International Venus Conference 2019
2019.6.1 9:55–10:10

Mapping of Venus' cloud top altitude from Akatsuki IR2 dayside images

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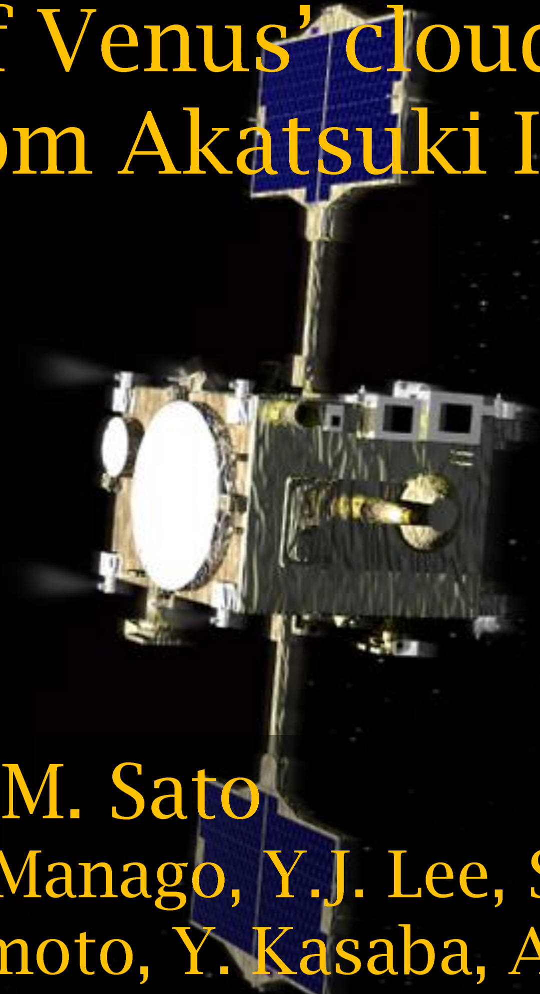
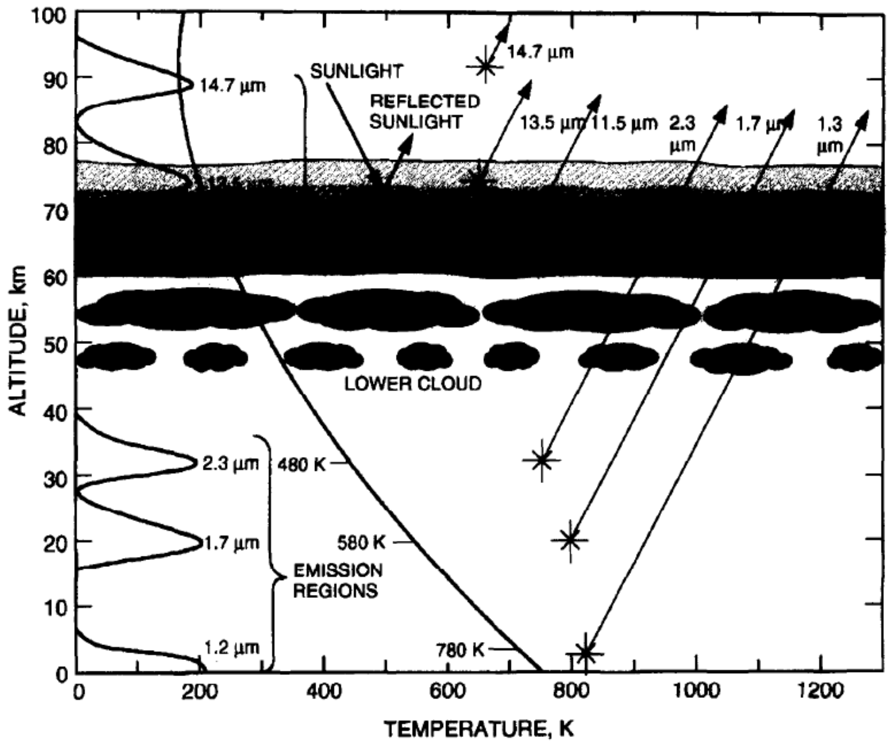


Introduction: Venus clouds



H_2SO_4 clouds
(47-70 km)

Fig. Schematic of Venus clouds and relationship between wavelengths and sounding altitudes (Taylor, 1998).

- ☐ Dense H_2SO_4 clouds (47-70 km)
- reflect ~76% of the incident sunlight back to space.
- absorb thermal radiation emitted from the lower atmosphere.
- ➢ significant impact on the atmospheric dynamics and the climate system
- ✓ Necessary to investigate what the cloud structure is like and how it changes spatiotemporally.

Introduction: how to retrieve cloud structure?

- CO_2: major constituent of the atmosphere of Venus, spatially well-mixed
  - ➢ The brightness contrasts seen in CO_2 absorption band are caused by the difference of the optical path length to the cloud top.
  2.02-µm channel of 2-µm camera (IR2) onboard Akatsuki used this principle.

