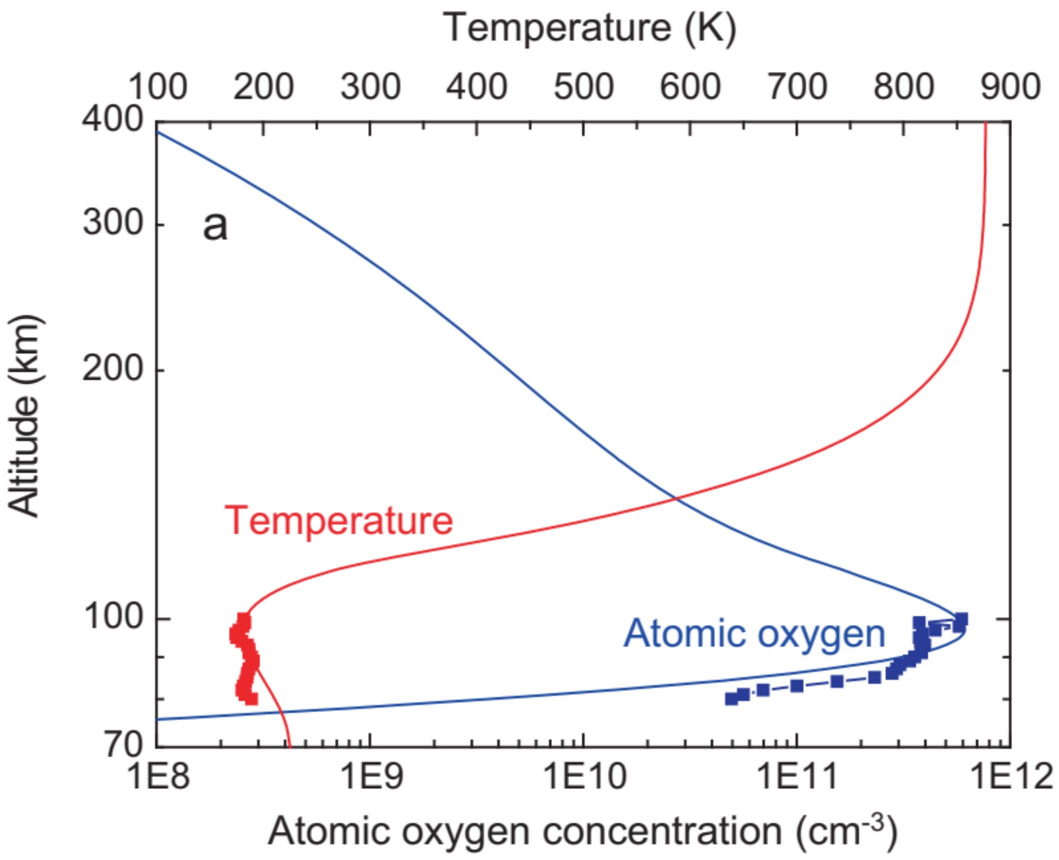
- is the main component of the Earth's mesosphere and lower thermosphere (MLT),
- extends from about 80 km to above 400 km,
- governs photochemistry and energy balance
- is a tracer for dynamical motions in the MLT
- decelerates satellites in Low-Earth-Orbit (LEO)
- causes corrosion of satellites in LEO

$^3P_1 \rightarrow {}^3P_2$



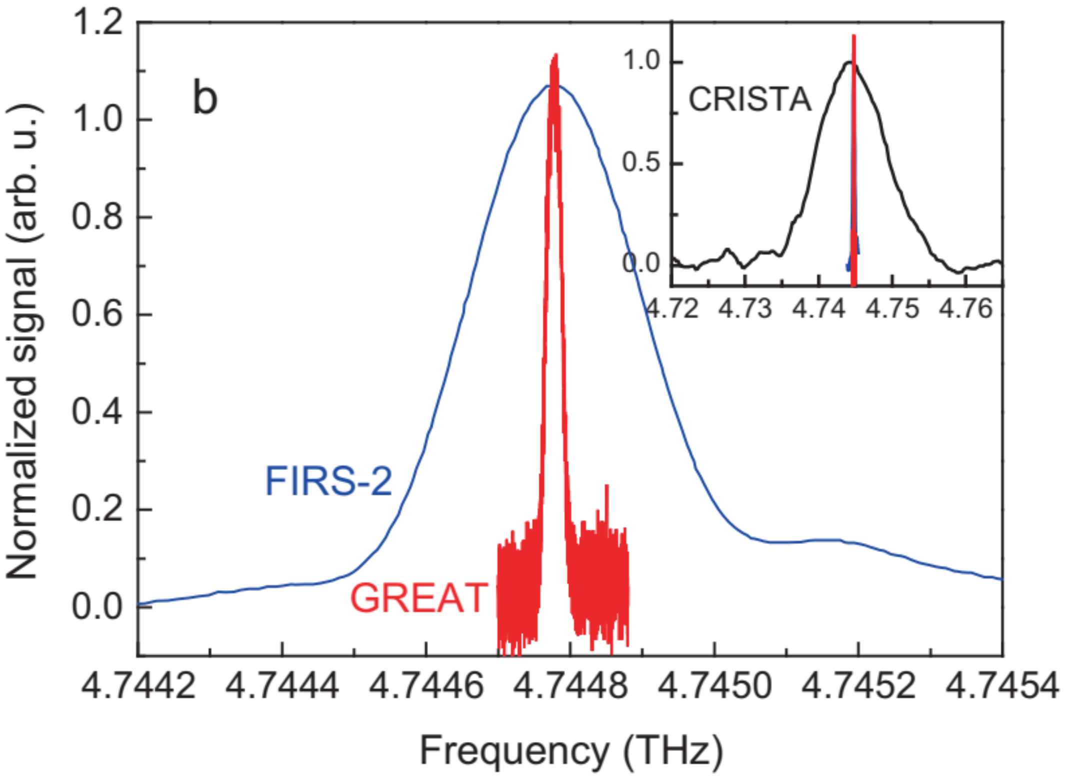
(energy levels not to scale)

