Venus Climate Orbiter AKATSUKI

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Venus Climate Orbiter (VCO), Akatsuki Chronology

- Mission approved in **2001** (officially named PLANET-C).
- Three organizations (NASDA, ISAS, and NAL) formed JAXA in **2003**.
- M-V (solid propellant rocket) discontinued and H-IIA became the launch vehicle for PLANET-C.
- Launched on 21 May **2010** from TNSC by H-IIA F17 (with IKAROS and 4 small satellites).
- VOI-1 attempted on 7 Dec **2010** but failed.
- Successful VOI-R1 on 7 Dec **2015** (followed by VOI-R2 on 20th) to orbit Venus with an orbital period of ~10.5 Earth days (different from what was originally planned).
- Slight orbit adjustment (PC1) on 4 Apr **2016** to orbit with P ~10.8 Earth days.
- Extended mission since April **2018** (second extension will start soon).
- Slight orbit adjustment (PC2) on 7 Oct **2020** to avoid extremely long umbrae.

Akatsuki in the History Timeline of Venus Exploration

Mariner 2 Flyby

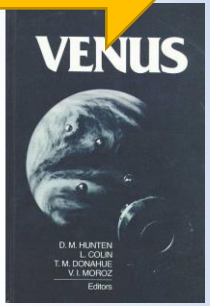
Pioneer Venus

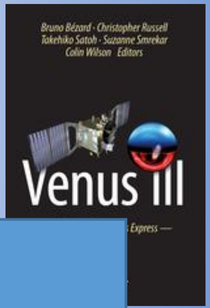
Magellan

1960's | 1970's | 1980's

Early-day Venus explorations

(VENERAs and VEGAs by USSR; Mariners and PV by USA)



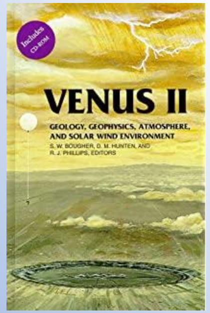


Galileo Flyby

Venus Express

Akatsuki

1990's | 2000's | 2010's



Venus Express (ESA)

More about *chemistry* and composition with spectroscopy (VIRTIS, SPICAV, PFS)

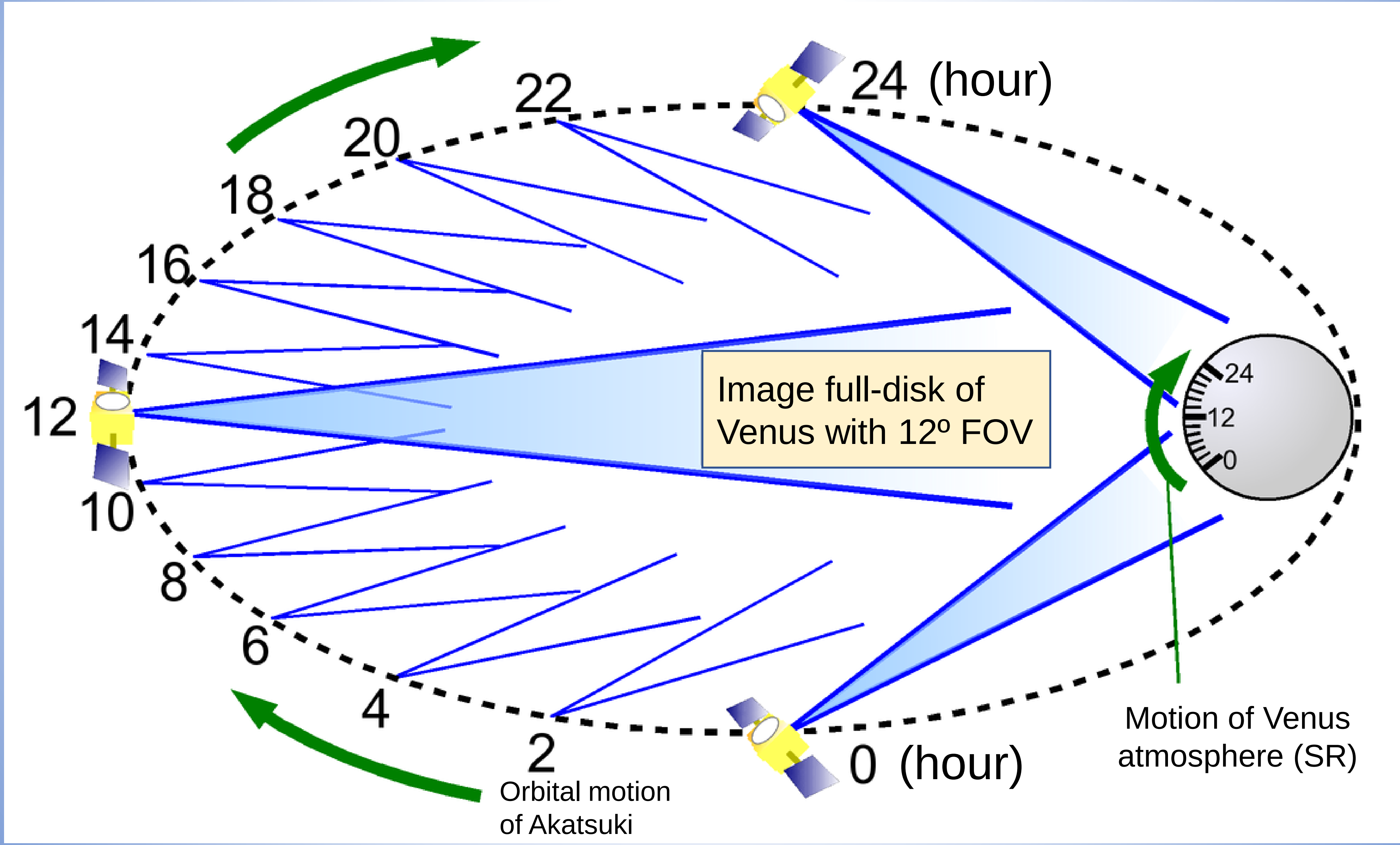
Akatsuki (JAXA)

Mostly about *dynamics* with imaging cameras (UVI, IR1, IR2, LIR, LAC)

Science Objectives of Akatsuki

- Understand in detail the atmospheric dynamics, by drawing 3-D views of wind fields, with multi-wavelength imaging observations (5 onboard cameras). Particular interest is in the “super rotation”.
- Describe spatial and temporal variabilities of clouds (**UVI, IR1, IR2, LIR**), to understand the role of clouds in dynamics and the current environment.
- Coordinated imaging and radio occultation measurements (**RS**) will allow us to study relationship between cloud morphology/dynamics and vertical profiles of the temperature (stability of the atmosphere) and the H_2SO_4 vapor.
- The ground surface is studied for mineralogy and volcanism (**IR1**).
- To answer the long-time controversy of Venus lightning with an “optimized” high-speed sampling sensor (**LAC**).

Planned 30-h Orbit in Synchronization with SR



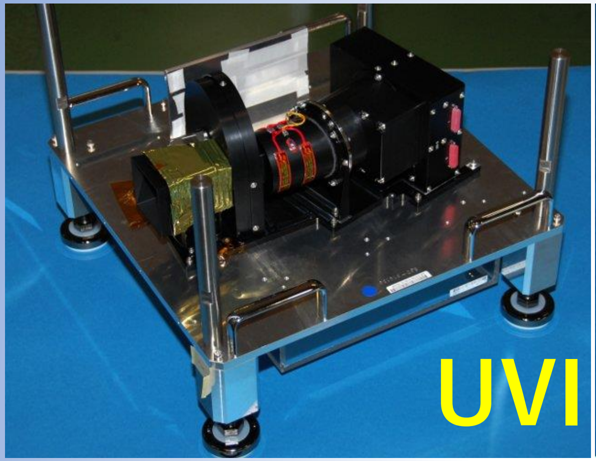
Akatsuki, the Meteorological Satellite of Venus

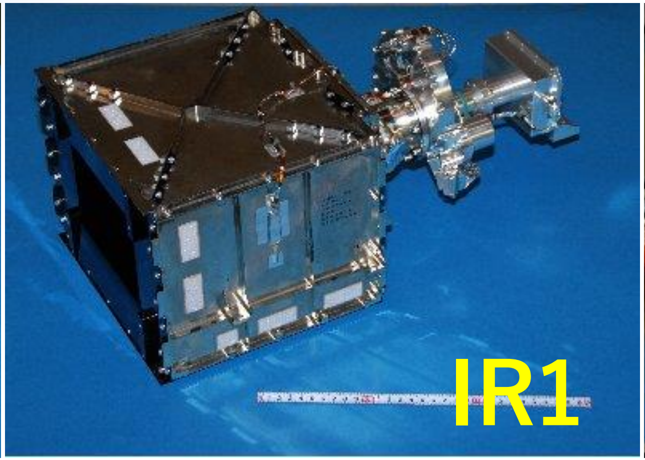
- Five on-board cameras:
  - Ultraviolet Imager (**UVI**)
  - 1-μm Camera (**IR1**)
  - 2-μm Camera (**IR2**)
  - Longwave Infrared Camera (**LIR**)
  - Lightning and Airglow Camera (**LAC**)
- Radio science with Ultra Stable Oscillator (**USO**, identical with the one on Venus Express)
- New phased-array HG antenna (X band only)
- Hayabusa-based bus (bias-momentum 3-axis stabilized) and data handling unit (DHU), plus chemical reaction propulsion system (ceramic thruster)
- 500 kg wet mass (dry: 300 kg, propellant: 200 kg)

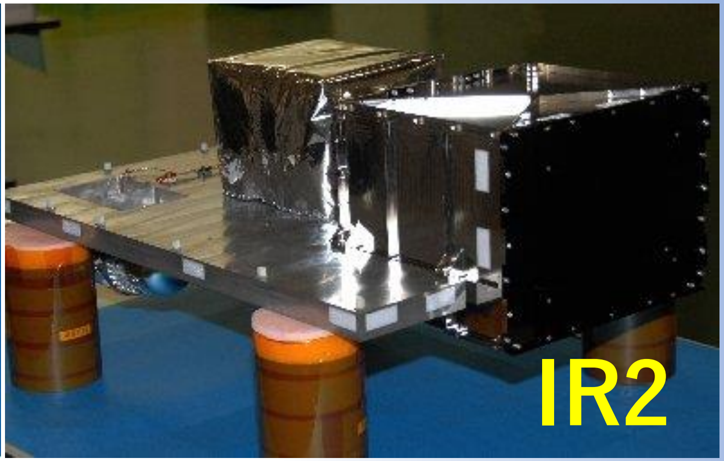
	UVI	IR1	IR2	LIR	LAC
Sensor	Si CCD 1024x1024	Si CSD/CCD 1024x1024	PtSi CSD/CCD 1024x1024	Uncooled Bolometer 320x240	Avalanche Photodiode 8x8
Wave-length	283 nm 365 nm	0.90, 0.97, 1.01 μm	1.65, 1.735, 2.02, 2.26, 2.32 μm	8-12 mm	777.4, 557.7, 545.0, 480-605 nm
Optics	Reflective/ Refractive F16	84.2 mm/ F8 (Triplet)	84.2 mm/ F4 (Triplet)	42.2 mm/ F1.4 (Ge Triplet)	61.9 mm/ F2.5 (Tele-centric)
Weight	4.1 kg	2.7 kg	13.4 kg PIM: 0.2 IR-AE: 3.5	3.3 kg	2.2 kg
Power	19.0 W	-→	AE: 36.8 W CDE: 72 W	22.8 W	14.4 W
PI	S. Watanabe	N. Iwagami	T. Satoh	M. Taguchi	Y. Takahashi
Manufac turer	NEC	SHI	SHI	NEC	Meisei Elec.

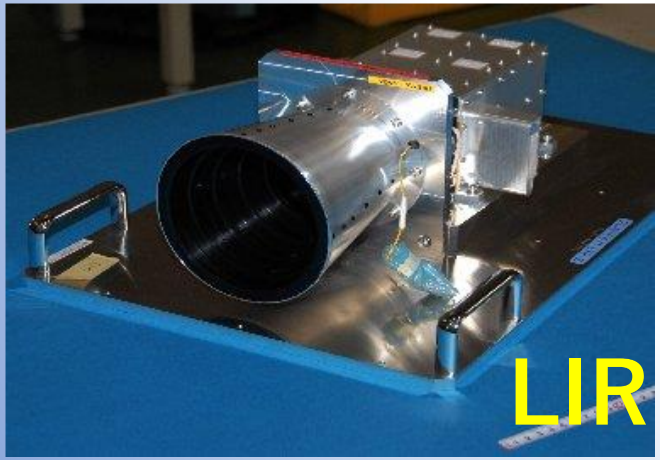
宇宙航空研究開発機構
Japan Aerospace Exploration Agency