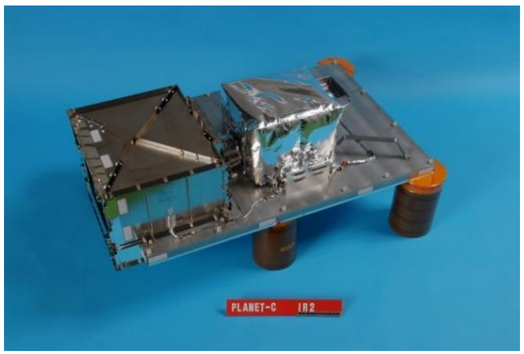


Fig. View of Akatsuki/IR2.

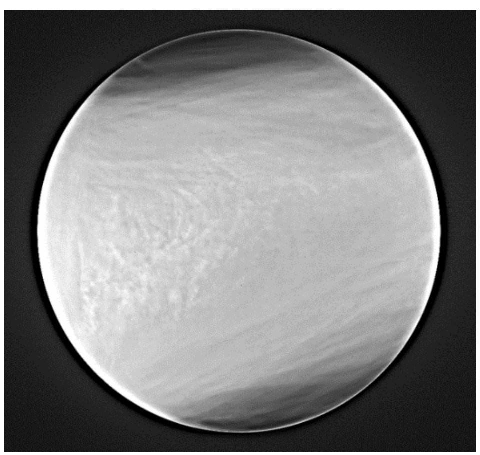


Fig. Feature-enhanced 2.02-µm image.

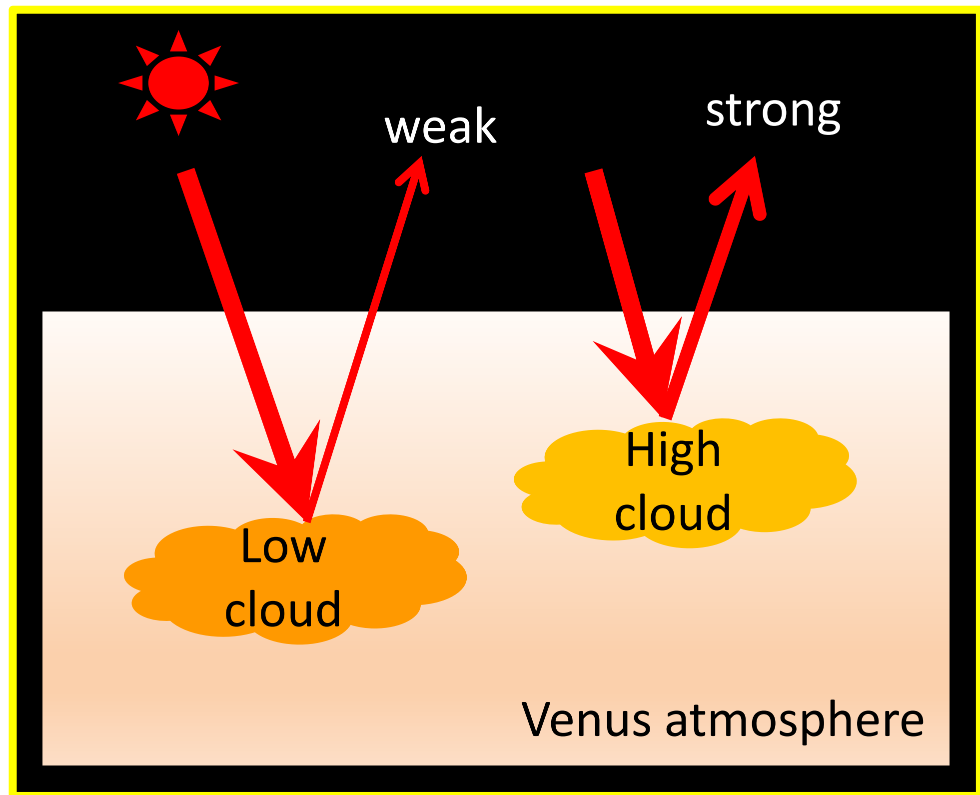


Fig. Conceptual diagram of observation principle.

Goal of this study

Goal of this study: To derive cloud top altitude map for each image

- 2.02-µm channel intensity is sensitive not only to cloud top altitude but also to cloud scale height and particle radius.
- In principle, it is IMPOSSIBLE to retrieve a few key parameters (cloud top altitude, cloud scale height, particle radius, …) for each pixel from single-wavelength intensity (i.e., ill-posed problem).