Atomic oxygen measurement with GREAT/SOFIA



Model (NLRMSISE-00): straight lines

Satellite (SABER/TIMED): squares

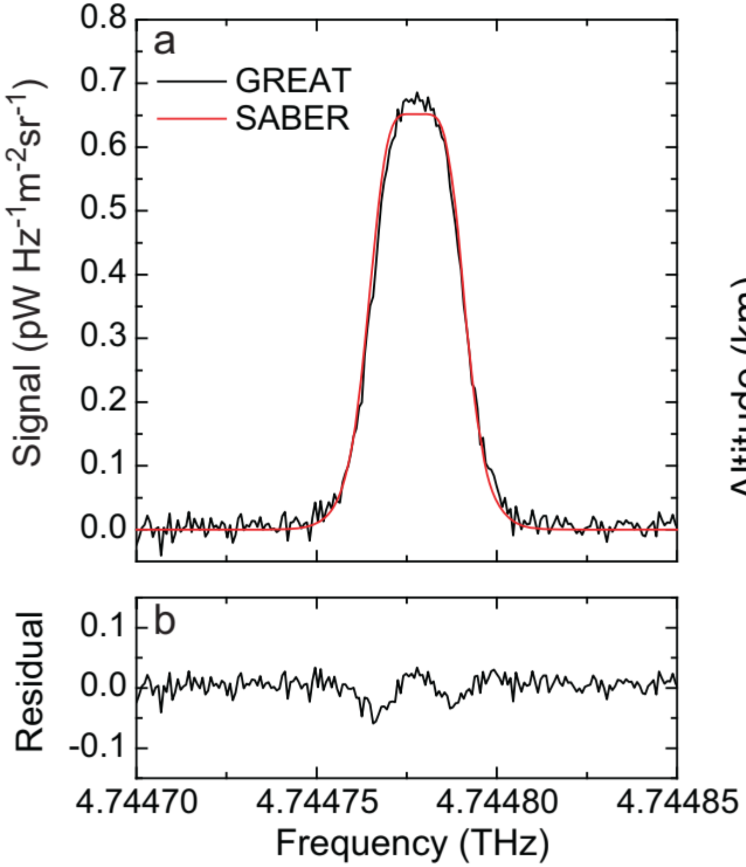


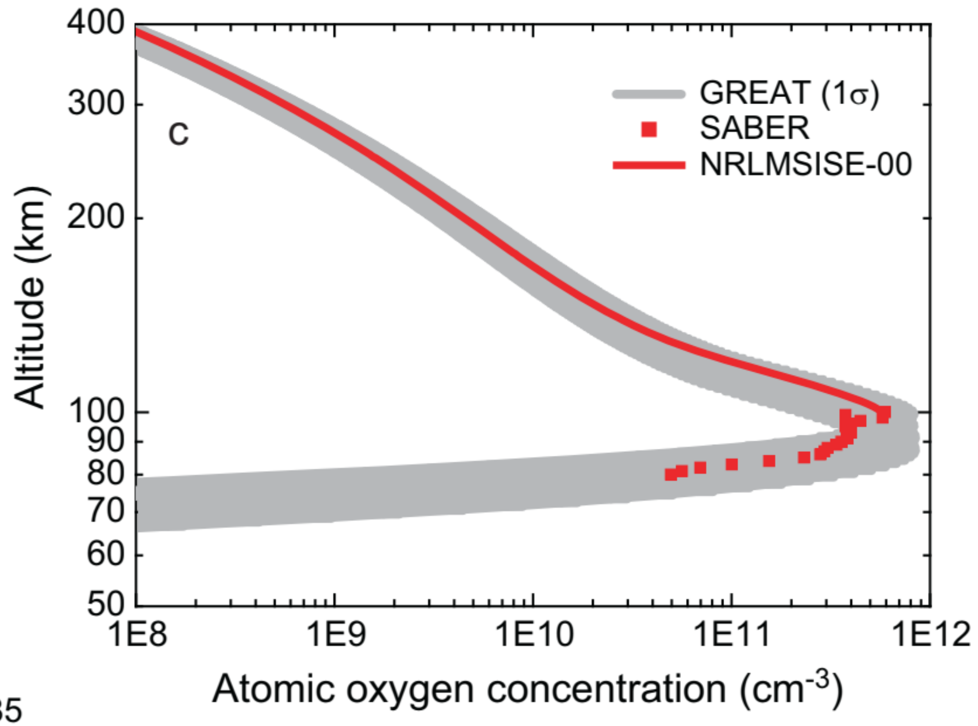
Black: CRISTA (Space Shuttle, grating spectrometer)
Blue: FIRS-2 (balloon, FTIR spectrometer)
Red: GREAT (SOFIA, heterodyne spectrometer)

H. Richter et al., Communications Earth and Environment **2**, 19 (2021)

Atomic oxygen in the MLT measured with GREAT/SOFIA

- Good agreement with model based on the semi-empirical NRLMSISE-00 model (>100km) and satellite data (SABER, 80-100km).
- It is possible to derive the concentration profile of atomic oxygen from the measured emission line shape at 4.7 THz.
- Main uncertainty
  - Water vapor absorption in the stratosphere

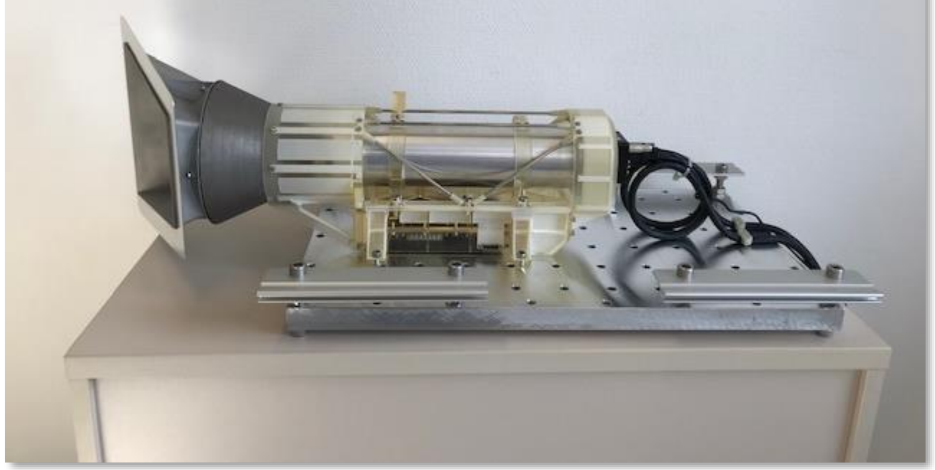




H. Richter et al., Communications Earth and Environment **2**, 19 (2021)

Renewed interest in Venus

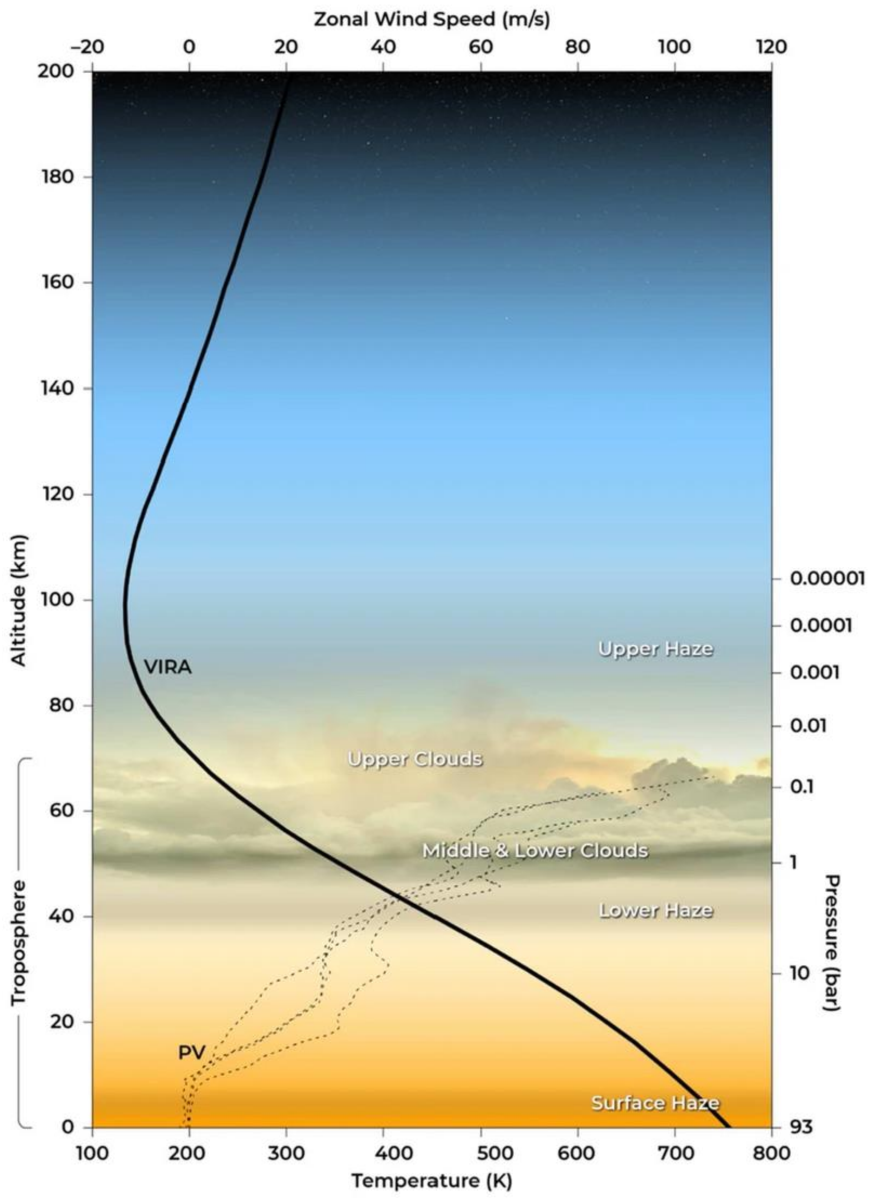
- VERITAS: NASA missions to Venus, selected June 2021, Launch: 2031
- DaVinci: NASA missions to Venus, selected June 2021, Launch: late 2020
- EnVision: ESA mission to Venus, selected June 2021, Launch: 2031