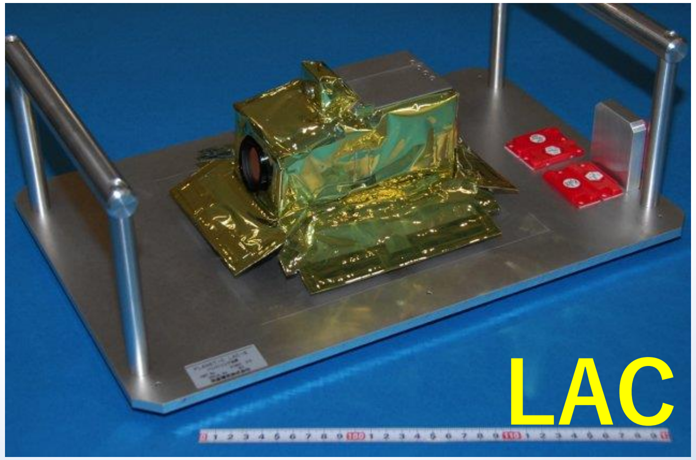
Science Instruments onboard Akatsuki

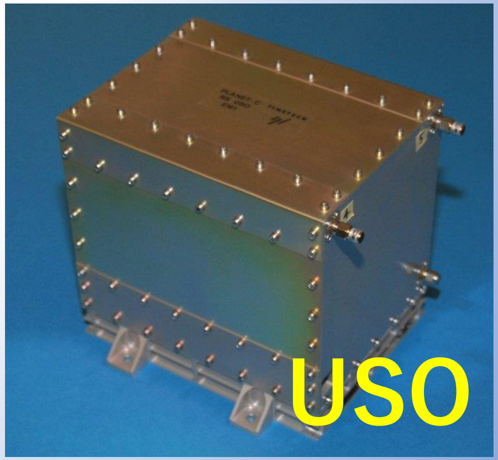




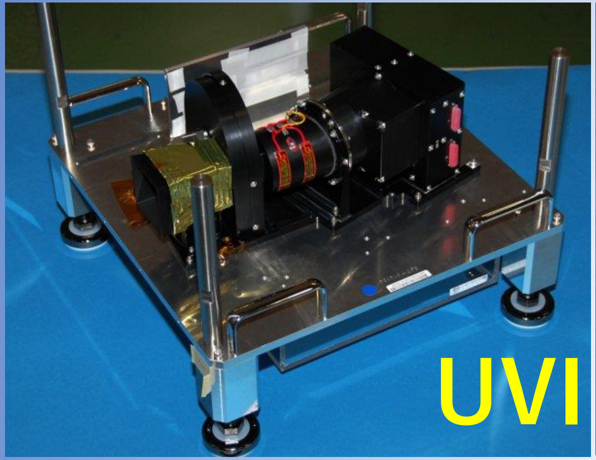


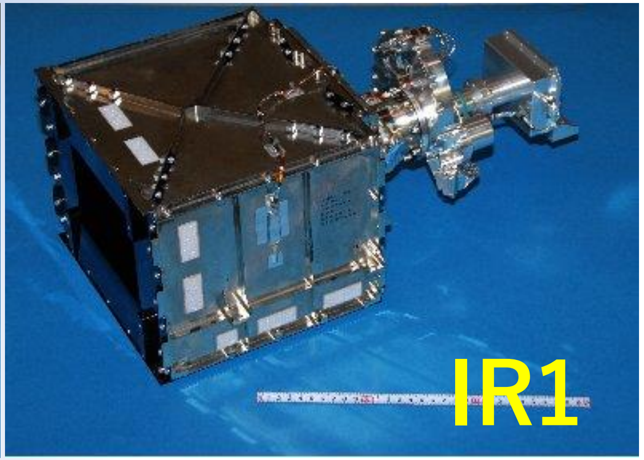


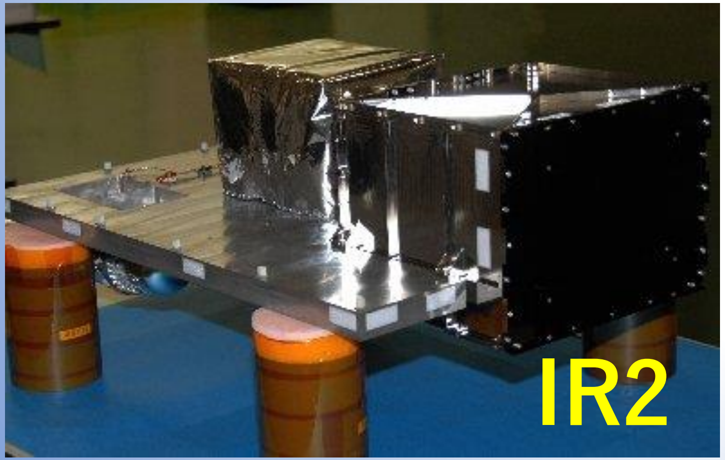


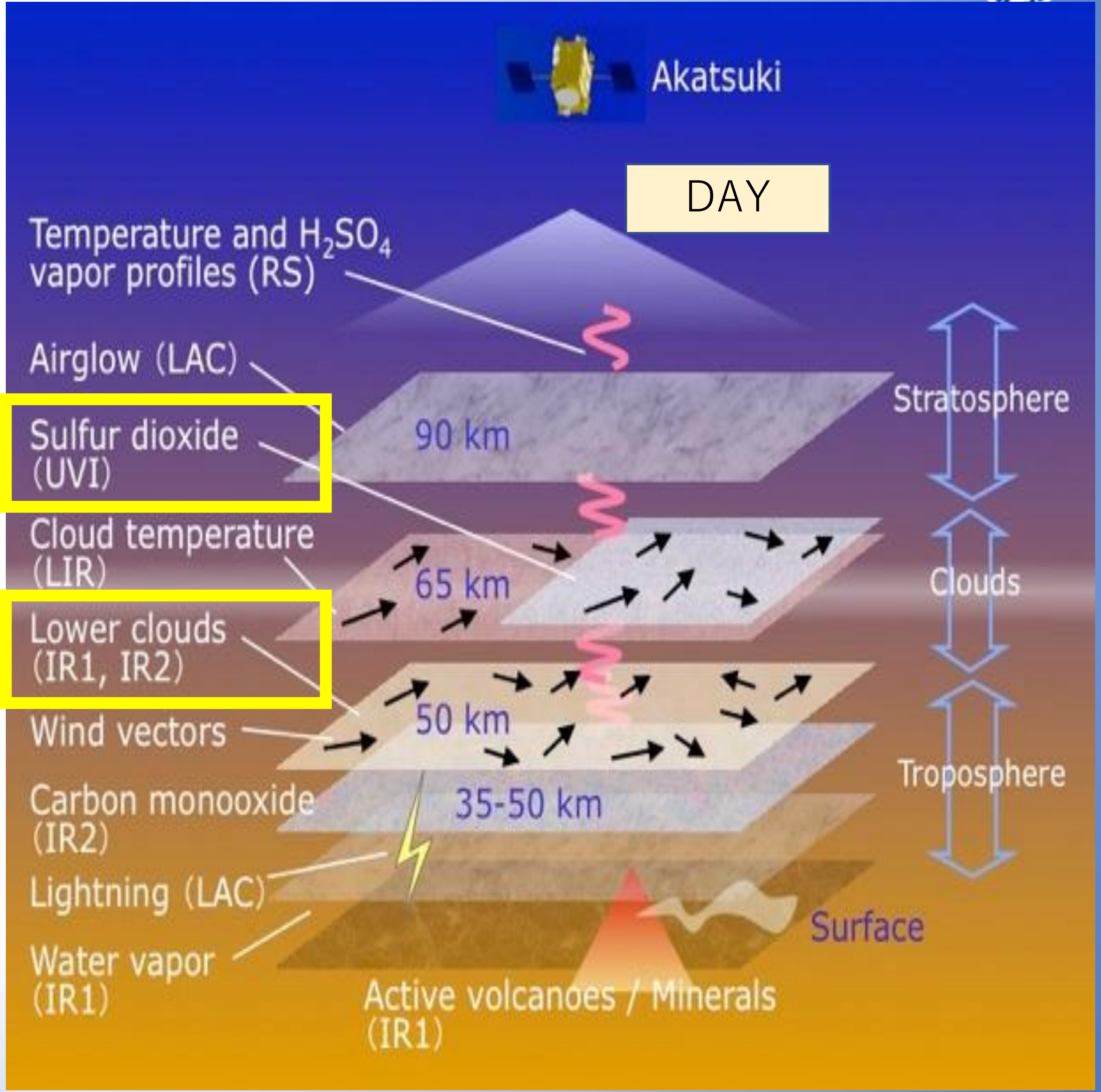


Observing Day-side of Venus

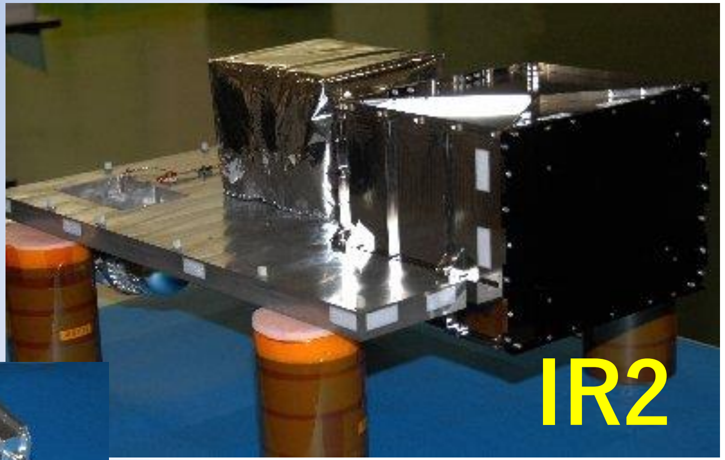


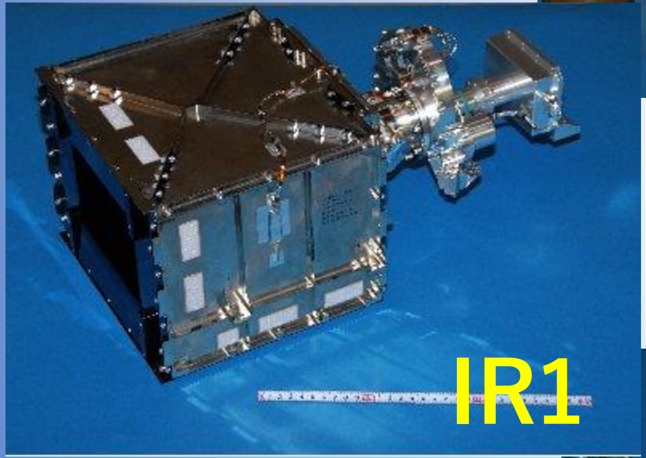


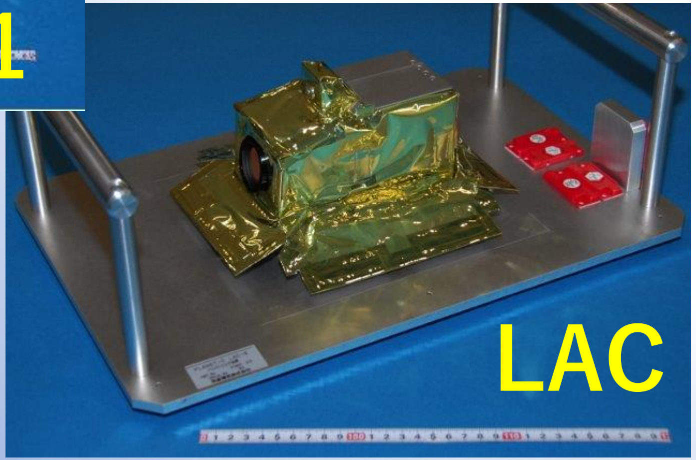


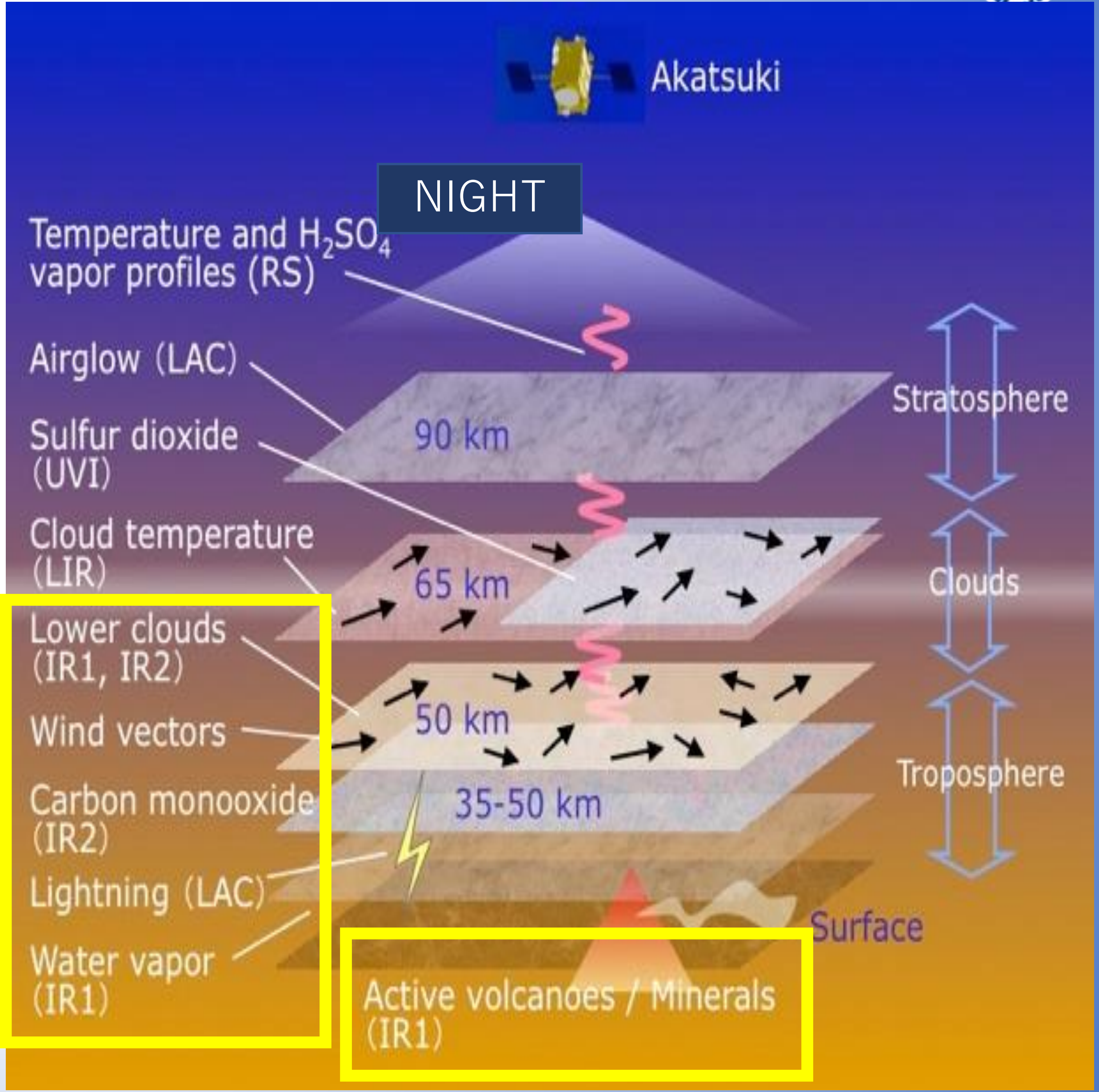


Observing Night-side of Venus

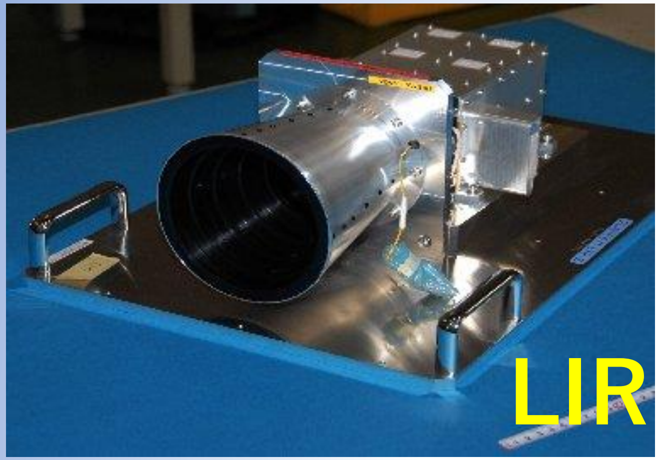


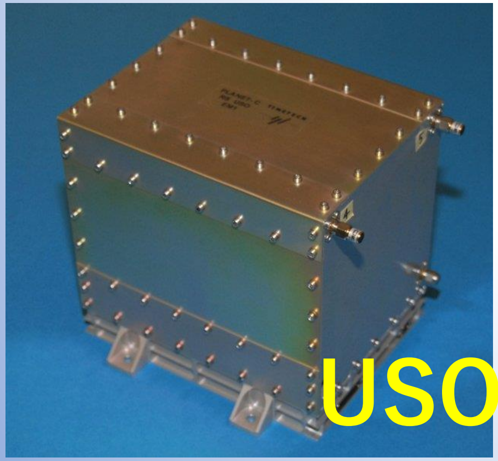