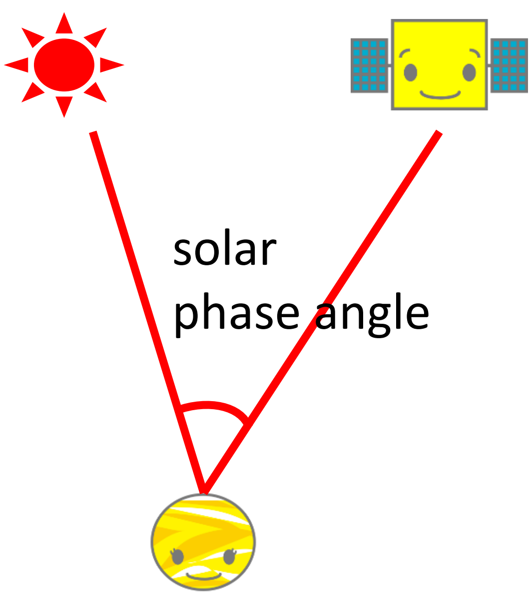
Step 1.
Derive spatially-averaged cloud top structure (mode 2 particle radius $\overline{r_2}$, cloud scale height $\overline{H}$, and cloud top altitude $\overline{z_c}$) by reproducing the observed phase curve of radiance in low-latitudes (≤30˚).

Step 2.
Derive cloud top altitude at individual locations under the assumptions that the pixel-to-pixel radiance variation arises as the deviation from the averaged cloud top structure and can be explained by the change of the cloud top altitude while keeping the other parameters ($\overline{r_2}$ and $\overline{H}$) unchanged.

Data used in this study

- 93 images taken with 2.02-µm channel during the period from April 4–May 25, 2016 (Orbit 12–16)
- For each image, we calculated observed radiance averaged in low-latitudes (≤30˚).
- ESA's Venus Express showed that average cloud top altitude in low-latitudes was uniform and had no significant local time dependence.

➢ The average cloud structure to be derived in Step 1 needed to reproduce the observed phase curve by a constant cloud top altitude.



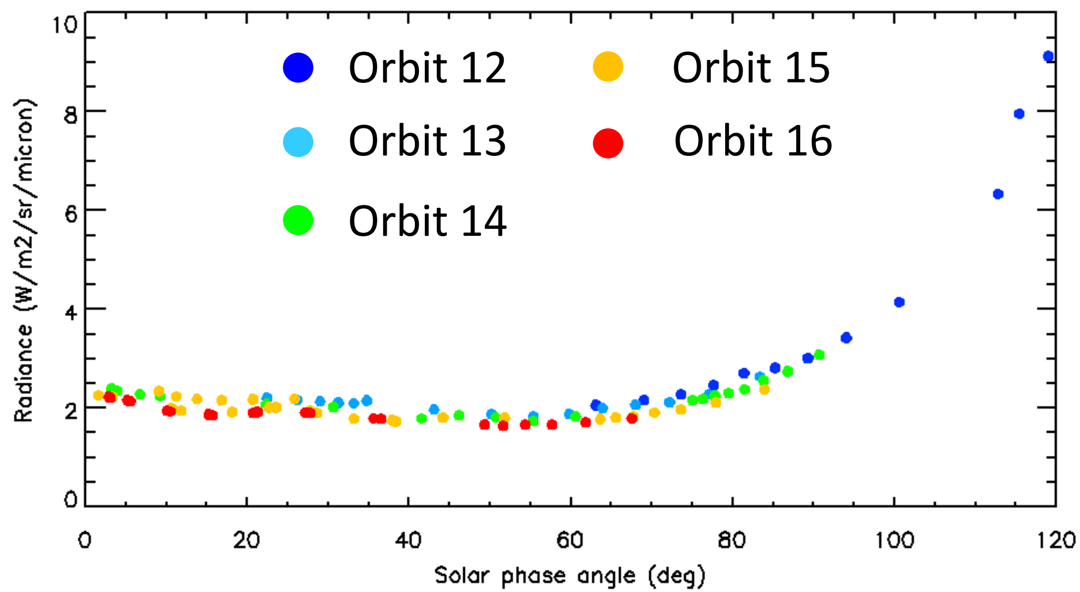
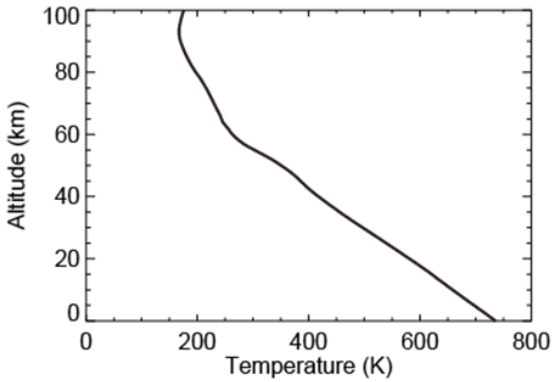
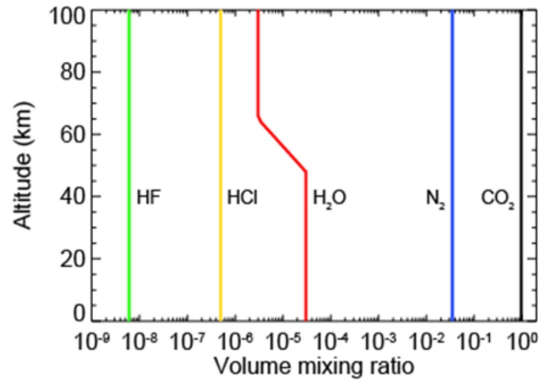