DLR's IR spectrometer for VERITAS & EnVision

Some basic facts about Venus

Parameter [Units]	Venus	Earth
Orbital and Rotational Parameters		
Semimajor Axis [10^6 km]	108.210	149.598
Sidereal Orbital Period [days]	224.701	365.256
Orbit Inclination [deg]	3.395	0.000
[1] Orbit Eccentricity	0.006772	0.0167
Sidereal Rotation Period [hrs]	5832.6	23.9345
Obliquity to Orbit [deg]	177.36	23.44
Bulk Planetary Parameters		
[2] Mass [10^{24} kg]	4.8675	5.9722
Equatorial Radius [km]	6051.8	6378.1
Polar Radius [km]	6051.8	6356.8
Volumetric Mean Radius [km]	6051.8	6371.0
Mean Density [kg/m^3]	5243	5513
Equatorial Surface Gravity [m/s^2]	8.87	9.80
J_2 [$\times 10^{-6}$]	4.458	1082.63
[3, 4] Tidal Love Number, k_2	0.295 ± 0.066	$0.30102 - i \cdot 0.00130$
[5] Moment of Inertia Factor	0.337 ± 0.024	0.3307
Surface and Atmosphere Parameters		
Solar Irradiance [W/m^2]	2601.3	1361.0
Average Surface Temperature [K]	737	288
Surface Pressure [10^5 Pa]	92	1.014
Mass of Atmosphere [10^{20} kg]	4.8	0.051
[6] Atmospheric constituents [by volume]	96.5% CO_2	78.1% N_2
	3.5% N_2	21.0% O_2
	20 ppm H_2O	~ 1% H_2O
	70 ppm Ar	9340 ppm Ar
	150 ppm SO_2	412 ppm CO_2 and rising

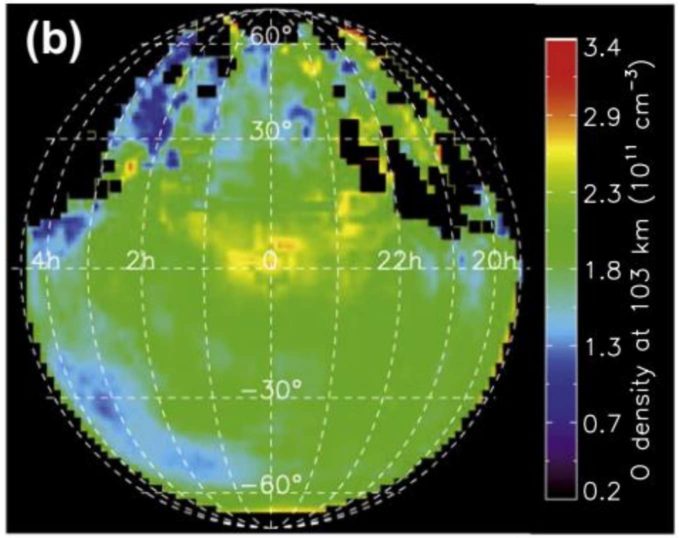


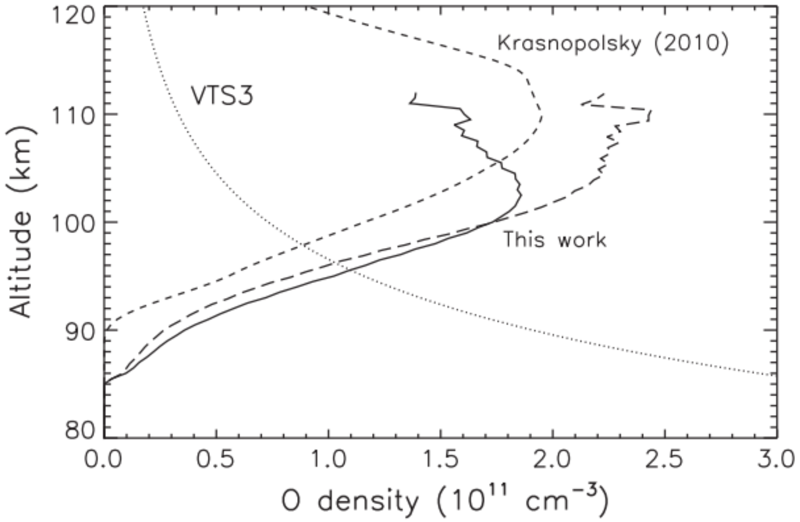
O'Rourke, et al. Space Science Reviews (2023) 219:10, https://doi.org/10.1007/s11214-023-00956-0

Atomic oxygen in the atmosphere of Venus

Atomic oxygen in the atmosphere of Venus

- is produced on the dayside of Venus by photolysis of carbon dioxide (CO_2) and carbon monoxide (CO).
- is transported to the nightside by the subsolar to antisolar circulation, where it accumulates near the antisolar point.
- recombines on the nightside.
- is important for the photochemistry, because it is very abundant in the mesosphere and lower thermosphere and interacts with many other molecules such as O_2, CO, and CO_2.
- is important for the energy balance, because CO_2 is collisional excited by atomic oxygen and the CO_2 15-µm emission is the dominant cooling mechanism of MLT.
- can be used as tracer for the global circulation.