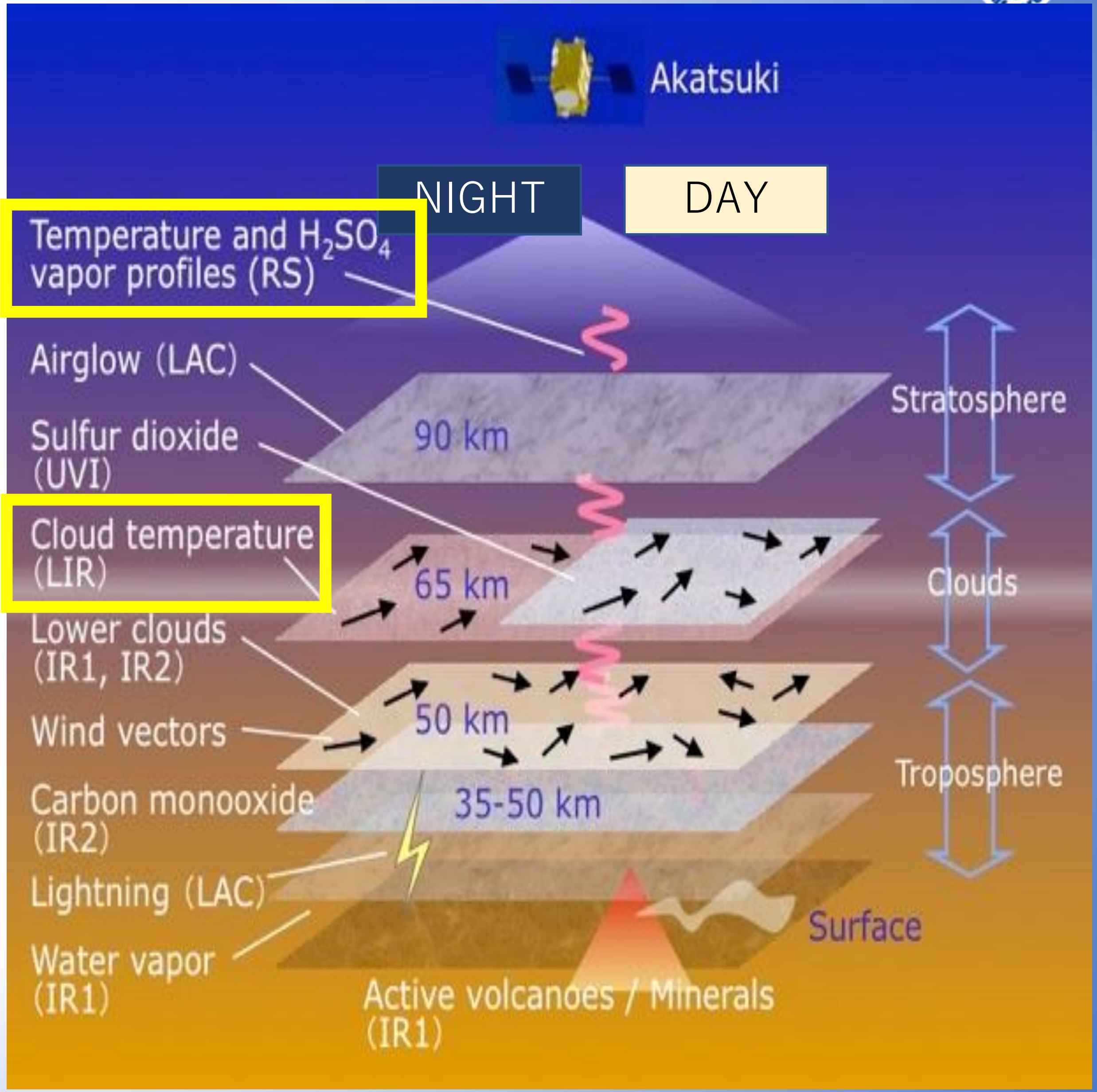




Observing Day & Night of Venus

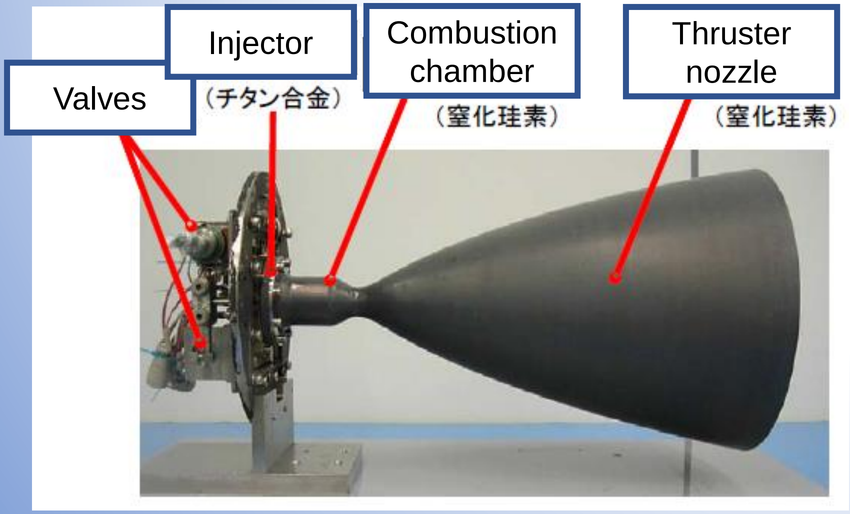


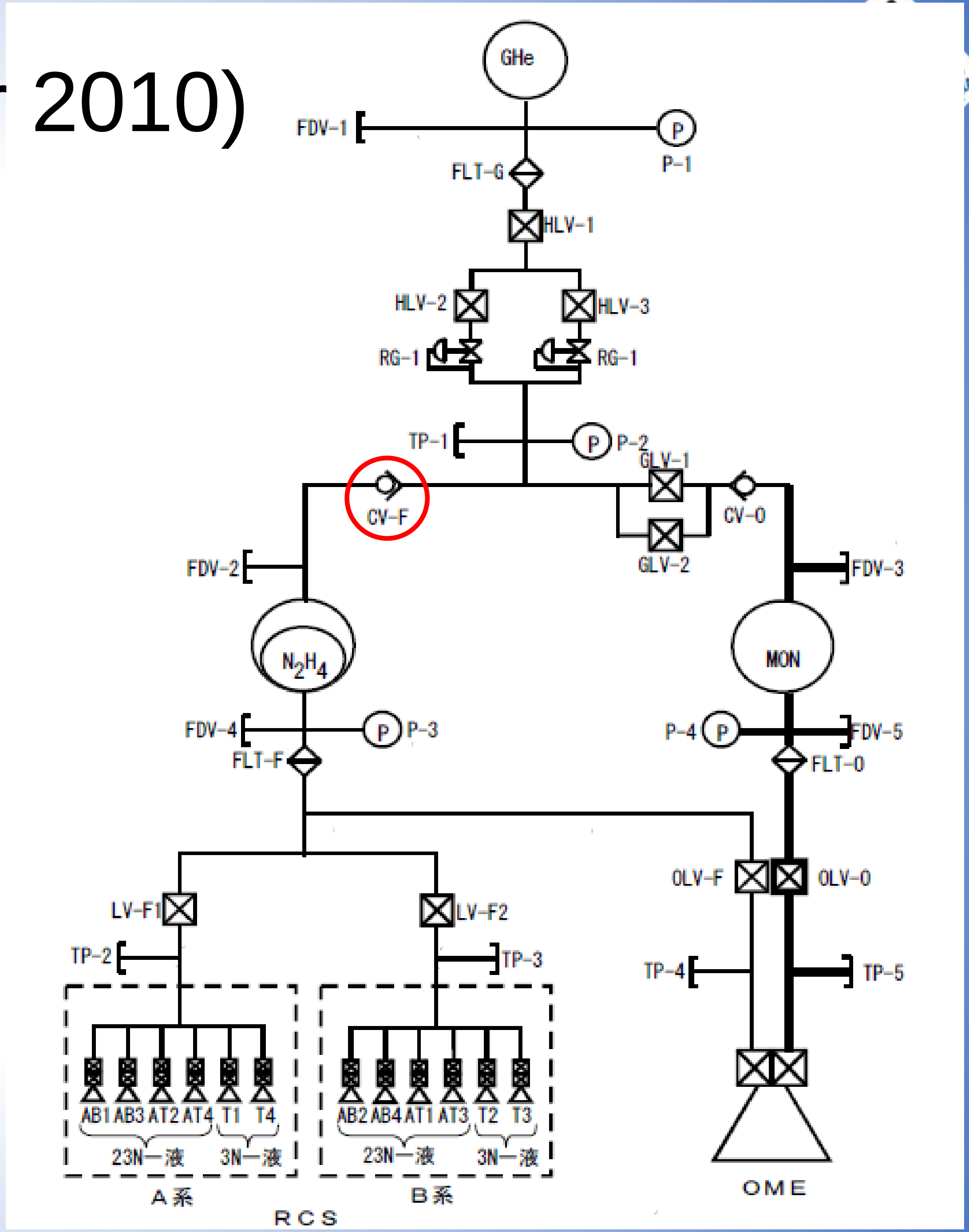




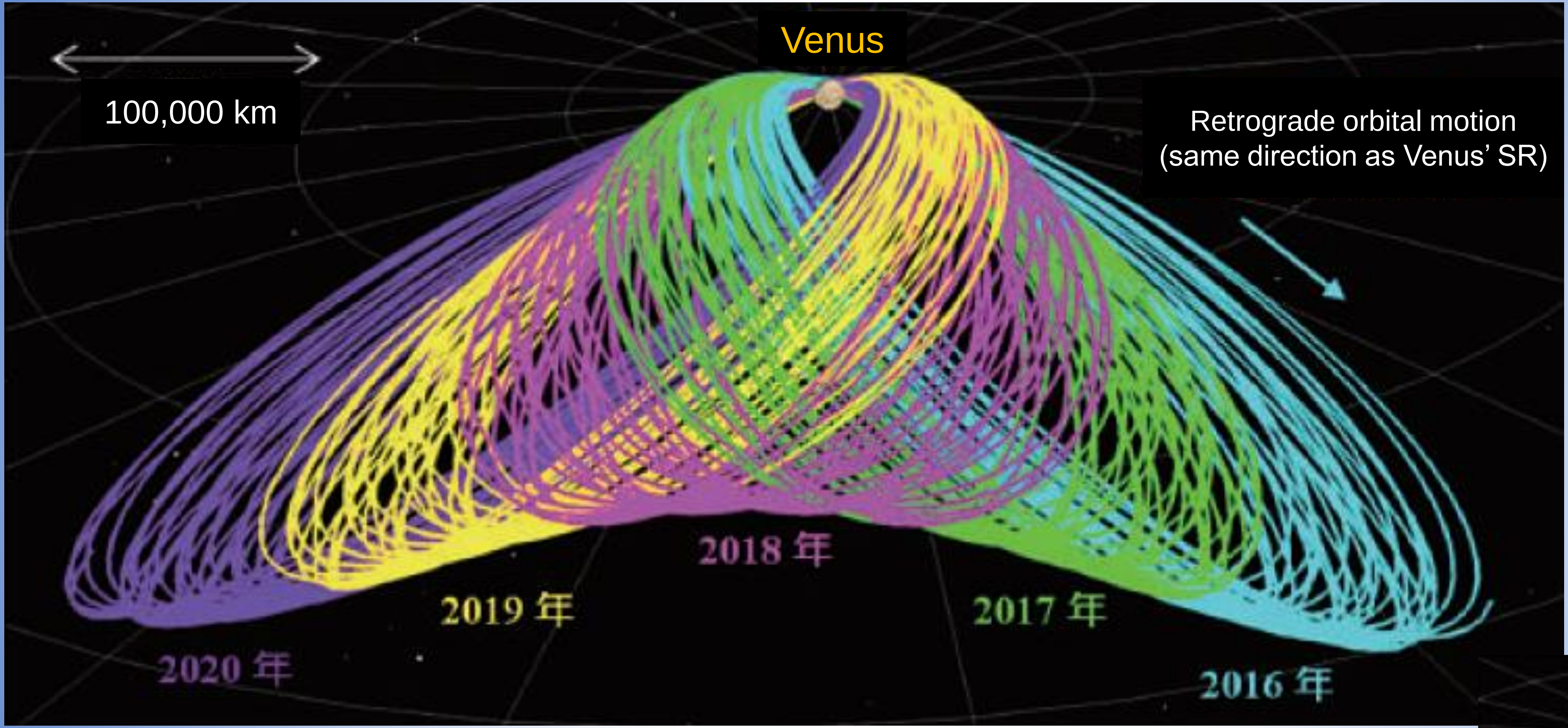
Failure of VOI-1 (7 December 2010)

- Vaporized fuel and oxidizer slowly permeated the polymer materials in valves.
- The vapor reacted to form solids at CV-F in the fuel line, causing the valve NOT to fully open.
- Unexpectedly "less fuel", compared to the oxidizer, was supplied to the main engine (O/F ~1.13).
- ALL fuel was burnt with no film cooling. Excessive heat destructed the ceramic thruster.