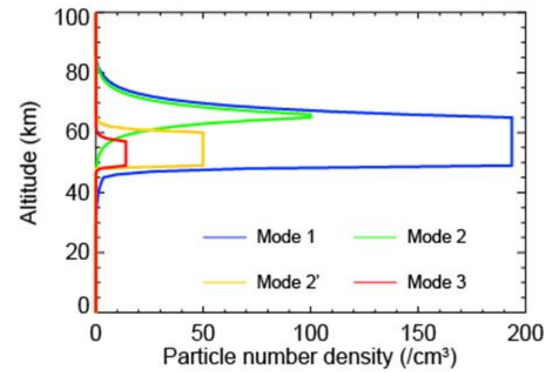
Fig. area-averaged radiance as a function of solar phase angle (phase curve).

Radiative transfer calculation

- Fixed parameters: vertical profiles of temperature, atmospheric molecules, clouds, etc







- Free parameters: mode 2 radius, cloud scale height, and cloud top altitude

Radiative transfer model
- originally-developed LBL model
- solver for scattering: adding doubling method

Compare the observed phase curve with the simulated one based on least square method

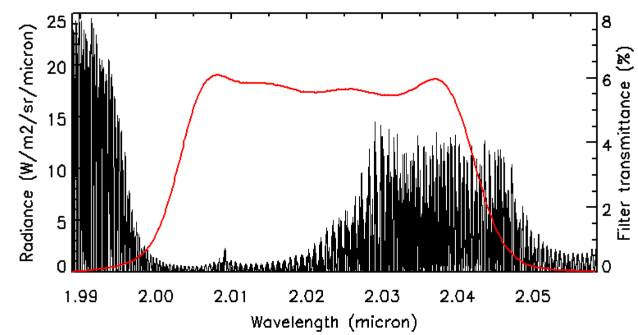
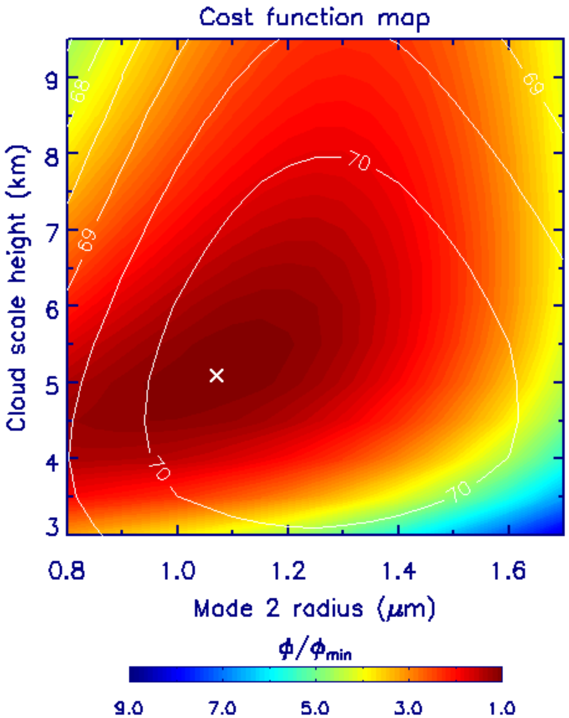
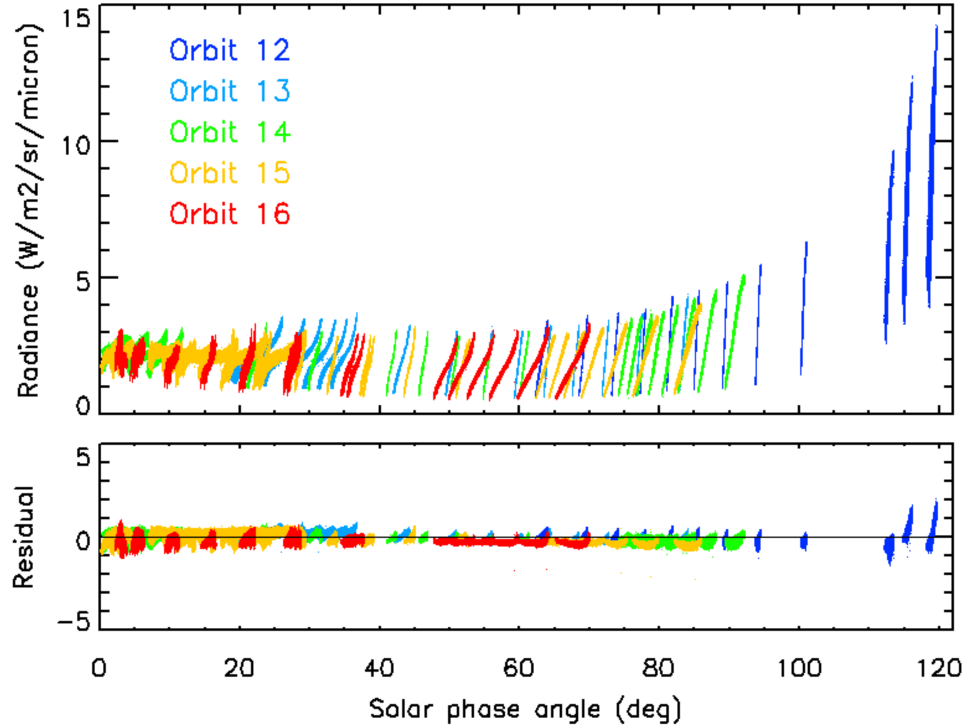