L. Soret et al., Icarus 217, 849–855 (2012)

Atmospheric circulation patterns on Venus

Two major wind directions:

- retrograde-superrotating zonal (RSZ) wind at 70km altitude (up to 100 m/s)
- Subsolar (SS) to antisolar (AS) winds at >120km altitude (up to 300 m/s)

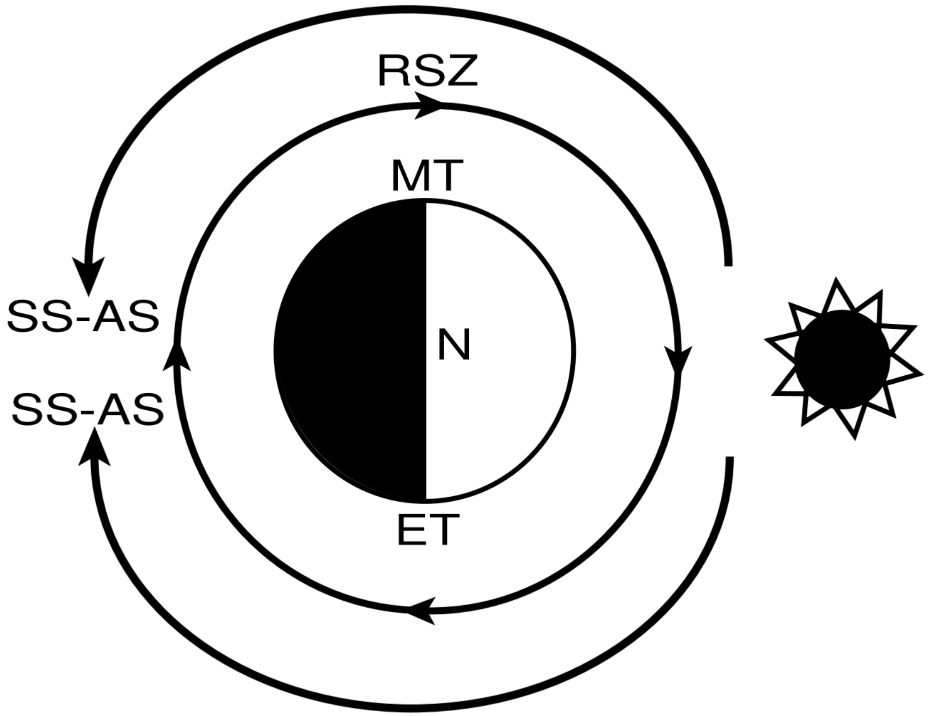
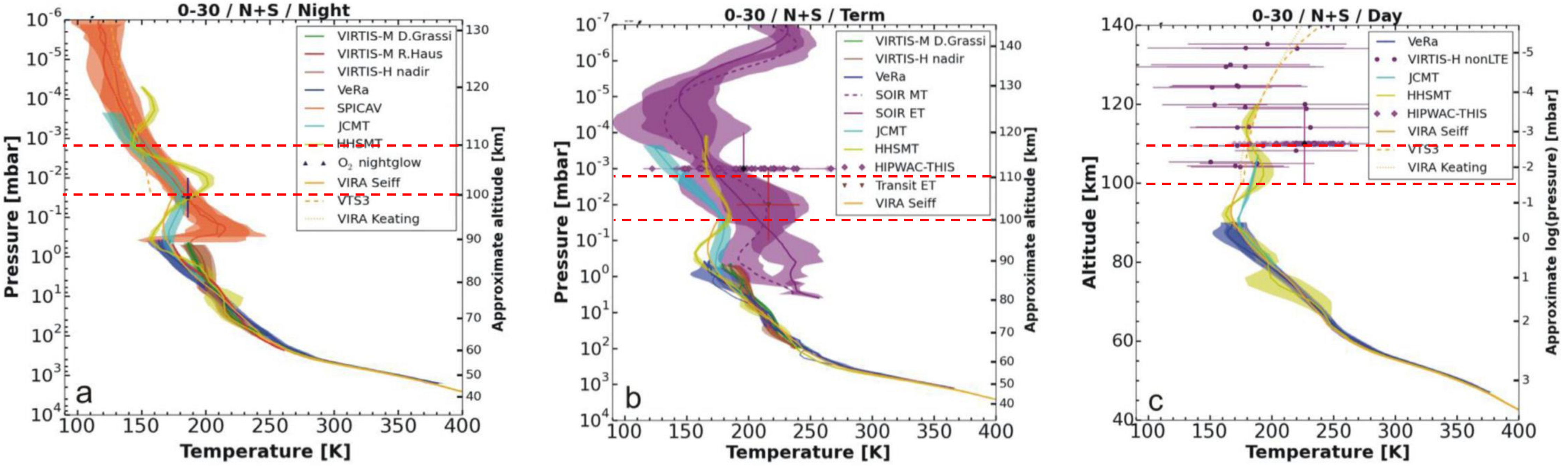


Figure 1. A cartoon of the Venus circulation patterns. The illustration is looking down at the north pole. MT is the morning terminator, ET is the evening terminator, SS-AS is the subsolar-antisolar wind pattern, RSZ is the retrograde superrotating zonal wind pattern. Adopted from *Schubert et al.* [2007].

A. S. Brecht et al., J Geophys. Res. 116, E8004 (2011)

Thermal structure of the atmosphere of Venus



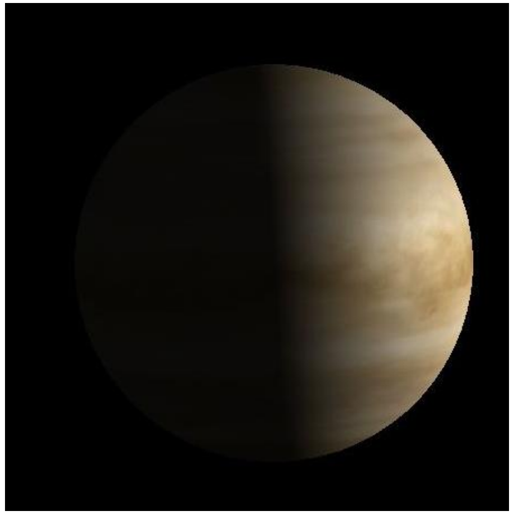
a) 0°-30°, northern and southern hemisphere, nighttime
b) 0°-30°, northern and southern hemisphere, terminator
c) 0°-30°, northern and southern hemisphere, daytime

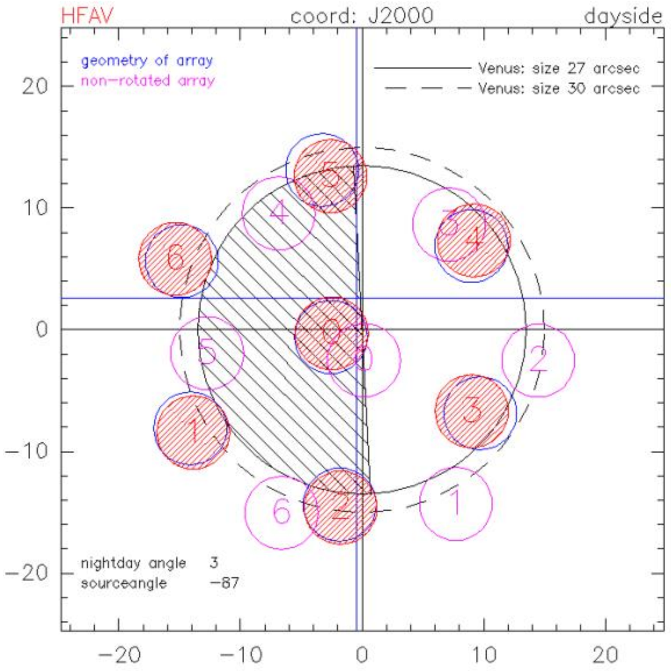
S. S. Limaye et al. Icarus 294, 124–155 (2017)

Observation of Venus with upGREAT on SOFIA

upGREAT:

- Dual channel THz heterodyne spectrometer (1.9 & 4.7 THz)
- 4.7-THz channel for atomic oxygen
- Array of 7 superconducting hot-electron bolometer mixers
- 4.7-THz QCL as local oscillator
- Digital fast Fourier transform back-end spectrometer
- 6 arcs FWHM of telescope beam,
- Three flights, approx. 20 min measurement time per flight