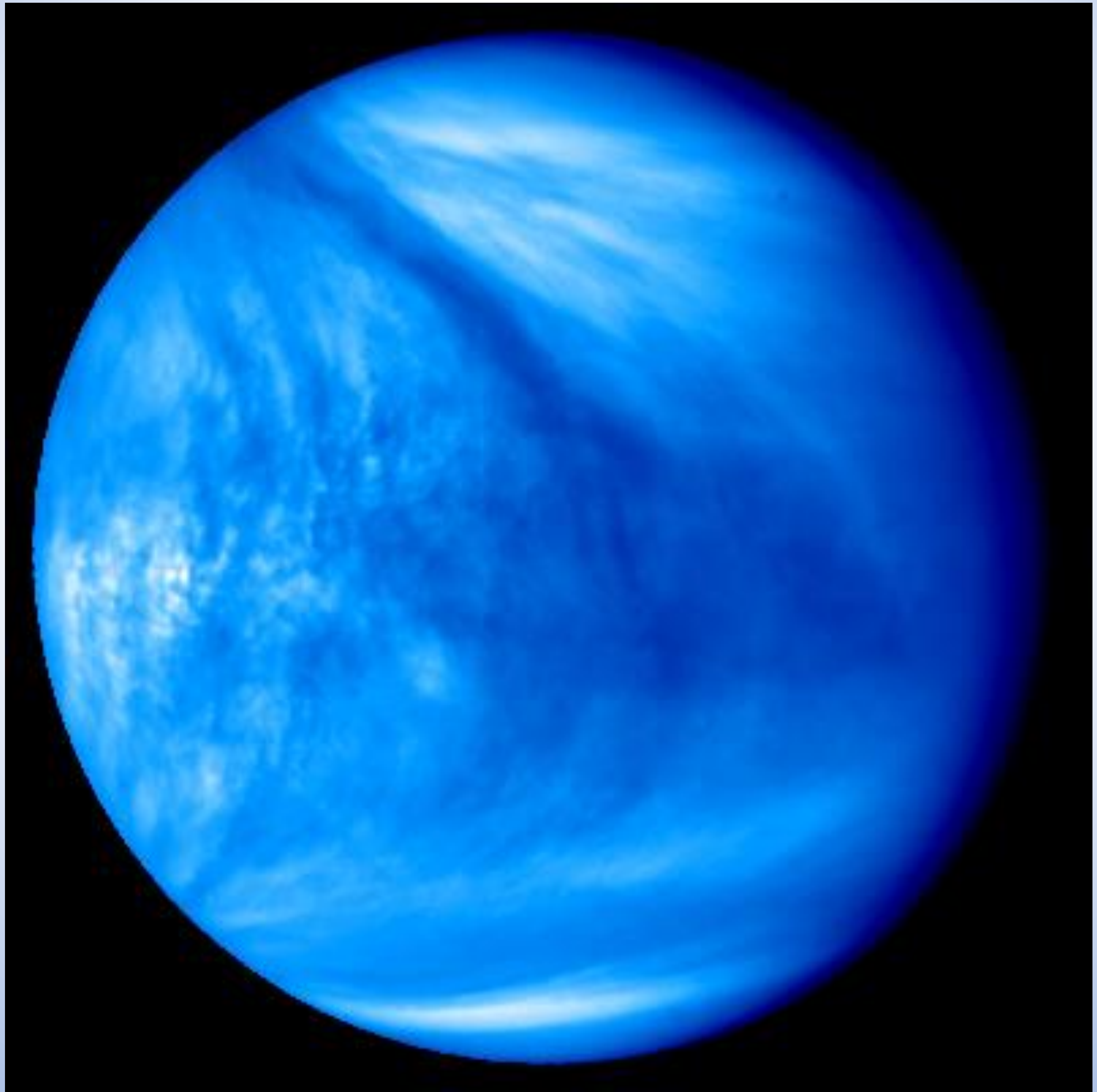




Achieved Orbit of Akatsuki after VOI-R2

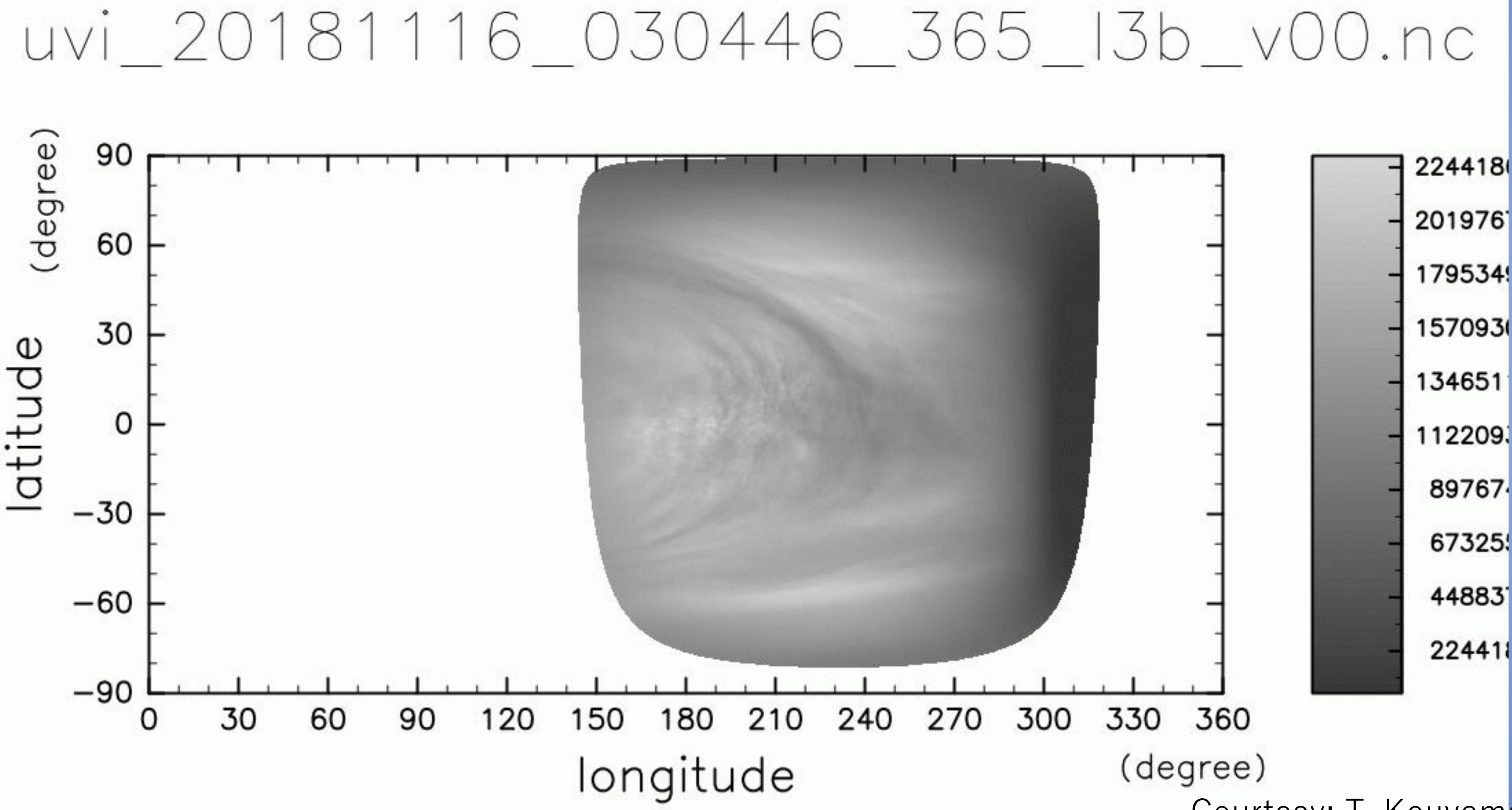


Two Ways of Displaying Akatsuki “Movie” Data (1)



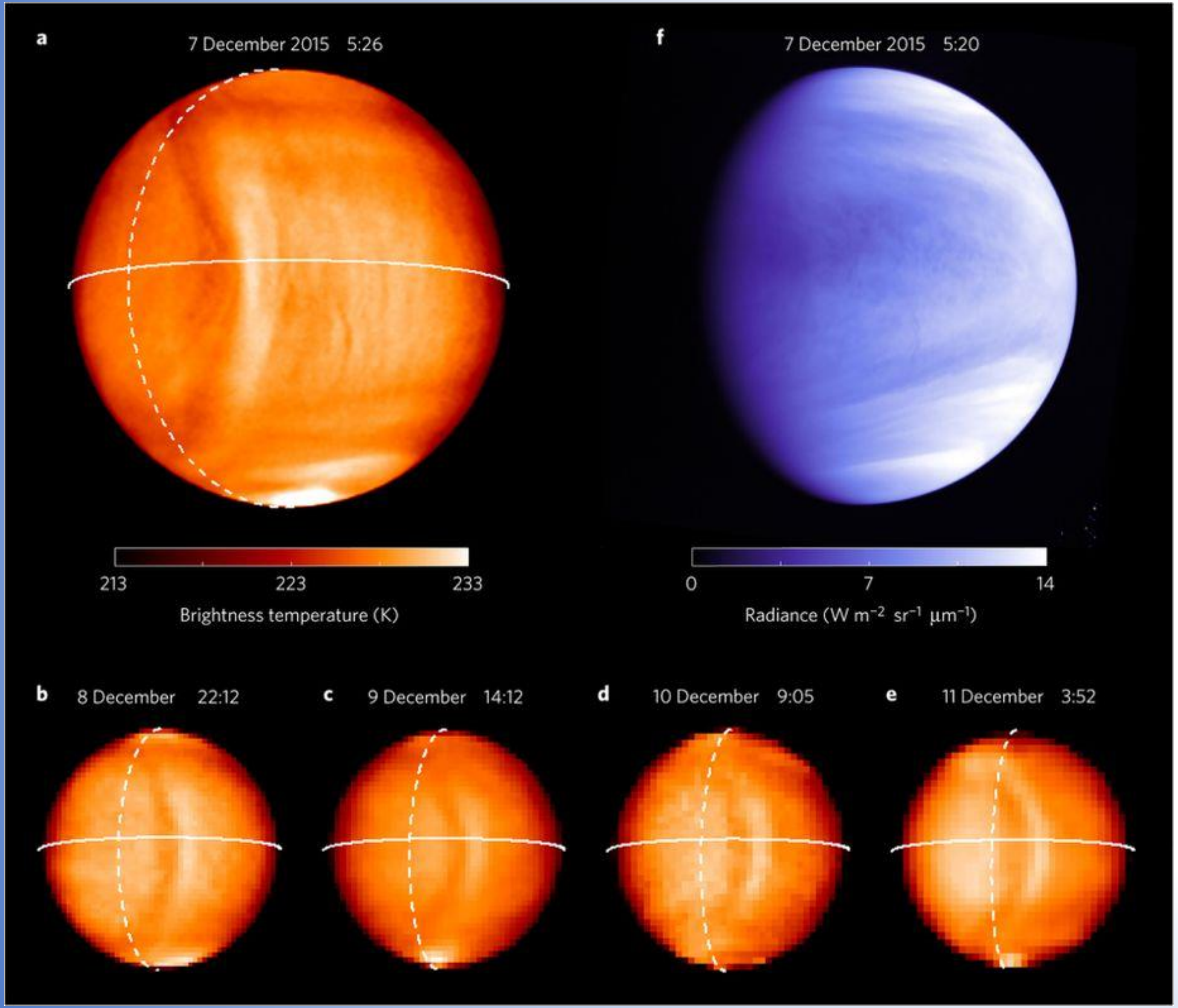
Courtesy: T.M. Sato

Two Ways of Displaying Akatsuki "Movie" Data (2)



Courtesy: T. Kouyama

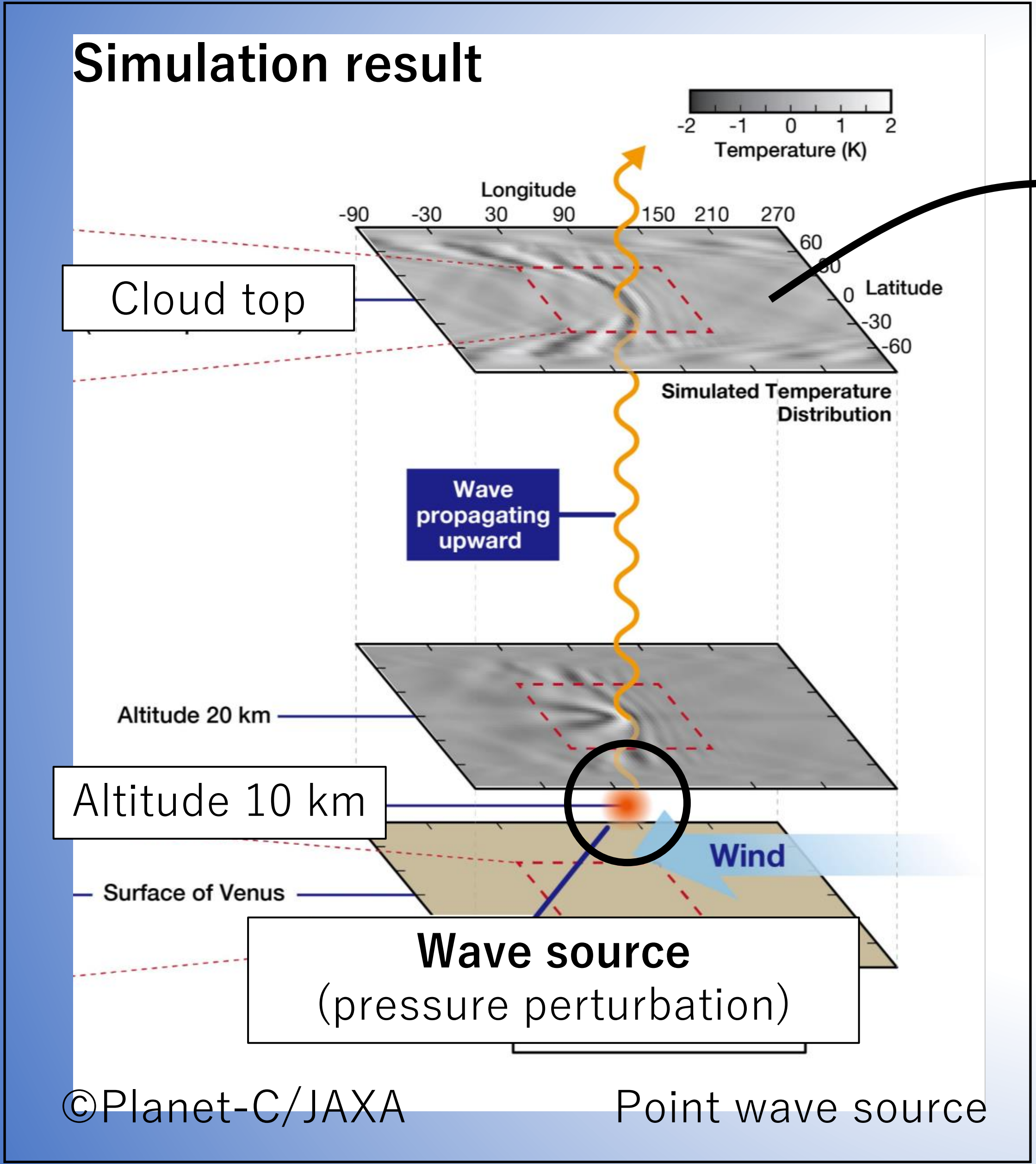
Discovery of Stationary Gravity-Wave Features

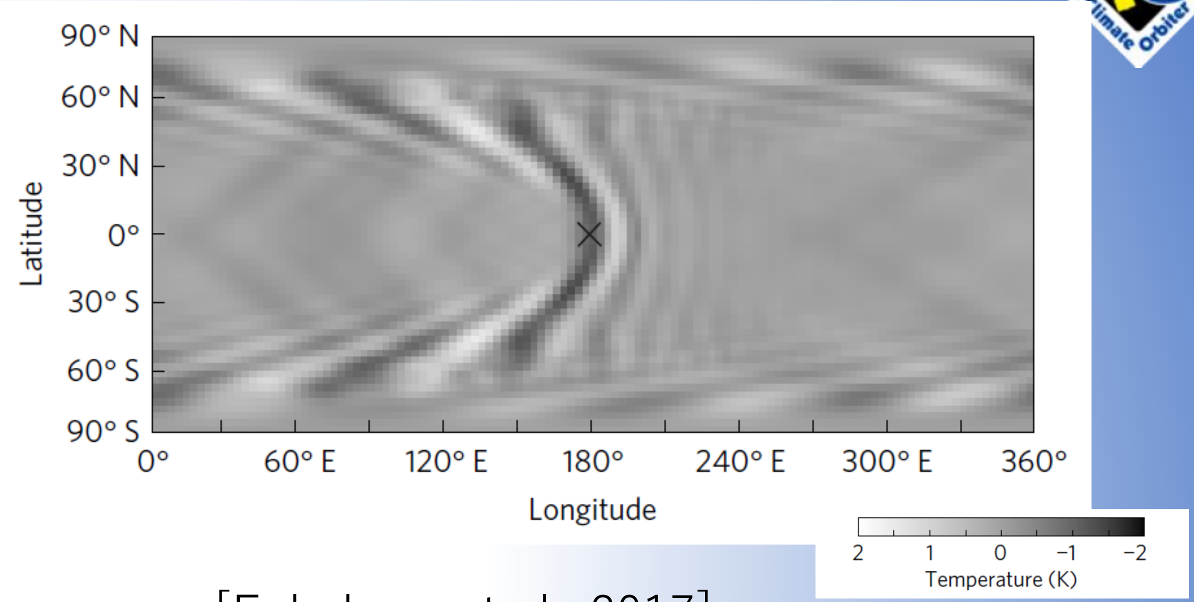


- The LIR thermal maps right after the successful VOI-R1 revealed a striking bow-shaped feature, which was observed until Dec 11 but disappeared when observation resumed in mid-January 2016. The amplitude of temperature variation is ±3 K.
  - The project had to prepare for VOI-R2 (20 Dec 2016) so the scientific observations paused for about a month.
- The feature was not moving at a speed of the super-rotation but appeared rather stational. Later analysis showed it was caused by gravity wave originating from Aphrodite Terra, a continental size highland belt near the Venus equator.