Fig. Example of simulated spectrum for IR2 2.02-µm channel with its filter transmission curve.

Results from Step 1

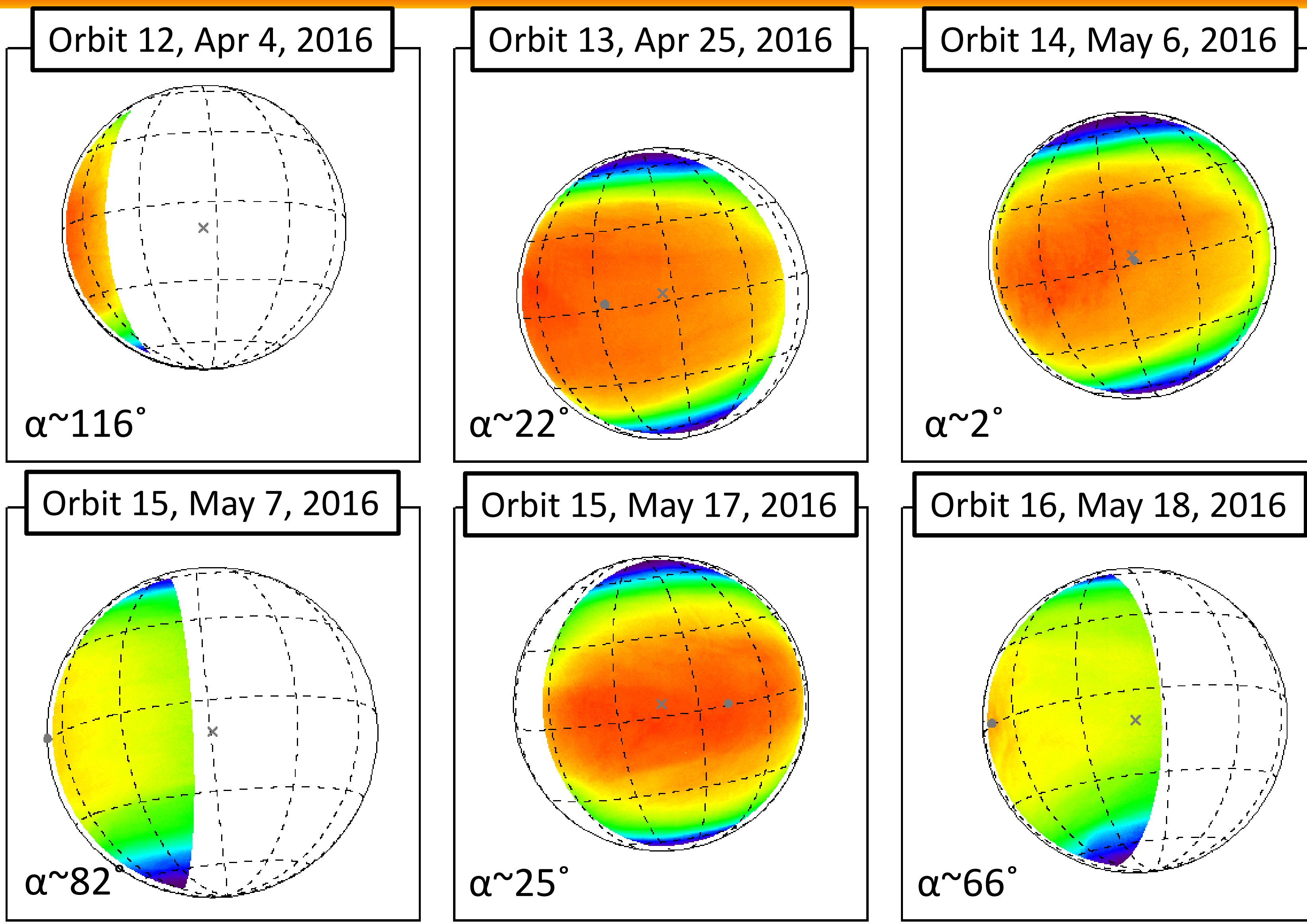


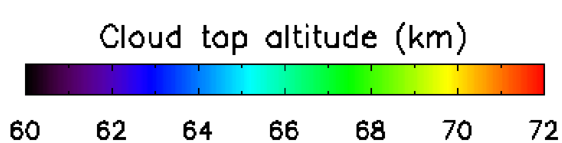


Figs. (left) Normalized cost function map as a function of mode 2 radius and cloud scale height (best-fit cloud top altitude is also superimposed on the map), (right) Comparison of phase curves between the observation and the best-fit model.