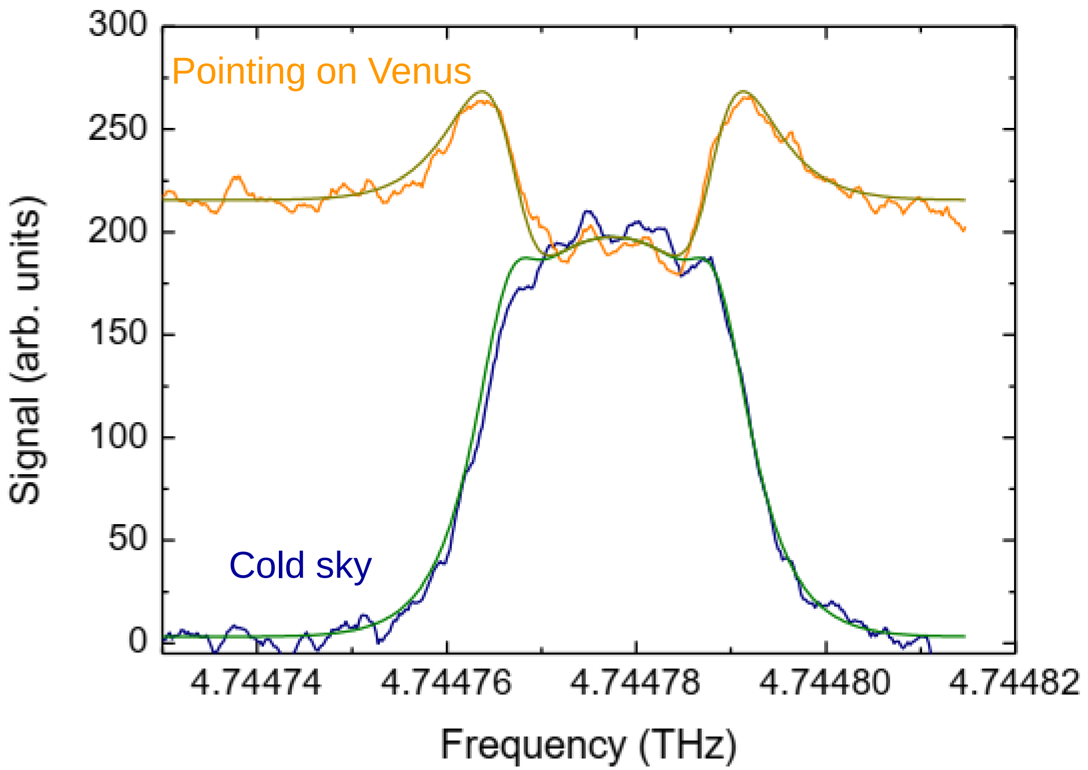


Date (2021)	Geocentric distance (au)	Apparent diameter (arcsec)	Phase angle (%)	Geocentric velocity (km/s)	Solar activity (Earth, F.10.7)
Nov. 10	0.58	28.7	43.2	−13.06	80
Nov. 11	0.57	29.0	42.6	−13.03	80
Nov. 13	0.56	29.8	41.4	−12.97	80

H.-W. Hübers et al., Nature Communications,14:6812 (2023)

Atomic oxygen line originating from the Earth's atmosphere

- Pointing on Venus: Line appears in absorption
- Looking at cold sky: Line appears in emission
- Straight lines: radiative transfer calculation
- Due to the low telescope elevation and the long path through the Earth atmosphere the telluric line is saturated in both spectra.
- Saturation occurs at the same temperature (196 K), which is the temperature of the Earth atmosphere at the altitude where the line becomes optically thick.