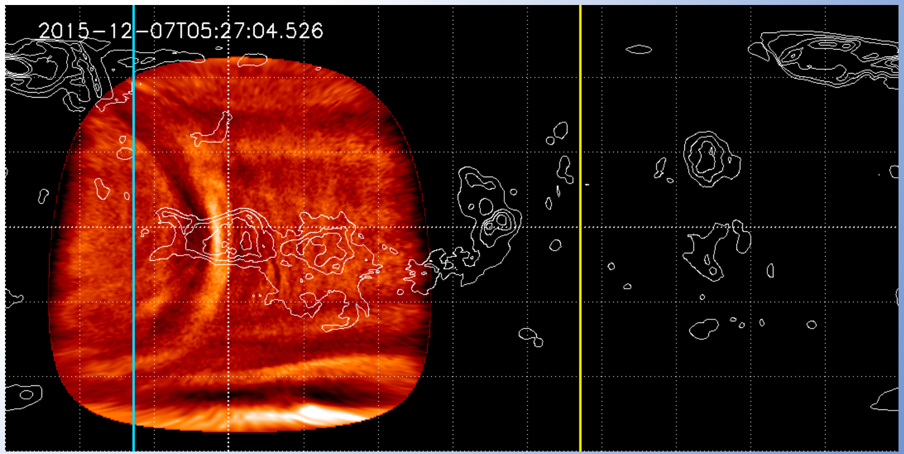
Fukuhara et al., 2017

Perturbation at lower altitudes can make the bow-shape structure





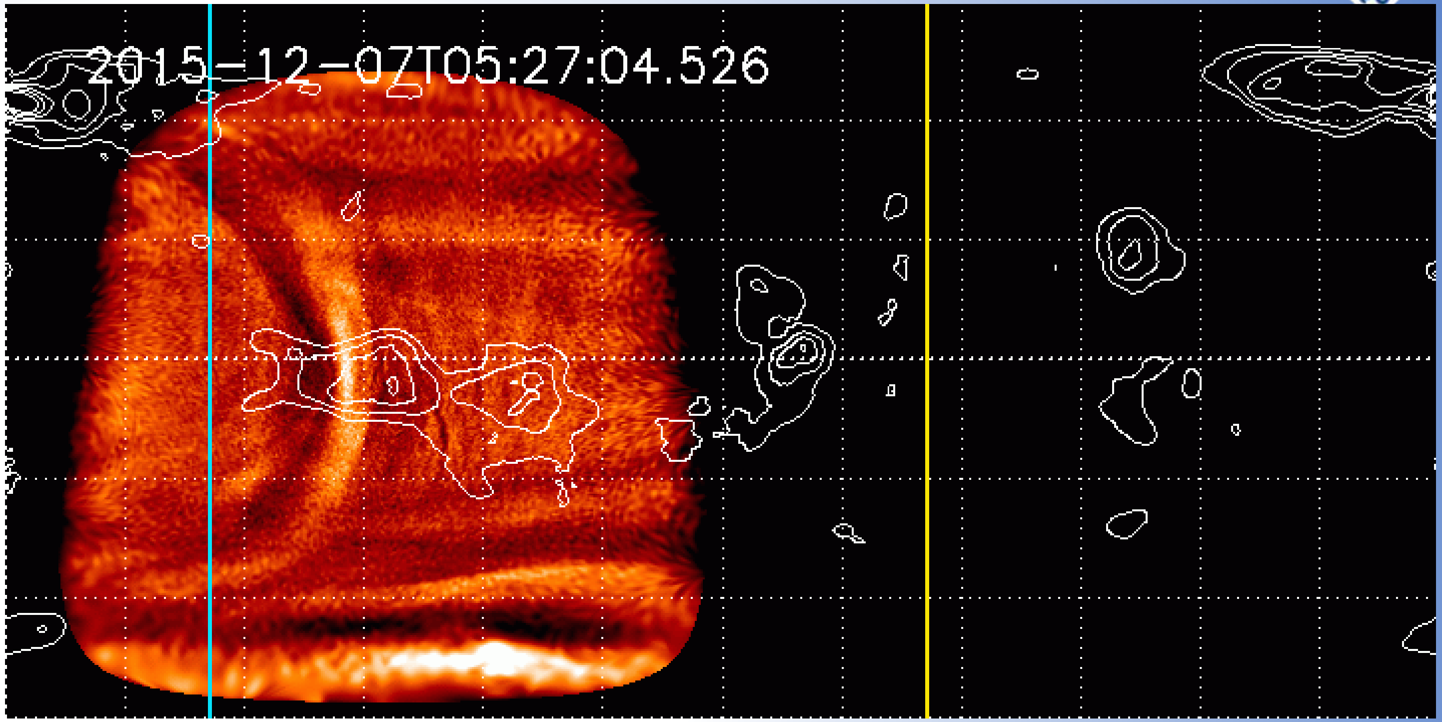
[Fukuhara et al., 2017]



Repetition of Stationary Gravity-Wave Features

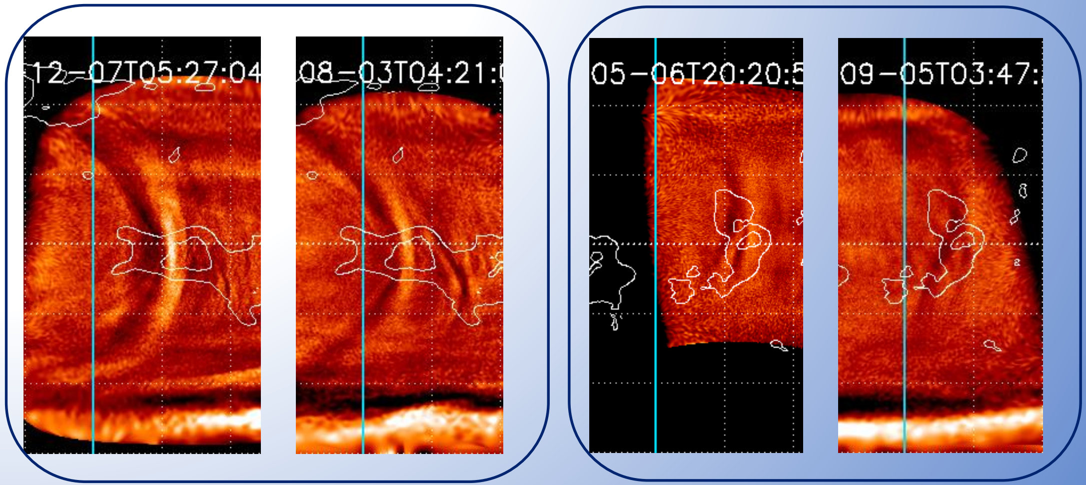
- The gravity-wave features were not only above Aphrodite Terra but above many of the equator to mid-latitude highlands.
- Such features are highly repetitive every Venus day. They appear very weak (or invisible) in the local morning but develop in the afternoon especially near the local dusk.

Kouyama et al., 2017

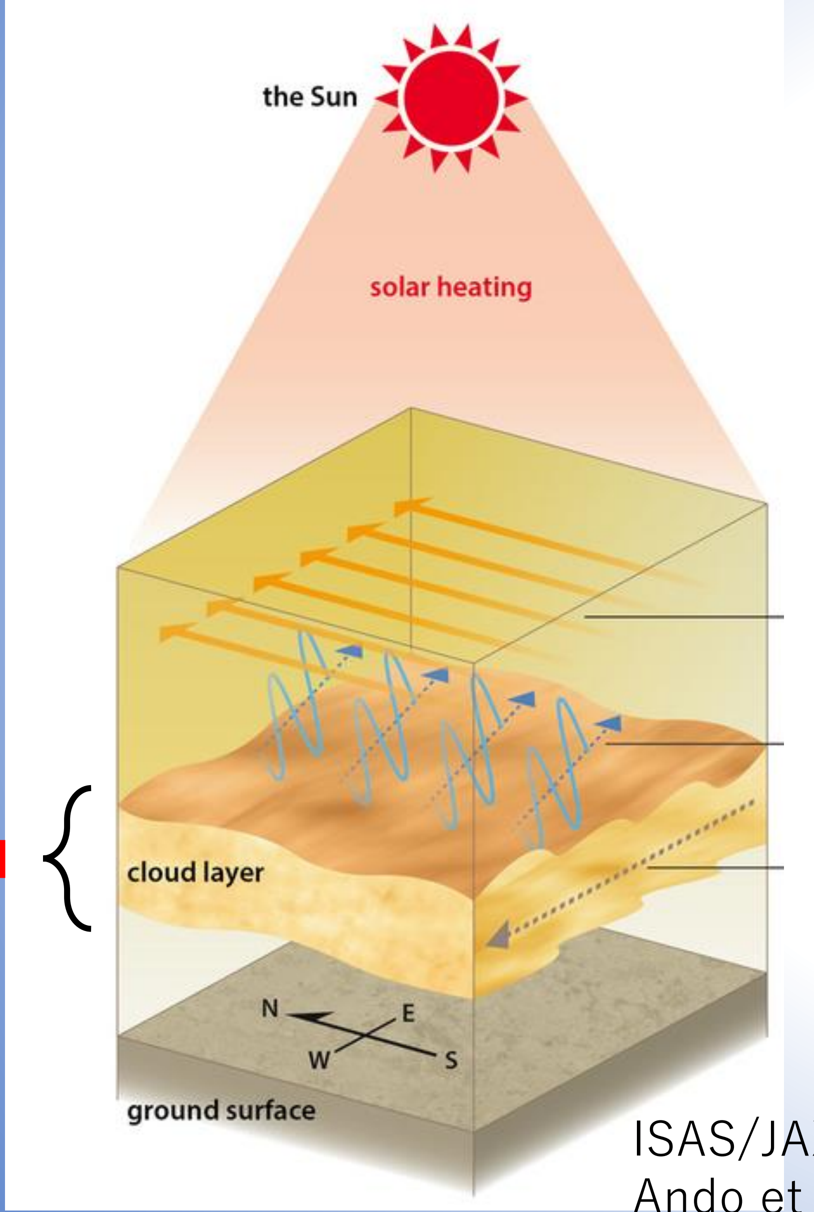


- Other cameras also detected the similar features but in variations of SO_2 absorption (UVI 283 nm) or the cloud-top altitude (IR2 2.02 μm).

Sato et al., in prep.



Planetary scale waves: Thermal tides

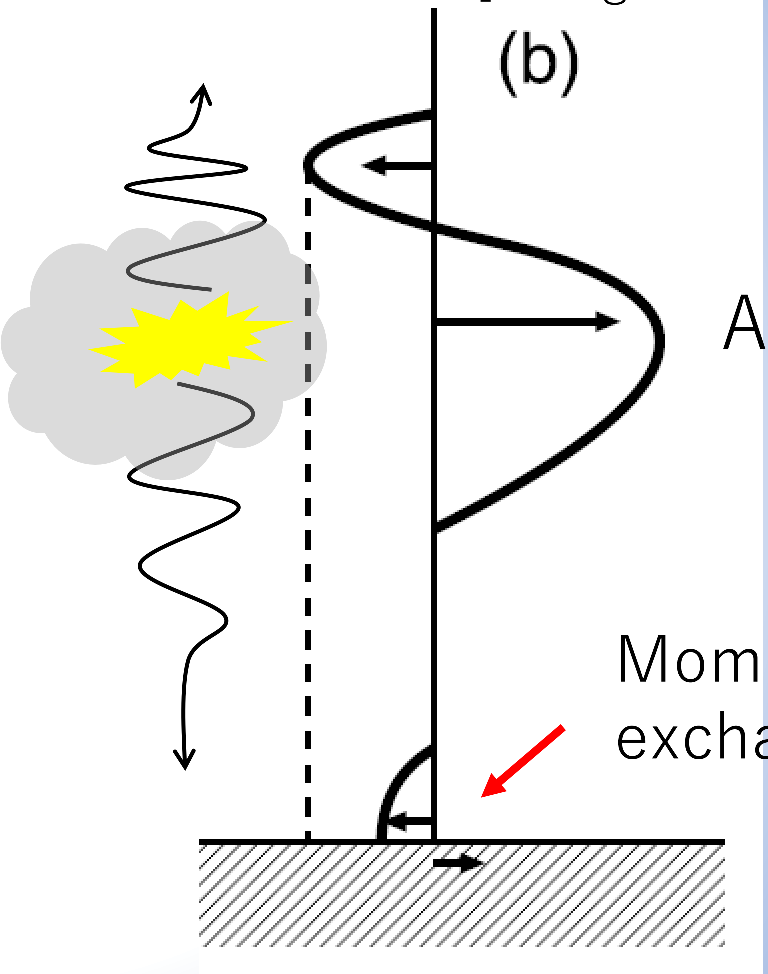


Heated

60-70 % of input solar energy absorbed

ISAS/JAXA
Ando et al., 2016

[Takagi and Matsuda, 2007]