- Best-fit parameters:
- Mode 2 particle radius: $\bar{r_2} = 1.07\ \mu m$
- Cloud scale height: $\bar{H} = 5.1\ km$
- Cloud top altitude: $\bar{z_c} = 70.3\ km$
- ➢ The best-fit model reproduced the observed phase curve.

Results from Step2





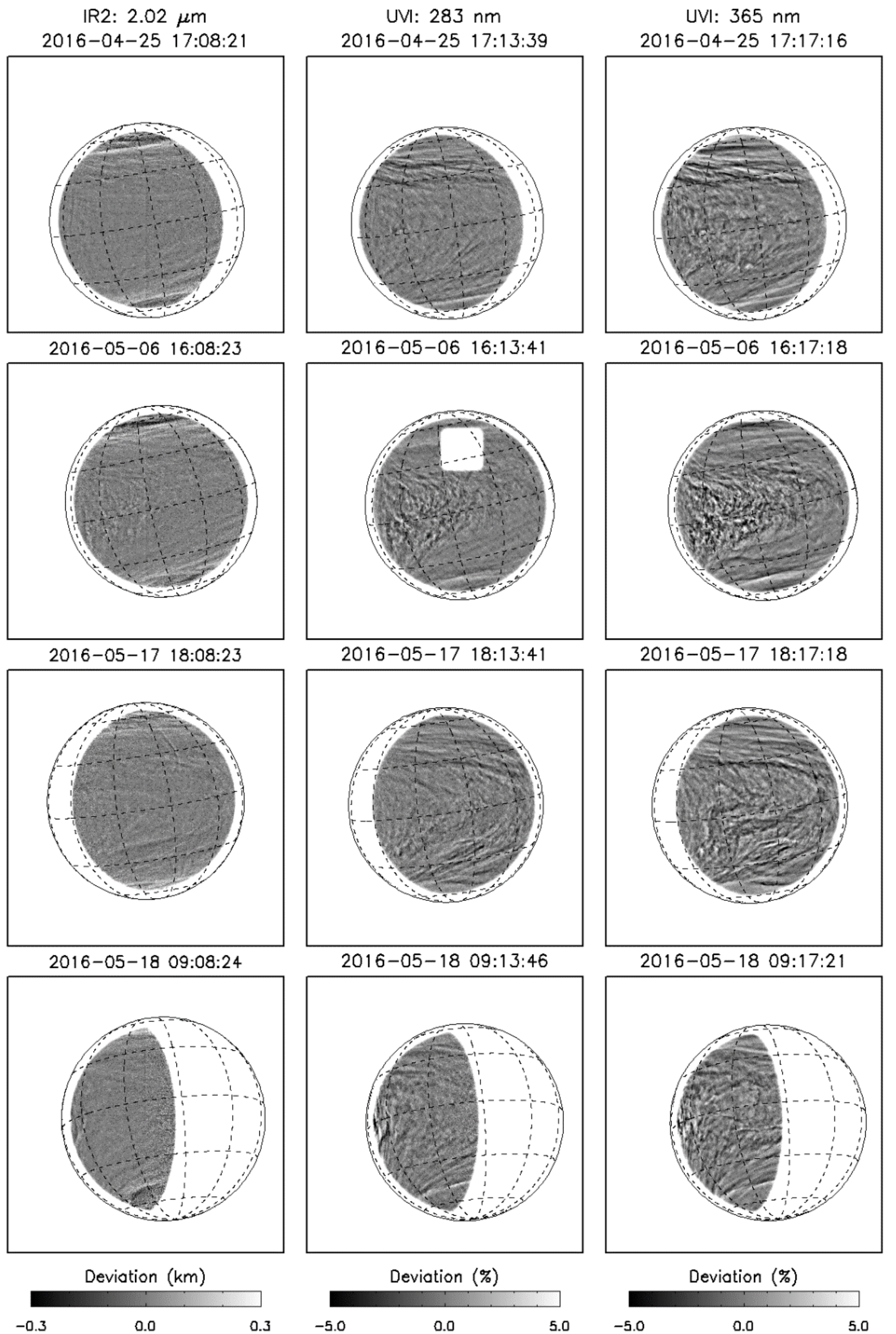
- Area where $\mu \geq 0.25$ and $\mu_0 \geq 0.25$ is shown.