Atomic oxygen in Earth and Venus atmosphere

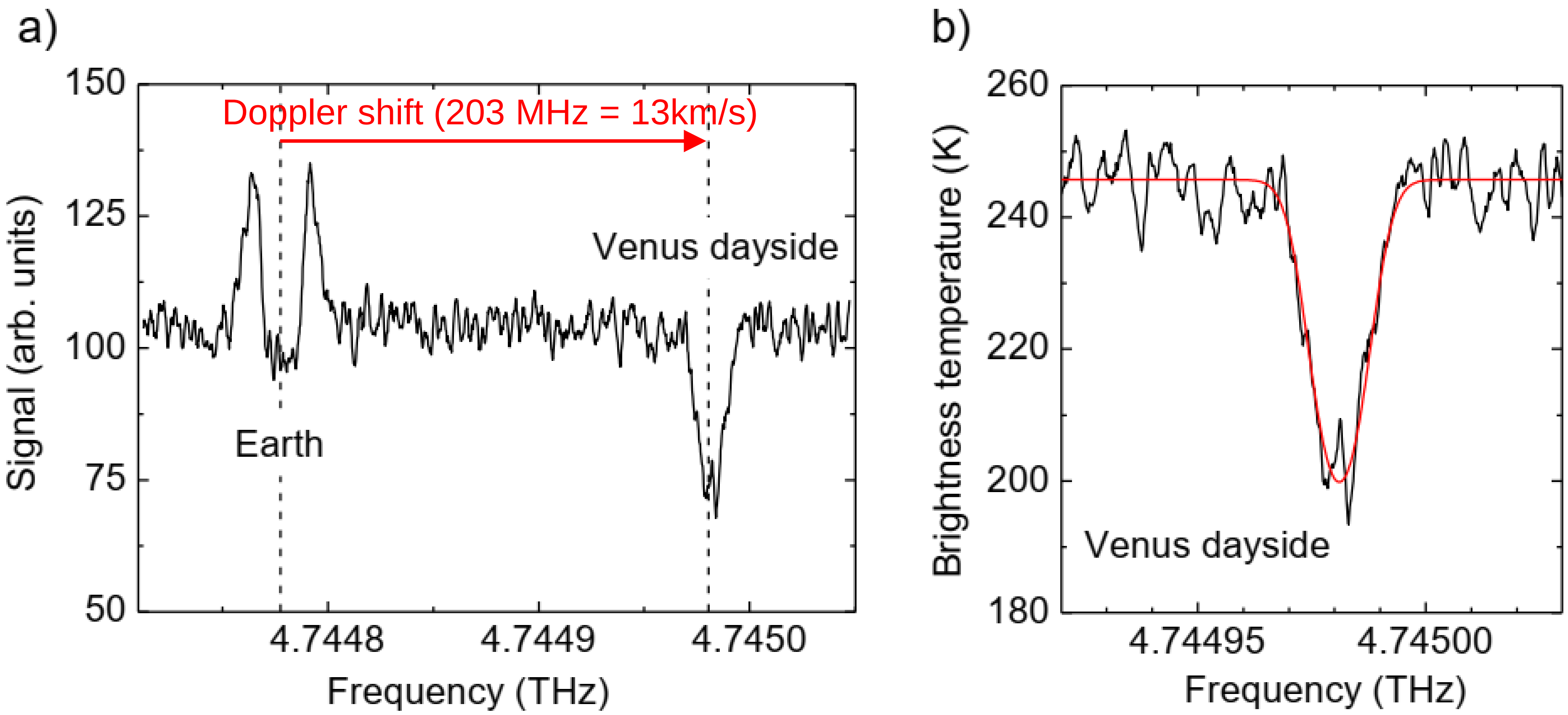
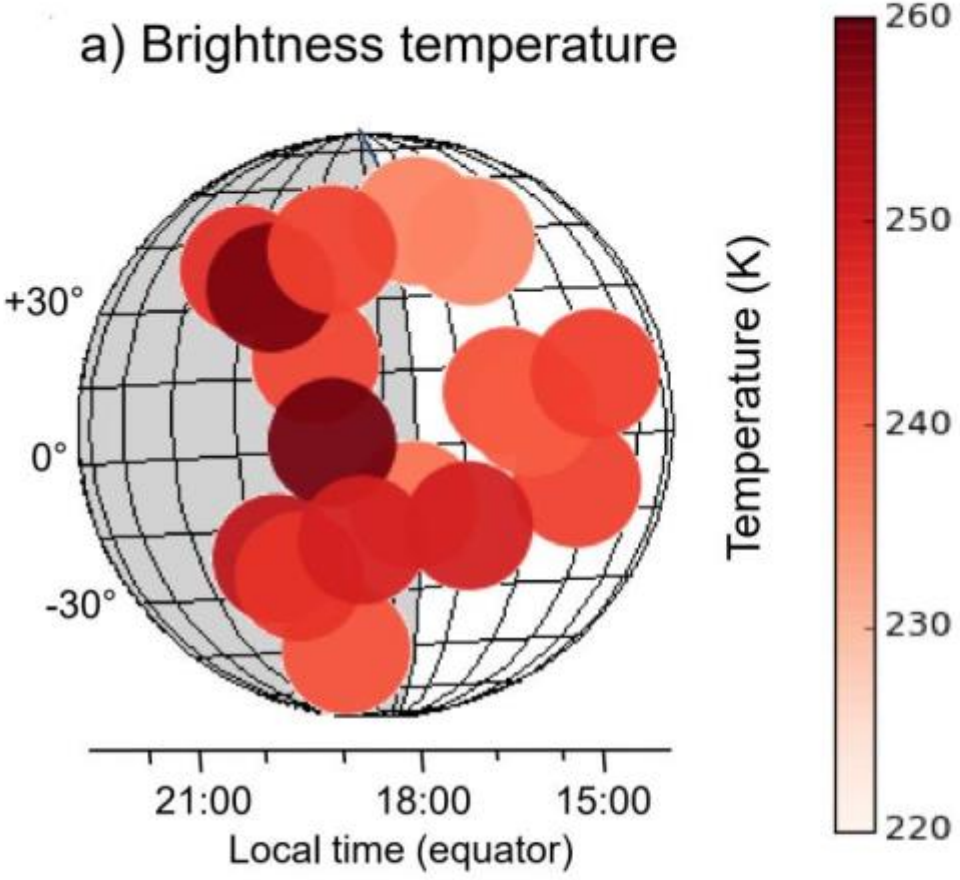
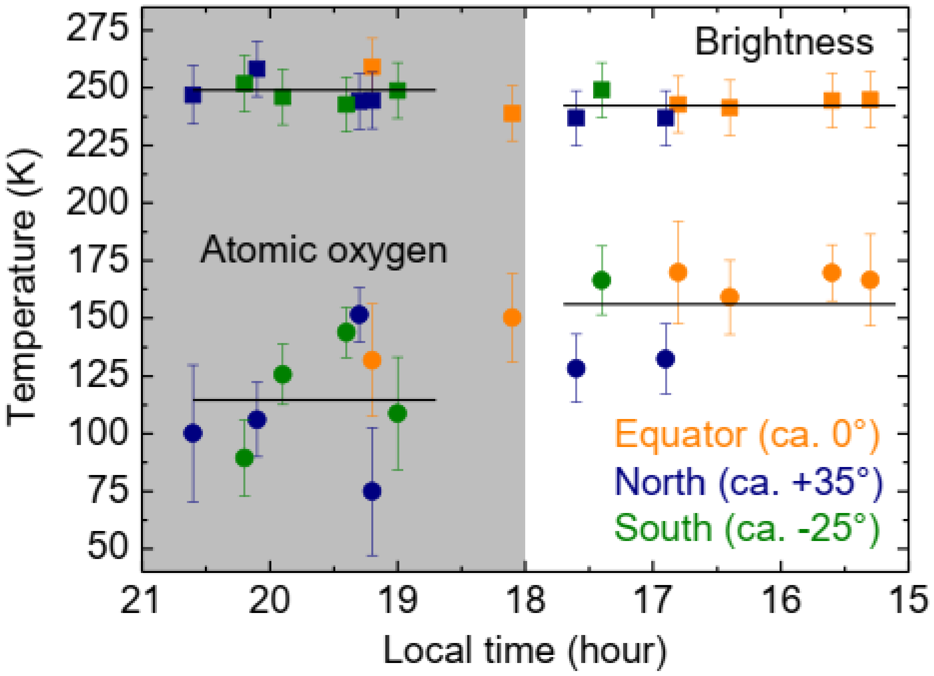


Fig. 1 | Spectra of the fine structure $^3P_1 \rightarrow {}^3P_2$ transition of atomic oxygen in the atmospheres of Earth and Venus. a Measured uncalibrated spectrum of atomic oxygen with the telluric line and the line originating from the dayside of Venus at 15:36 LT close to the equator (9.8° south). The Venus line is Doppler-shifted by 203 MHz from the telluric line. The centers of both lines are indicated by dashed lines. **b** Close-up of the Venus line in **a**. The temperature scale is calibrated. The red line is a fit with our radiative transfer model. Source data are provided as a Source Data file.

H.-W. Hübers et al., Nature Communications,14:6812 (2023)