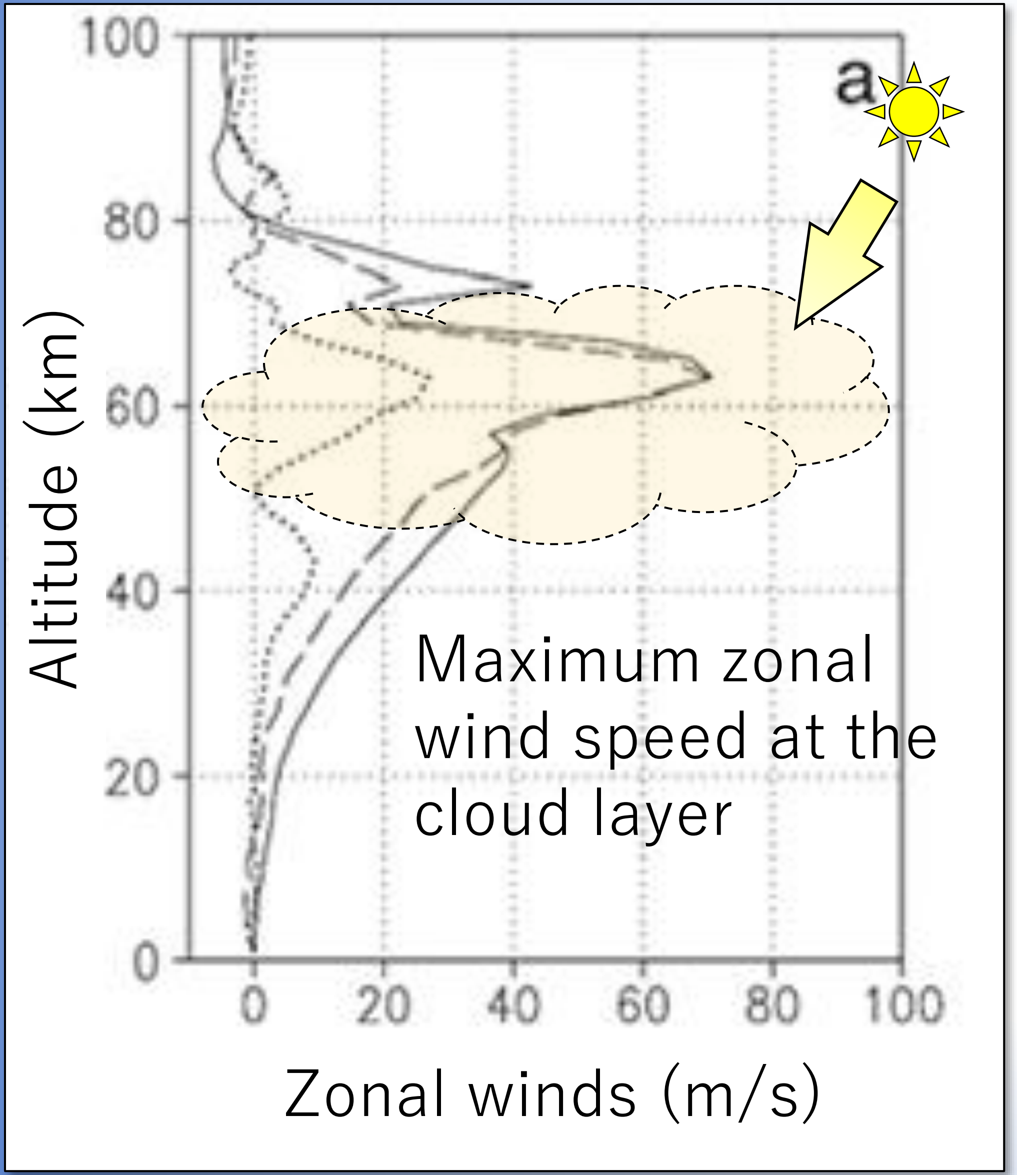


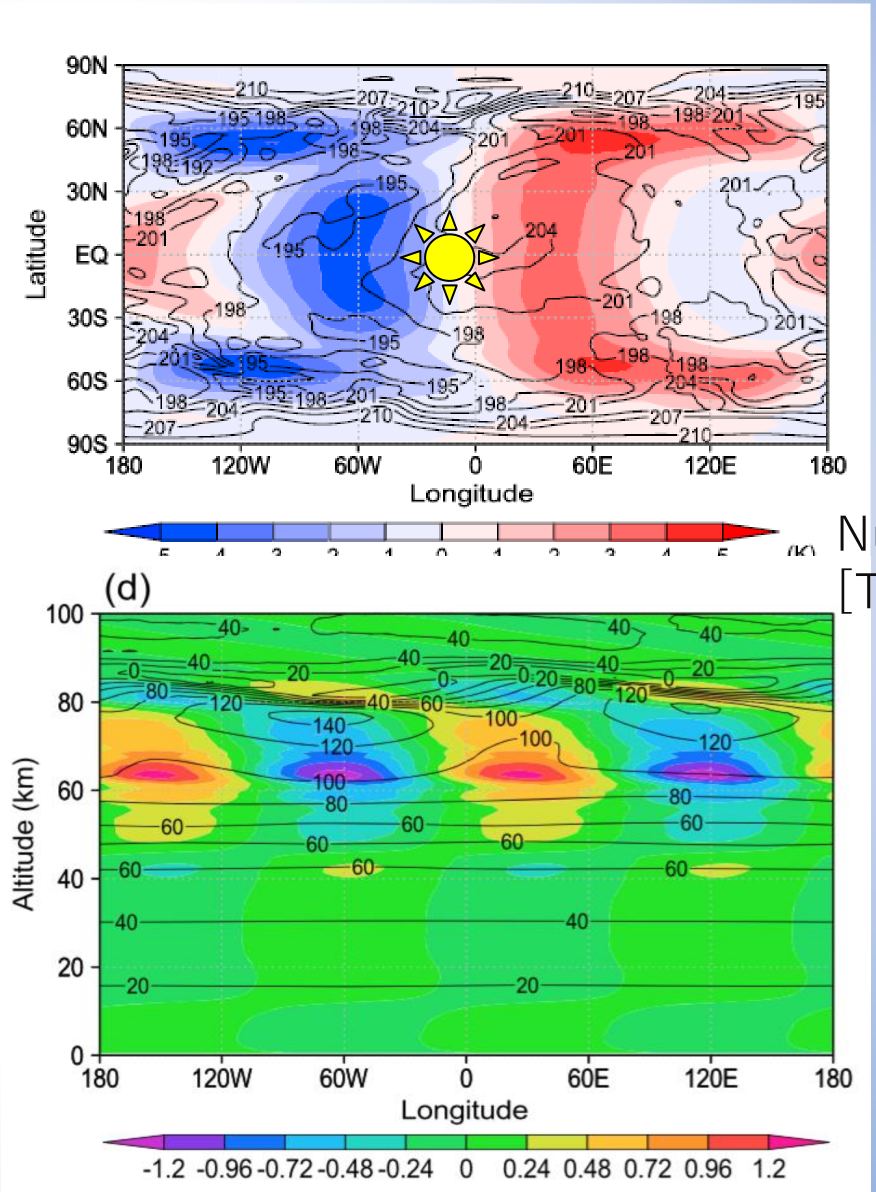
Accelerating

Momentum exchange

Thermal tides may maintain the super-rotation of Venus atmosphere

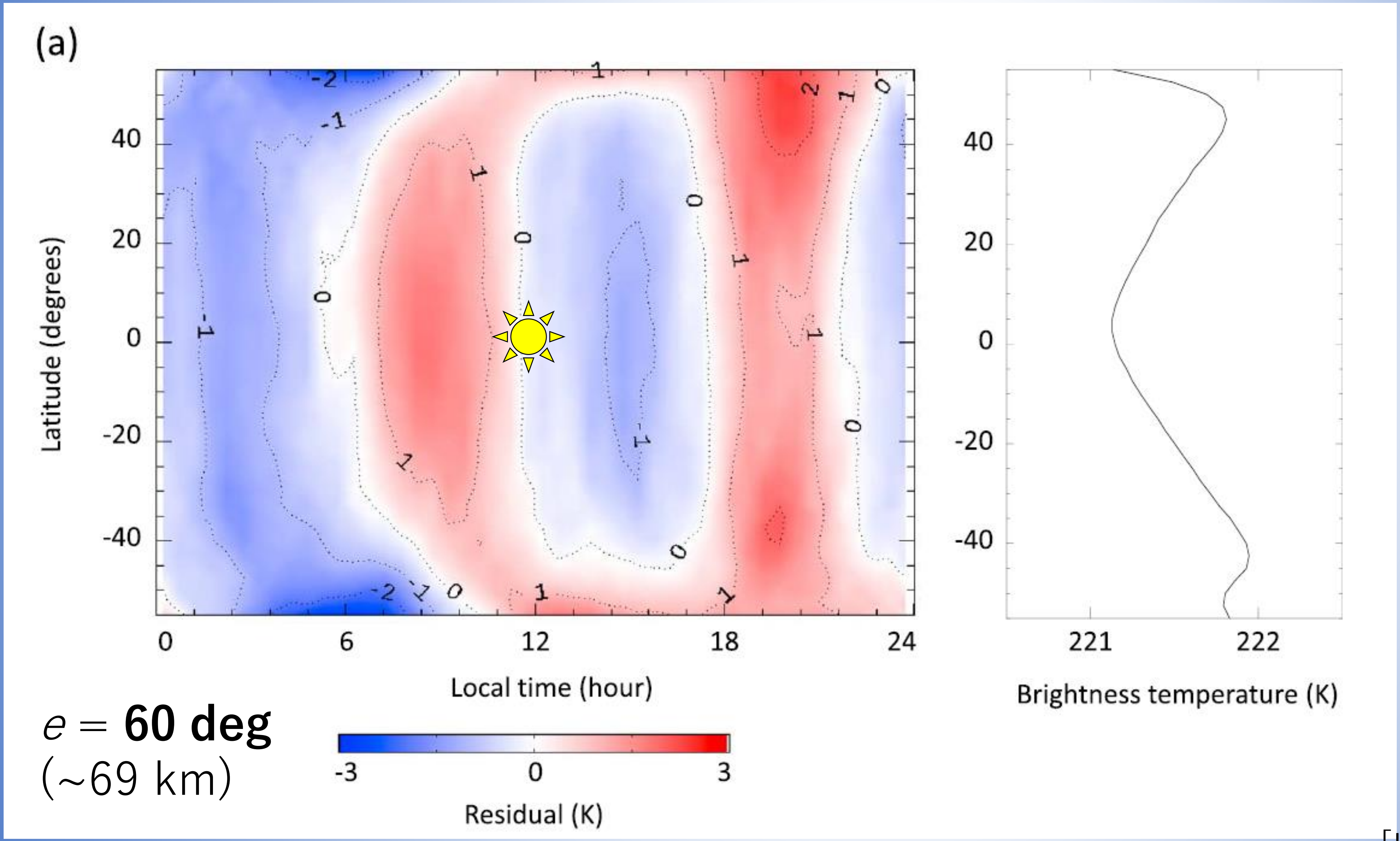
Planetary scale waves: Thermal tides

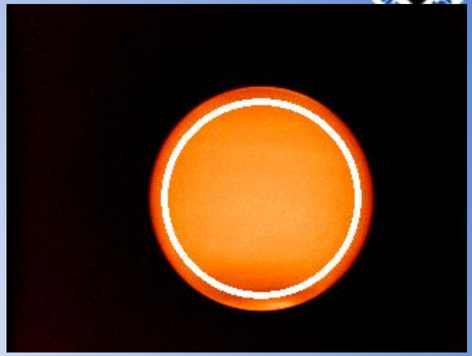




Numerical expectation
[Takagi et al., 2018]

Global Structure of Thermal Tides from Observations





Time-averaged thermal tide structure over three Venusian years by LIR

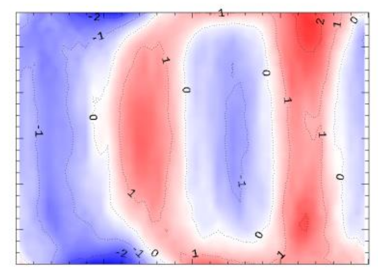
First observational result of revealing the global structure of thermal tides at the cloud top

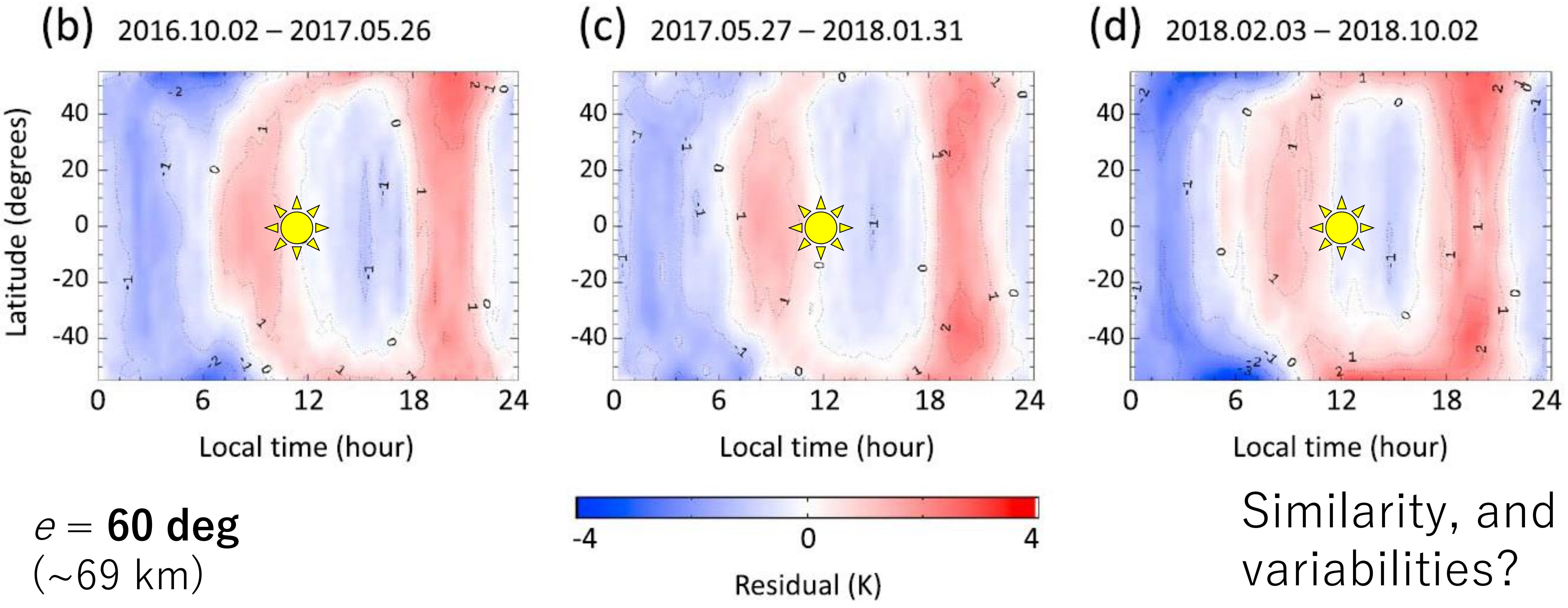
[Kouyama et al., 2019]

Global Structure of Thermal Tides from Observations

Time series of thermal tides (one Venus year)

Whole period





$e =$ **60 deg**
(~69 km)

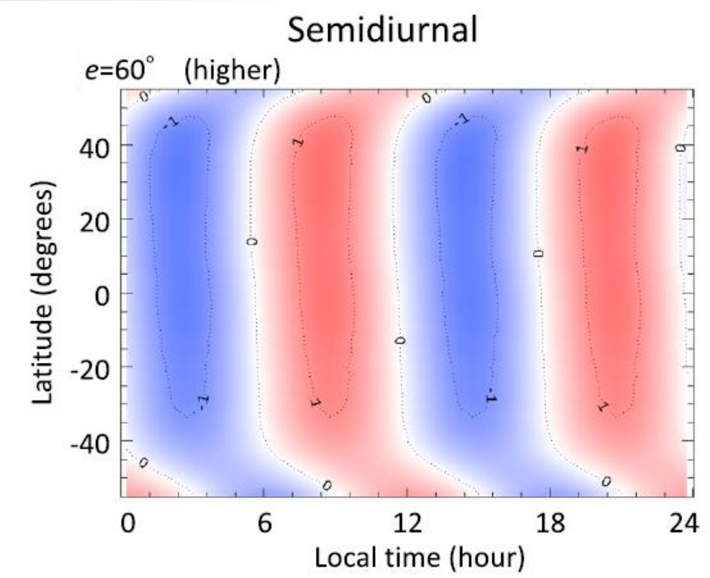
Similarity, and variabilities?

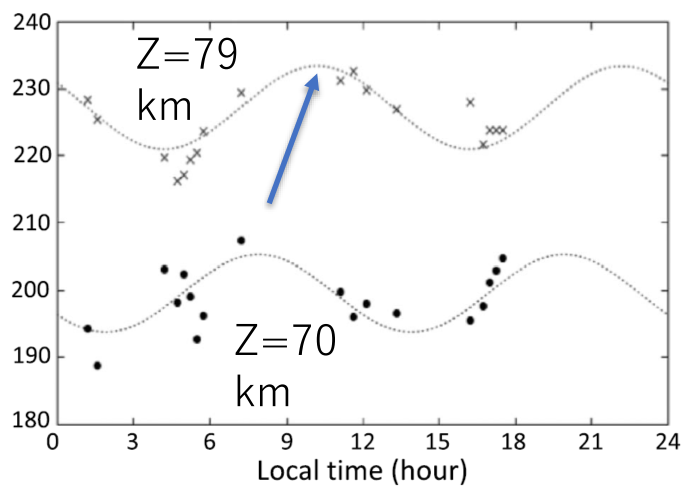
宇宙航空研究開発機構
Japan Aerospace Exploration Agency

Thermal Tides seen by LIR & RS

Three-dimensional structure of each tidal component is now revealed

LIR: **horizontal** ion: **vertical**





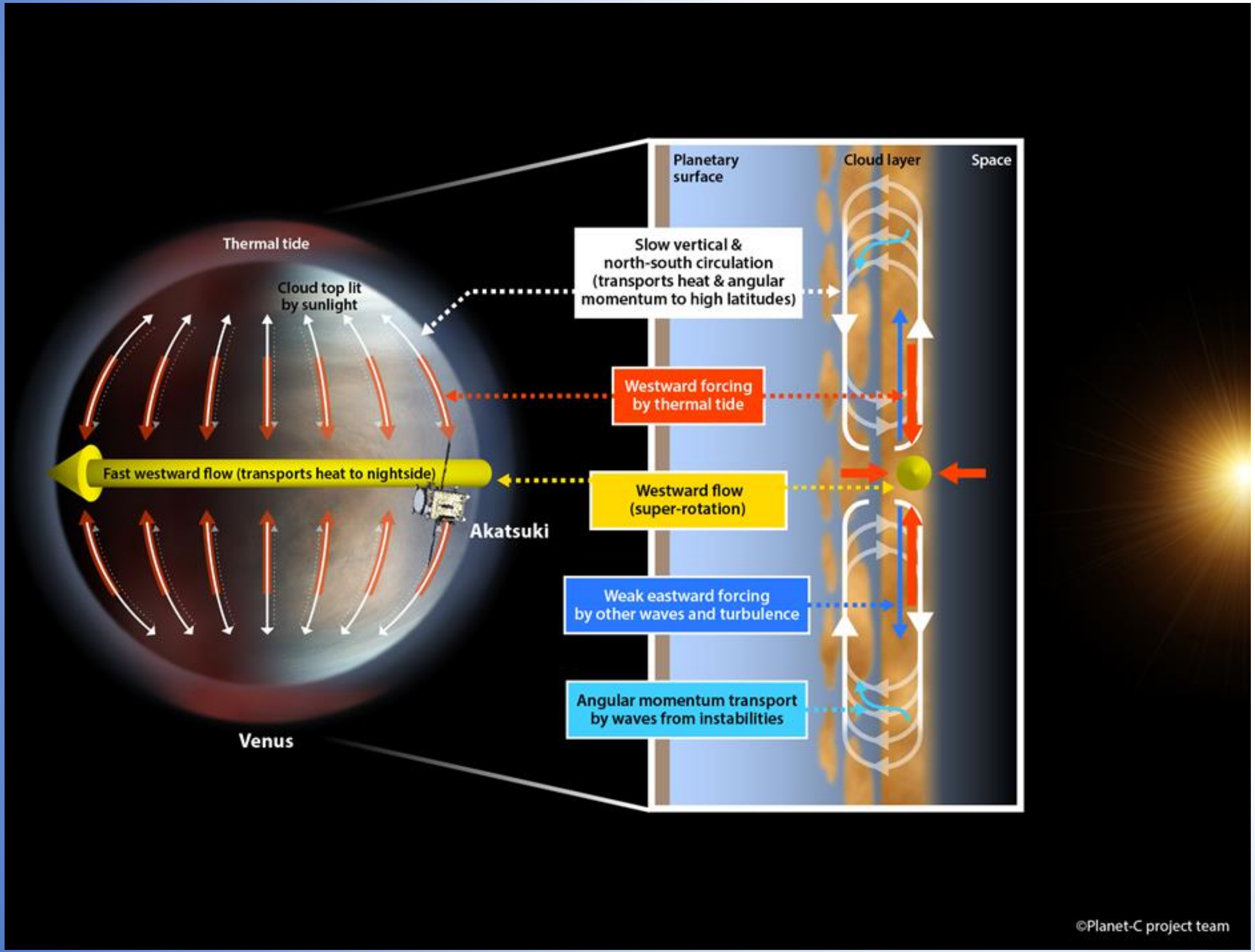
[Ando et al., 2018]

Good example of achievement of Akatsuki's 3D observation strategy

- Phase variation with altitudes = evidence of vertical propagation
- Physical parameters (e.g. latitudinal extent, vertical wavelength, phase, etc..) of the tides were **quantitatively** determined.