Results from Step2

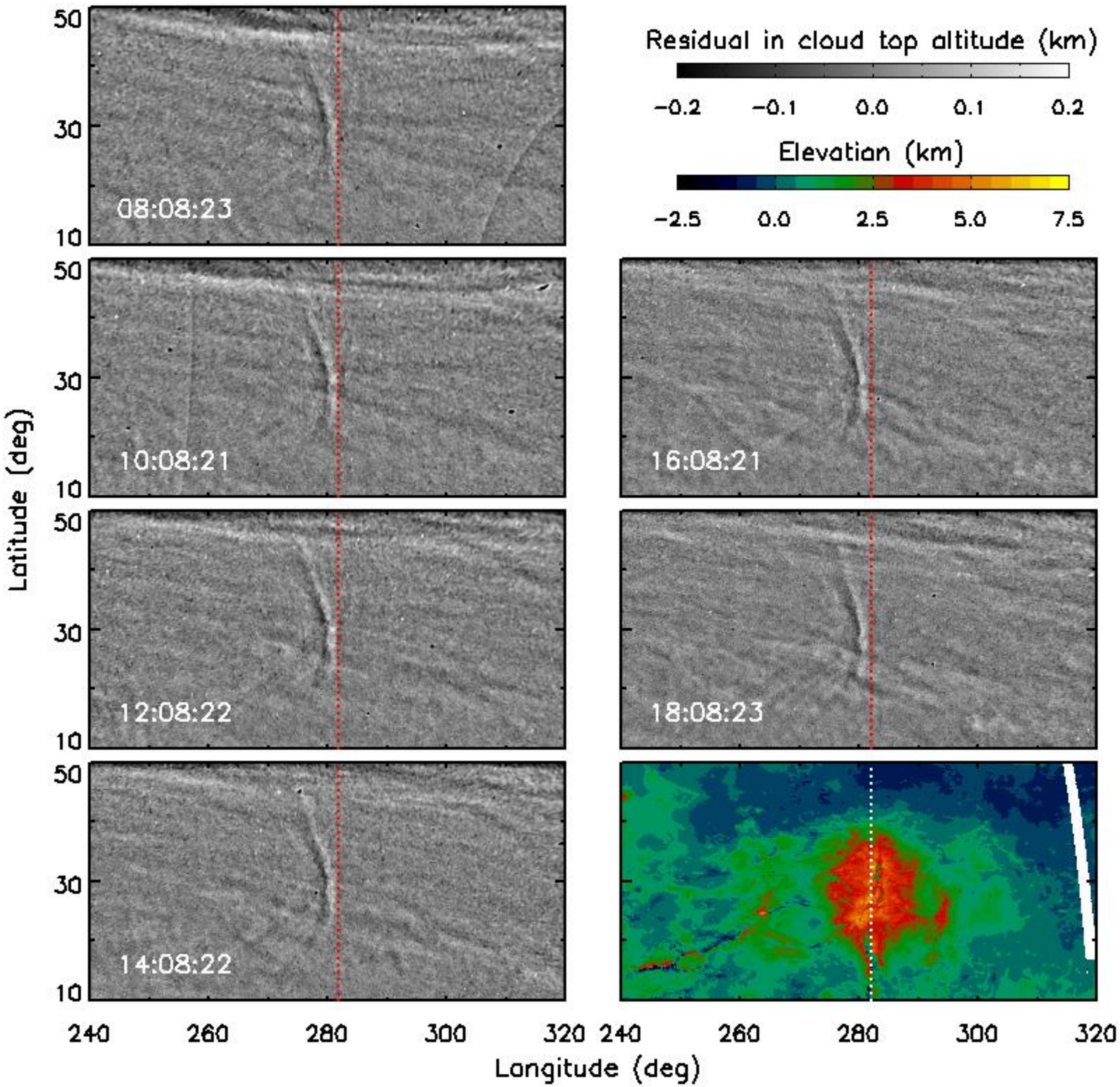
- Small amplitude features were extracted by subtracting an Gaussian-smoothed image from original image.

- The local variation in cloud top altitude occurred within several 100 m, including stationary gravity wave feature.

- UV channels exhibited mottled and patchy patterns ubiquitously distributed in the low and middle latitudes, suggesting the existence of convection and turbulence at the cloud top level. However, the corresponding patterns did not necessarily appear as the local variation in cloud top altitude.



Stationary features on topography map



- The longest-lived stationary feature (May 13-25)
- position above Beta Regio
- Half wavelength: ~100 km
- Peak-to-peak value in cloud top altitude: ~0.2 km

Fig. Temporal changes in a stationary feature acquired at an intervals of 2-hours on May 17, 2016.