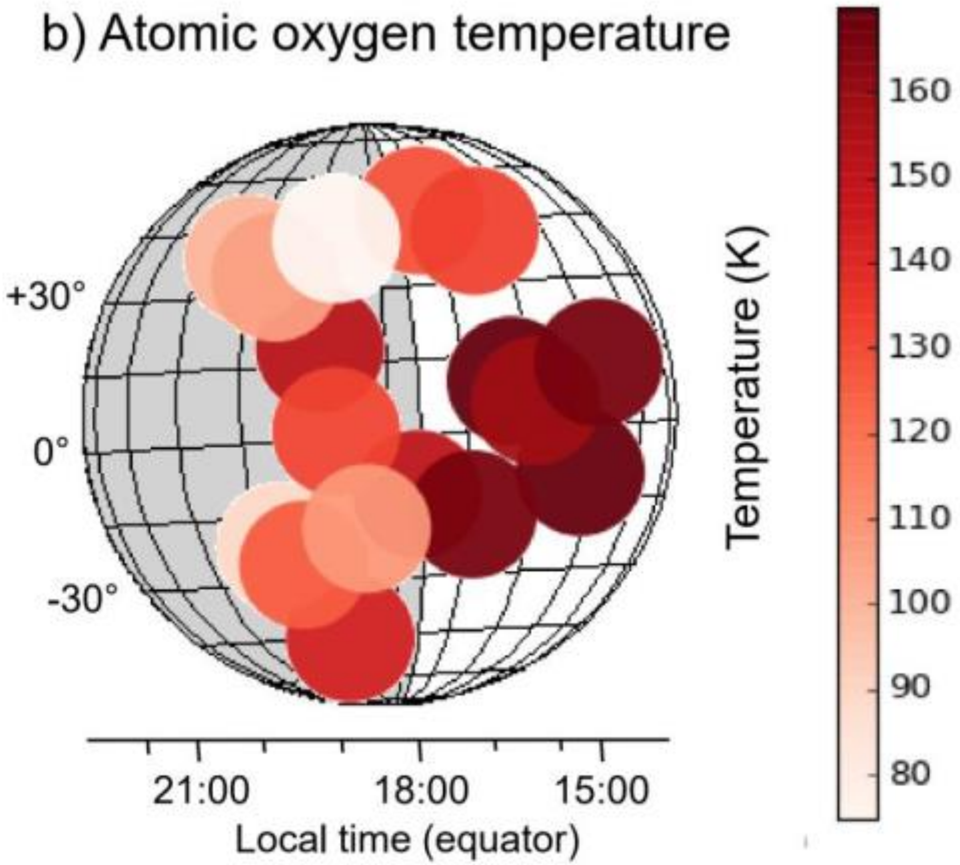
Brightness temperature

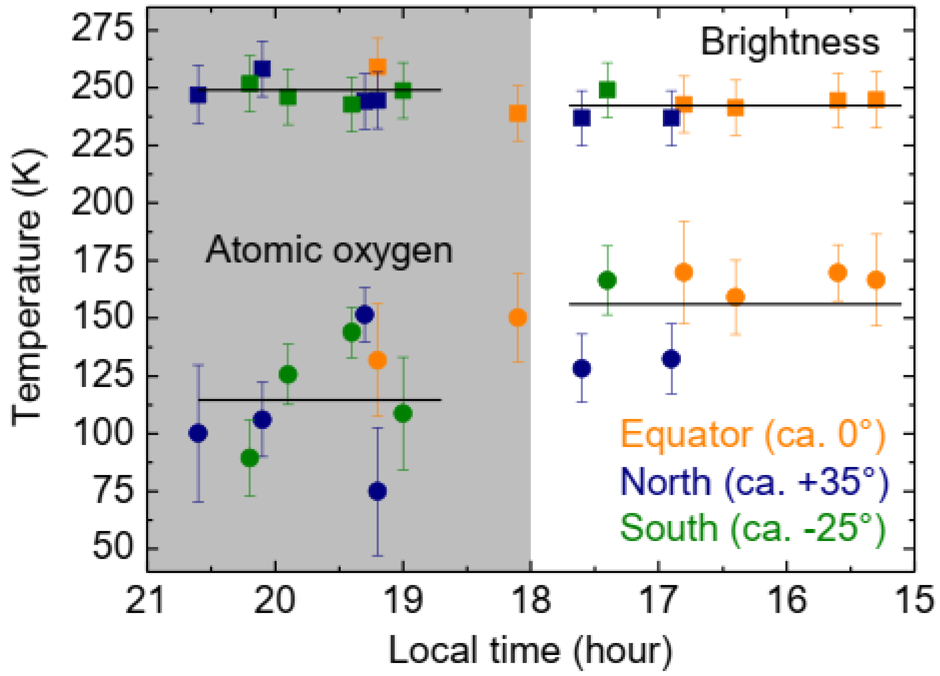




- The average continuum brightness temperature is 246 ± 6 K (nighttime: 249 ± 6 K, daytime 242 ± 4 K).
- The temperatures correspond to altitudes right above the cloud-top level at around 70 km.
- For all local times the brightness temperatures are in agreement with previous observations (255 ± 7 K @ 47 to 67 µm, 240 K @ 50 µm).

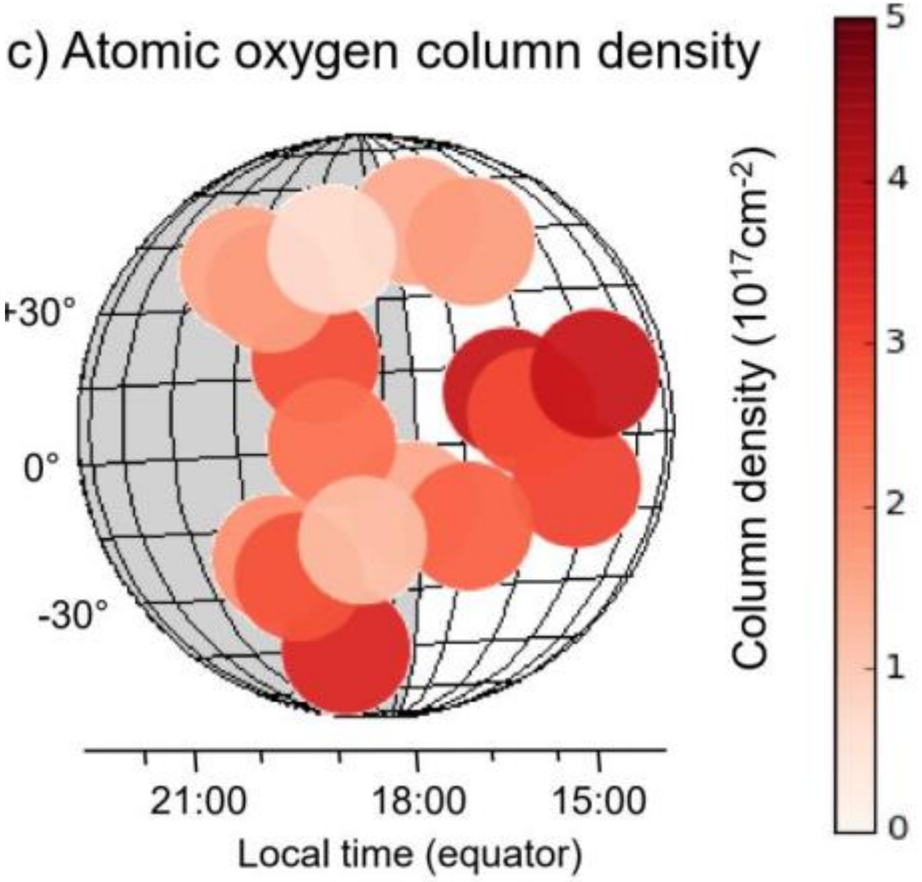
Atomic oxygen temperature

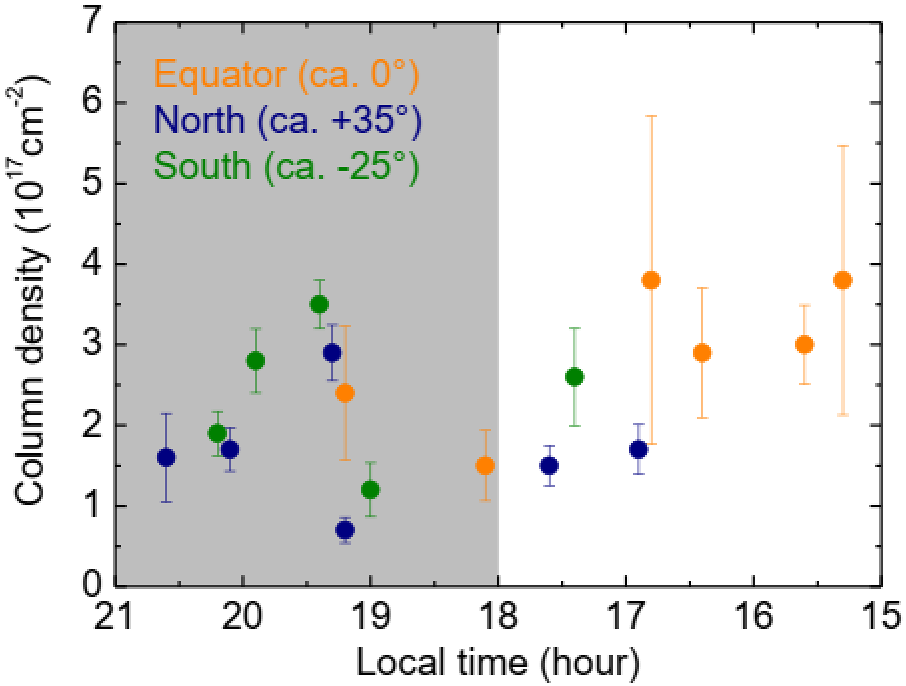




- Average dayside temperature: 156 ± 18 K.
- Average nightside temperature: 115 ± 25 K.