=> Important information for future numerical studies

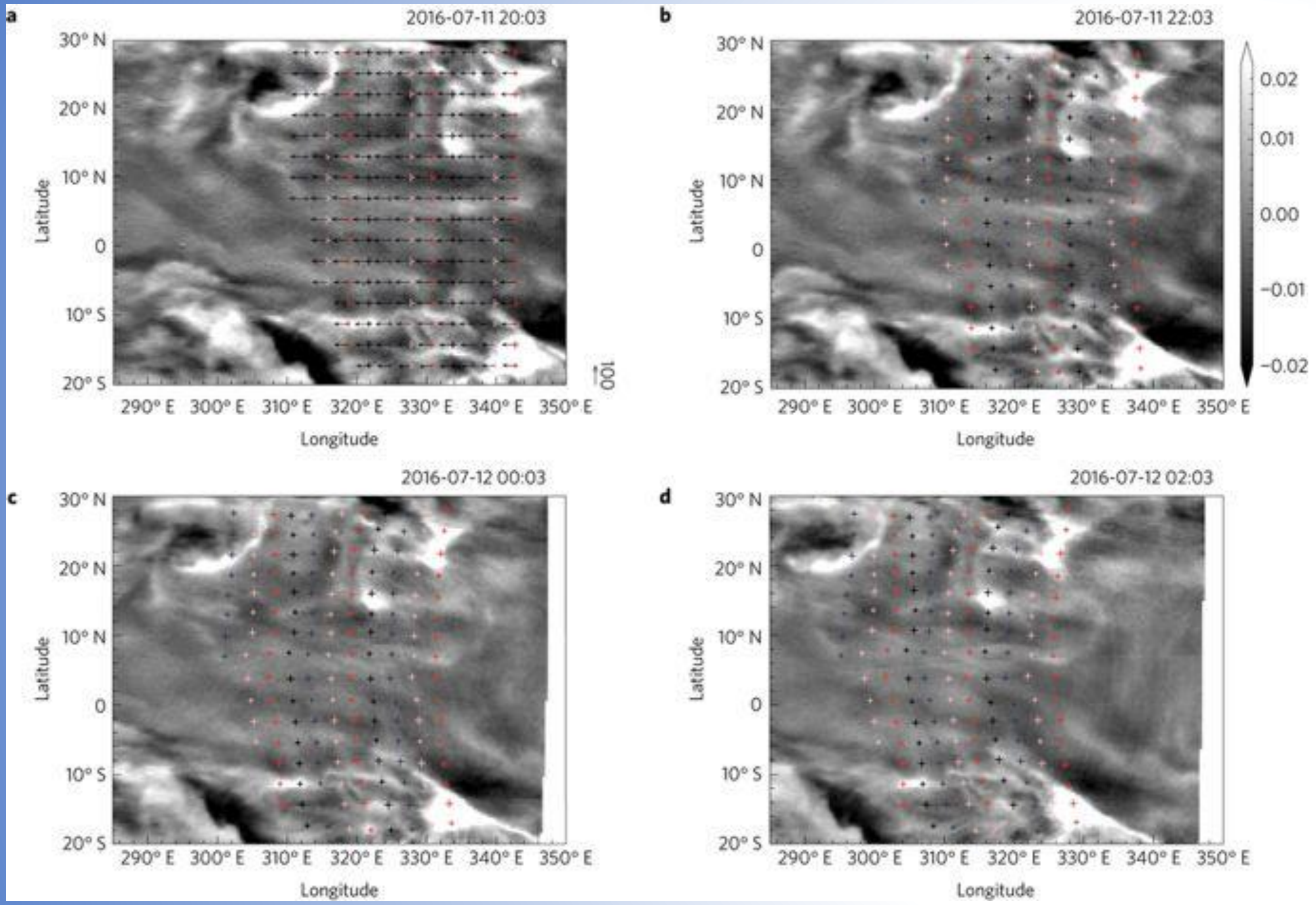
Super-Rotation Maintained by Thermal Tides



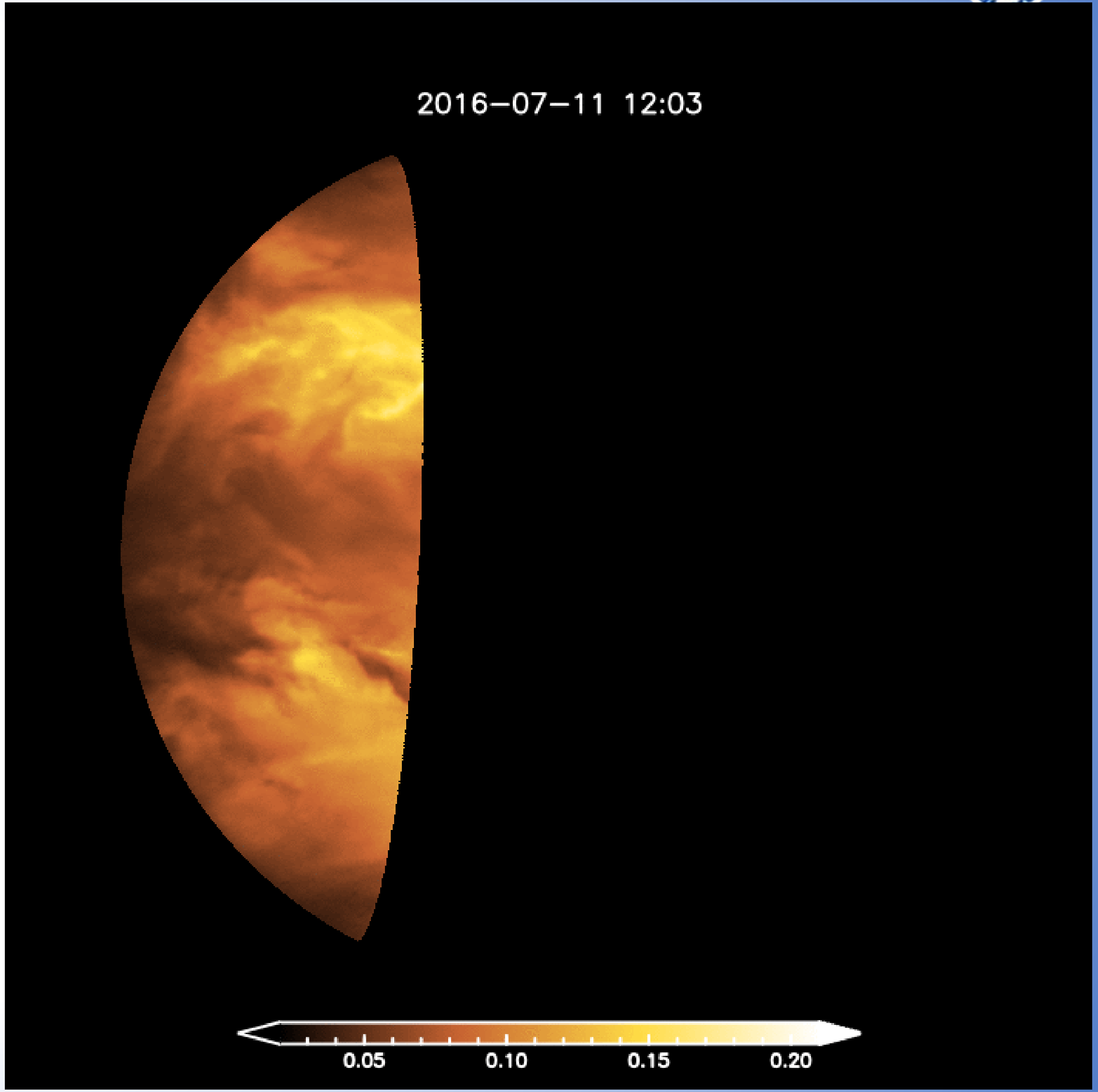
- Careful cloud-tracking analysis indicates that the super-rotation is maintained by the thermal tides (red arrows), while other waves and turbulences actually work to weaken the SR (blue arrows) in the equator to low latitudes.
- In the middle to high latitudes, however, other waves possibly work to maintain the SR (light blue arrows).
- “True” meridional motion should be very small (of the order of a few m/s) and difficult to determine only from the day-side (UV) measurements. Need higher precision night-side measurements.

Horinouchi et al., 2020

Equatorial Jets in the Lower to Middle Clouds

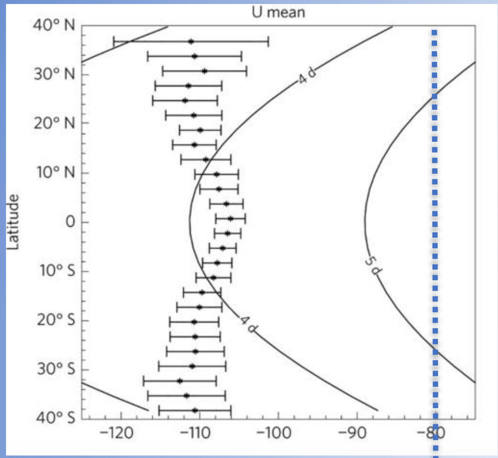


Grey-scale shading represents the four two-hourly nightside IR2 radiance maps from 20:03 UTC, July 11, used for cloud tracking (in W m^{-2} sr^{-1} μm^{-1}). Arrows in panel **a** show the horizontal velocities (m s^{-1}).



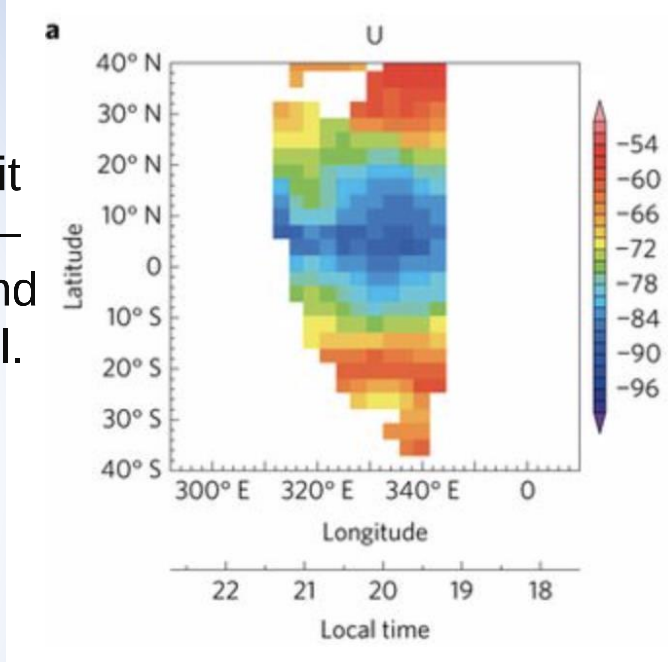
Horinouchi et al., 2018

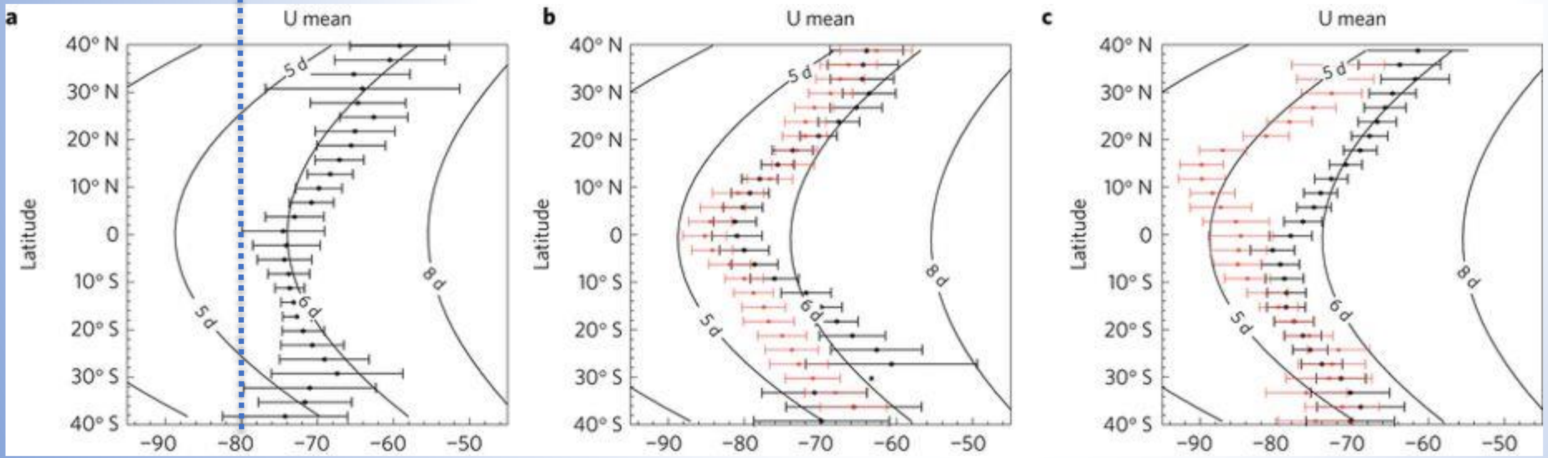
Equatorial Jets in the Lower to Middle Clouds



Zonal wind at the cloud top (UVI data) exhibits a weak wind-speed minimum at around the equator
11 July, 2016

Zonal (east–west) wind is defined as positive if it is eastward. Longitude – latitude plot of zonal wind (m s^{-1}) in the right panel.