Atomic oxygen temperature

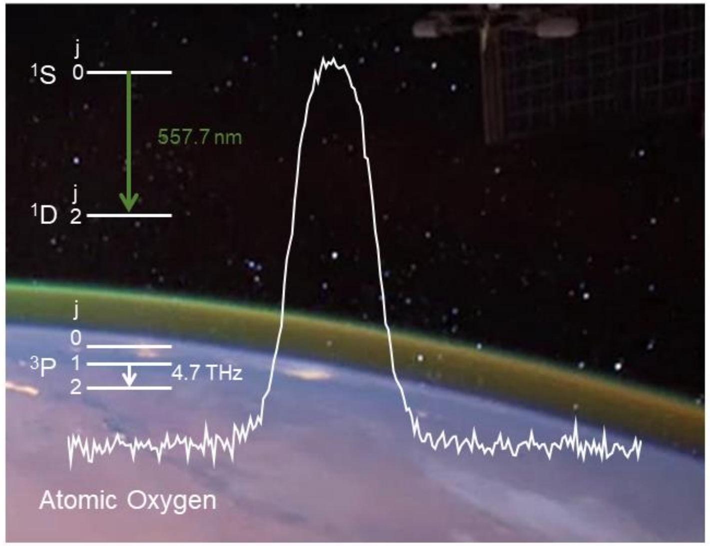


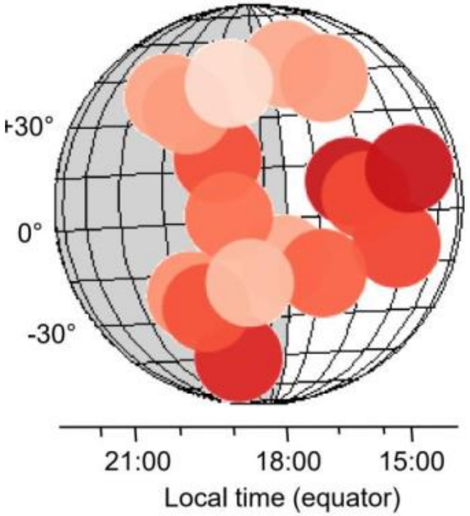


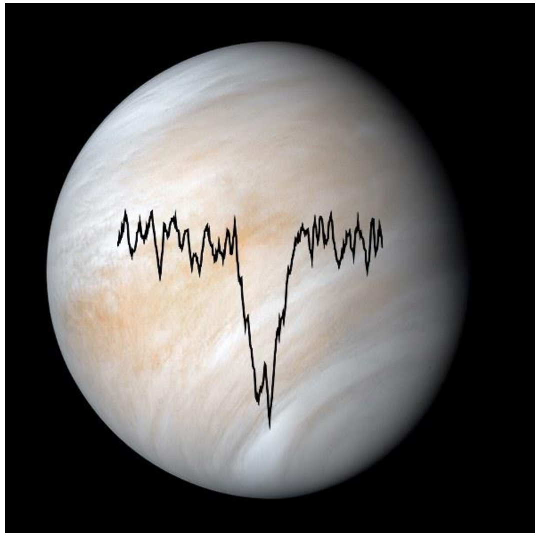
The column density varies between 0.7 and 3.8 × 10^{17} cm^{-2}. These values are similar to values obtained by models or derived from observations of the infrared O_2 nightglow and photochemical models (approx. 3 ×$10^{17} cm^{-2}$ to 6 × $10^{17} cm^{-2}$).

Conclusions

- High-resolution THz spectroscopy makes an important contribution to the understanding of planetary atmospheres.







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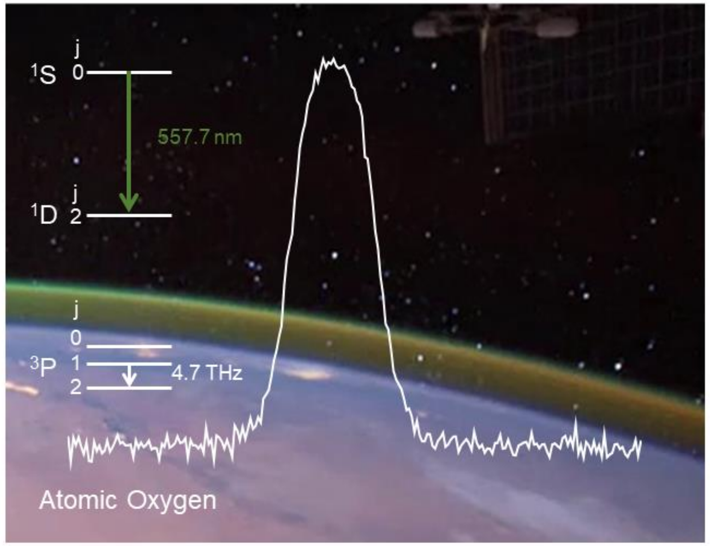
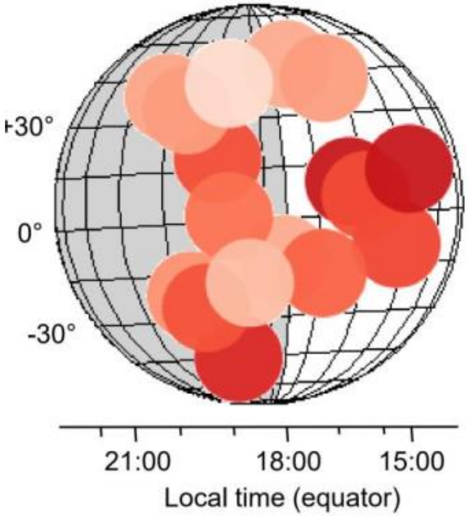
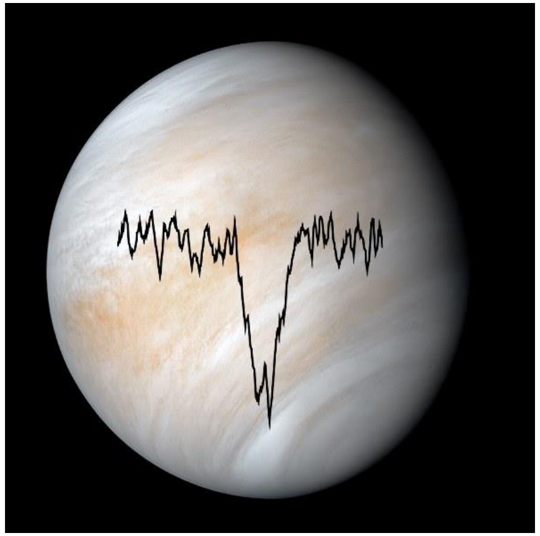
- It is a shame that further measurements with SOFIA are no longer possible.







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Thank you for your attention!