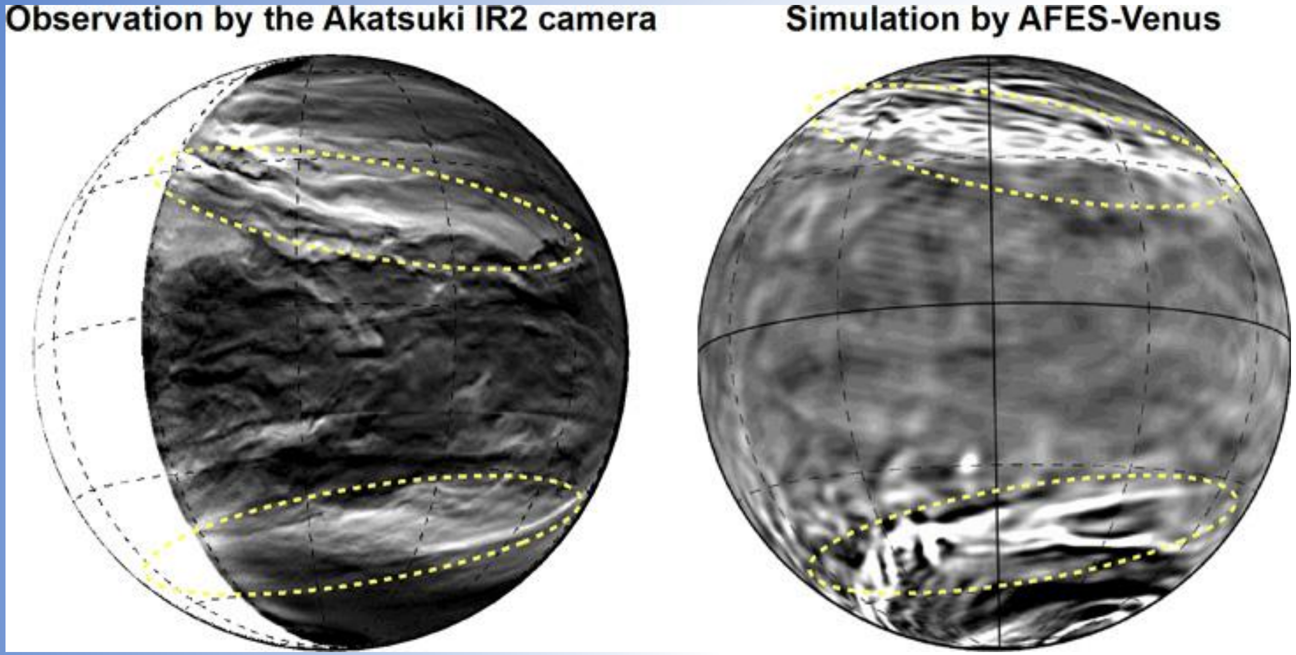
March 25, 2016
No equatorial jet

August 13, 2016
(black) and 15 (red)
The jet exists

August 25, 2016
(black) and 26 (red)

Zonal winds in the lower cloud at various times

Numerical Approaches: Planetary-Scale Streaks

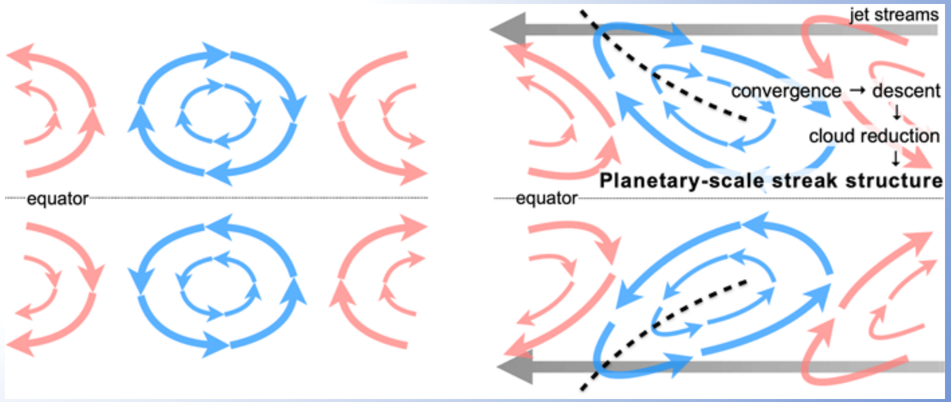


[left] The lower clouds of Venus imaged with the Akatsuki IR2 camera (25 March 2016). Clouds appear as silhouette with the backlight of thermal emissions from deeper levels. The bright parts correspond to where the clouds are relatively (optically) thin.

[right] The planetary-scale streak structure reproduced by AFES-Venus simulations. The bright parts show a strong downward flow. (Partial editing of image in the Nature Communications paper).

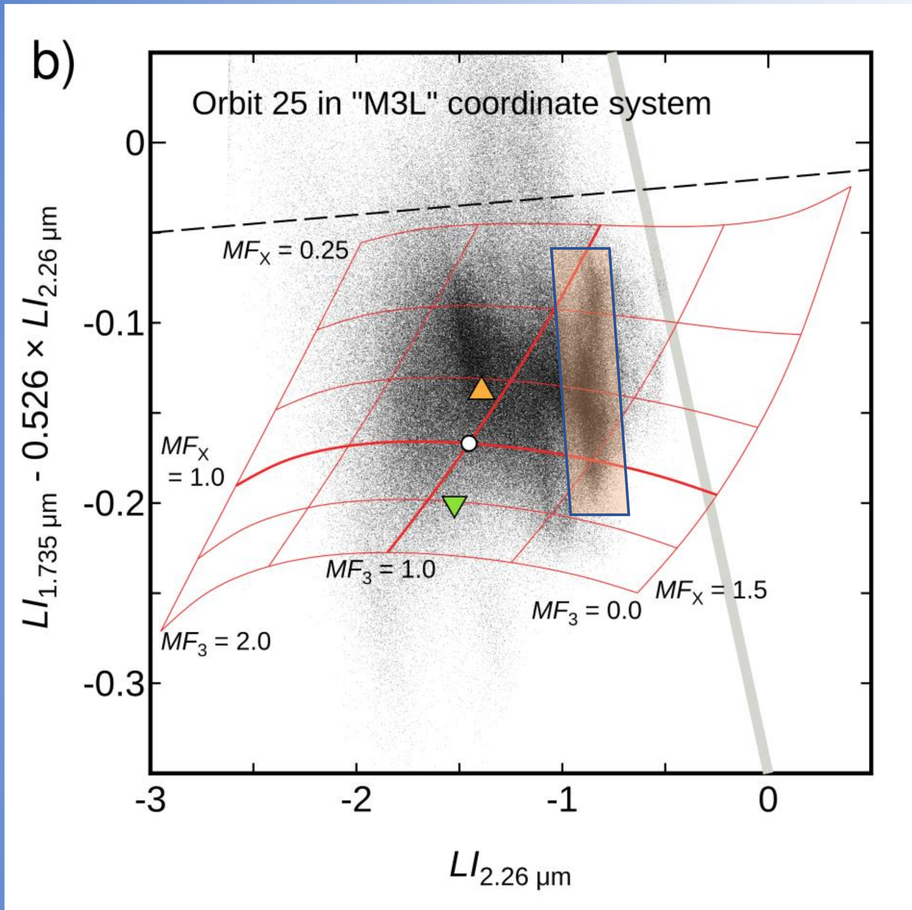
The giant vortices due to the equatorial Rossby waves (left) become tilted and stretched by the high-latitude jet streams (right).

Tilted vortices form convergence zones (dashed lines), then downward flows, which would thin the lower clouds by evaporating the particulates.

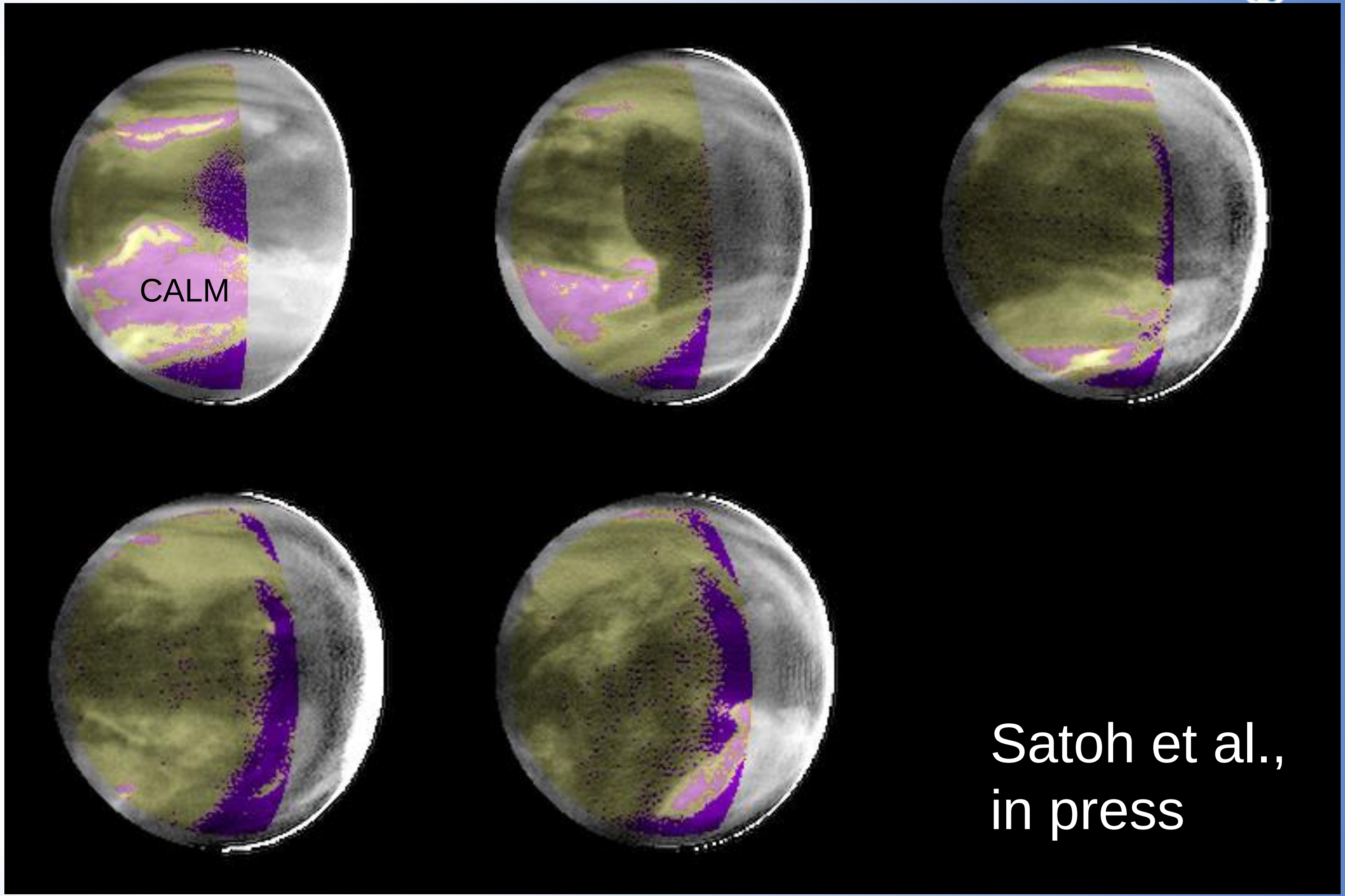


Kashimura et al., 2019

Discovery of “CALM”: Streaks Excluded

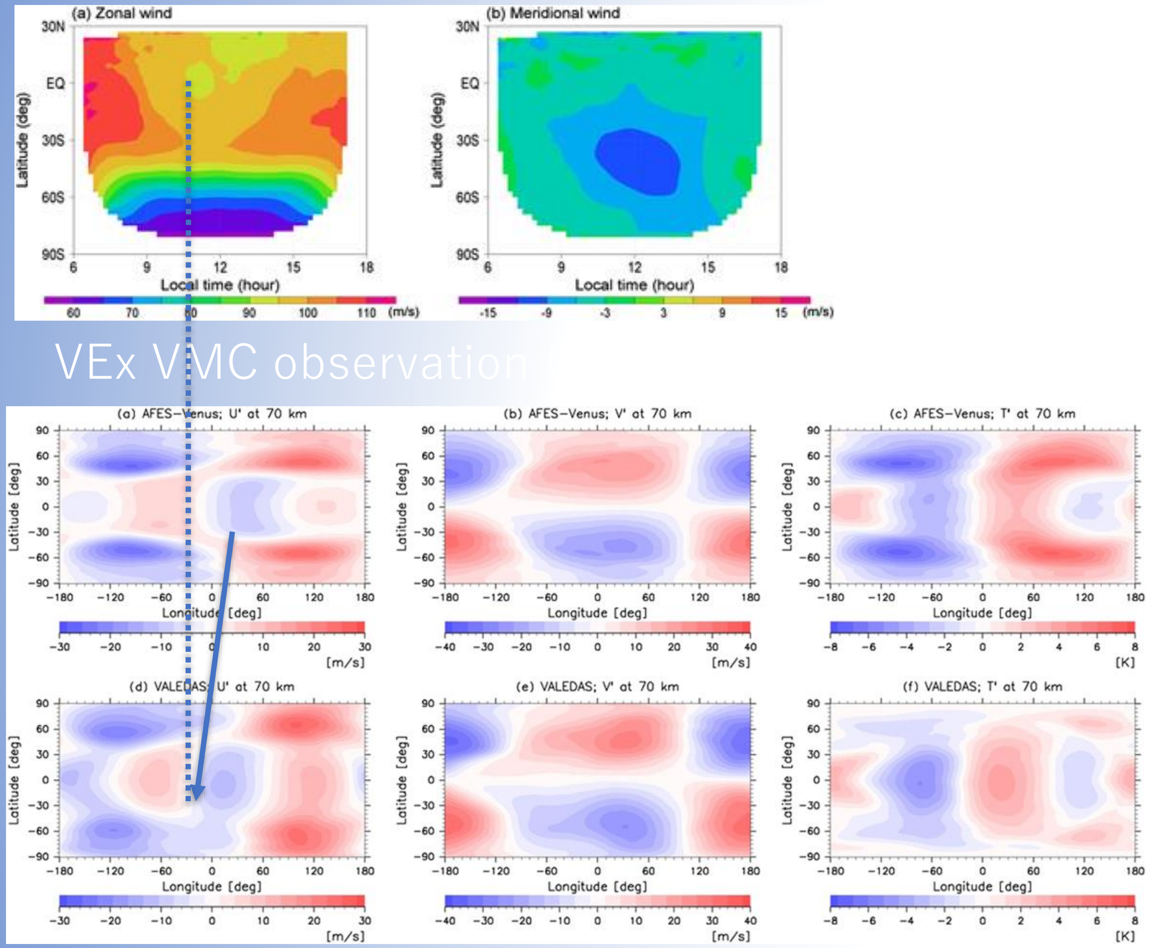


IR2 night-side data (1.735 and 2.26 μm) are examined in a new coordinate system (M3L). A region of very-confined data is interpreted as a dynamically quiescent region where equilibria dominate (aerosols & H_2SO_4).



Pink: quiescent regions. Yellow: more chaotic mixture of aerosols, indicating sort of dynamical activities (probably downwelling in the streaks).
Purple: regions where contaminations from day-side is more significant.

Numerical Approaches: Data Assimilation



Numerical calculation (upper) and data assimilation results (lower panels). (Zonal flow, meridional flow, and the temperature)

Data assimilation with VEx VMC data improved dramatically the numerical calculation results, not only the wind results but also the horizontal temperature structure.

Akatsuki team provides them the wind data of every two hours, for better data assimilation study

If data assimilation is successful, phenomena occurring in places where there is no observation would be reproduced by computer with more reliability.

Sugimoto et al., 2019

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Summary of Akatsuki Mission (1)

- Proposed as a first “**meteorological**” satellite of a planet other than the earth. Developed to fulfill the requirements, launched and inserted to the Venus orbit successfully in 2015.
- **The orbit** (~11 Earth day period and apocenter altitude of ~0.38M km) is different from the one originally planned (~30h period and apocenter altitude of ~80K km). Still it is near the equatorial plane and the orbital motion in retrograde (the same direction with the SR of Venus’ atmosphere), distinct from any of previous missions.
- Improved **digital tracking** techniques before successful VOI-R. The L3/CT team benefited from existing VEx/VMC data.
- **Data archiving** and documentation (in PDS3 standard) assisted by NASA Participating Scientists (based on NASA-JAXA LoA).
- **ALL scientific instruments** worked fine for the first year (Dec 2015 to Nov 2016) in the Venus orbit. IR1 and IR2 became in-operational in Dec 2016 due to failure of the control electronics, IR-AE. Other SI’s continue working to date.

Summary of Akatsuki Mission (2)

- **Discoveries:** stationary gravity-wave features at the cloud-top levels (suggesting unexpectedly strong coupling between the surface topography and the atmosphere); the equatorial jets in the middle to low cloud layers (requiring some mechanism that accelerates the wind near the equator); the microphysically quiescent regions.
- A possible **lightning** event finally (recorded in March 2020, manuscript in prep.).
- It is identified that **the thermal tides** are the primary agent to maintain the super-rotation in the equator to low latitudes. Other waves work opposite but they may likely work to maintain the SR in the middle to high latitude regions.
- To quantitatively study **the meridional circulation**, more measurements (especially in the nigh-side with higher precision) are definitely needed. 3-D views of this is essential to evaluate other hypotheses for the SR.
- Long-term monitoring of **albedos and wind speeds** is of great help to understand the climatology of Venus and other planets + exoplanets.
- **Data assimilation** with Akatsuki data in progress.