Results from Step2

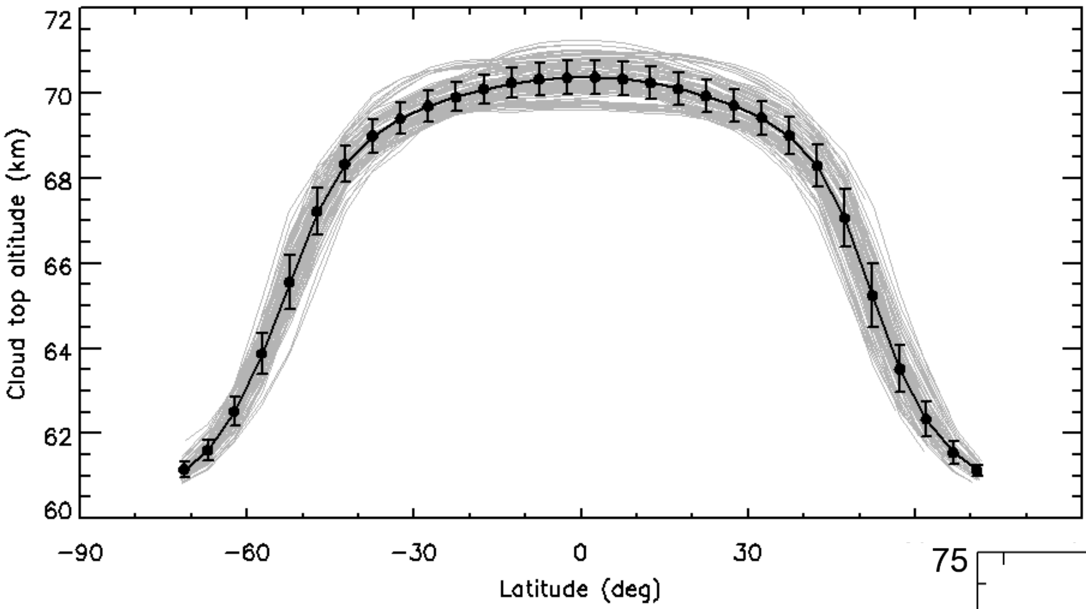


Fig. Latitudinal variation of zonally-averaged cloud top altitude.

- Symmetric to equator
- Cloud top equatorward of 45˚ ranged in altitudes of 68-70 km.
- Cloud top rapidly dropped at latitudes of 50-60˚ and reached 61 km in latitudes of 70-75˚.

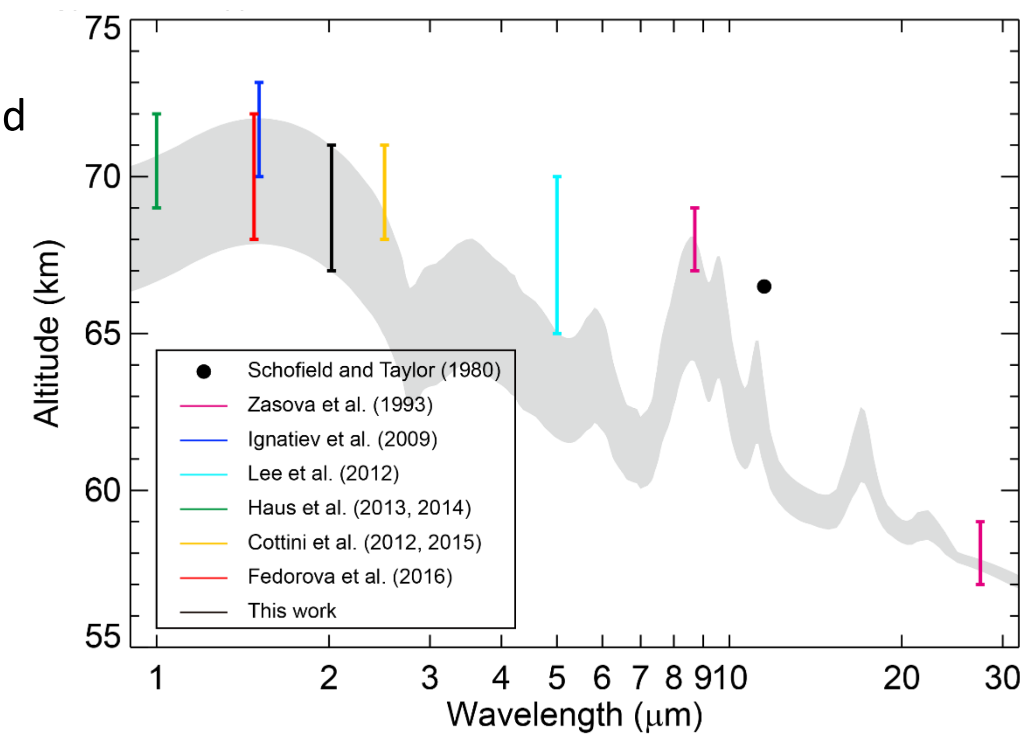


Fig. Comparison of Venus' cloud top altitudes in low and middle latitudes.

Results from Step2

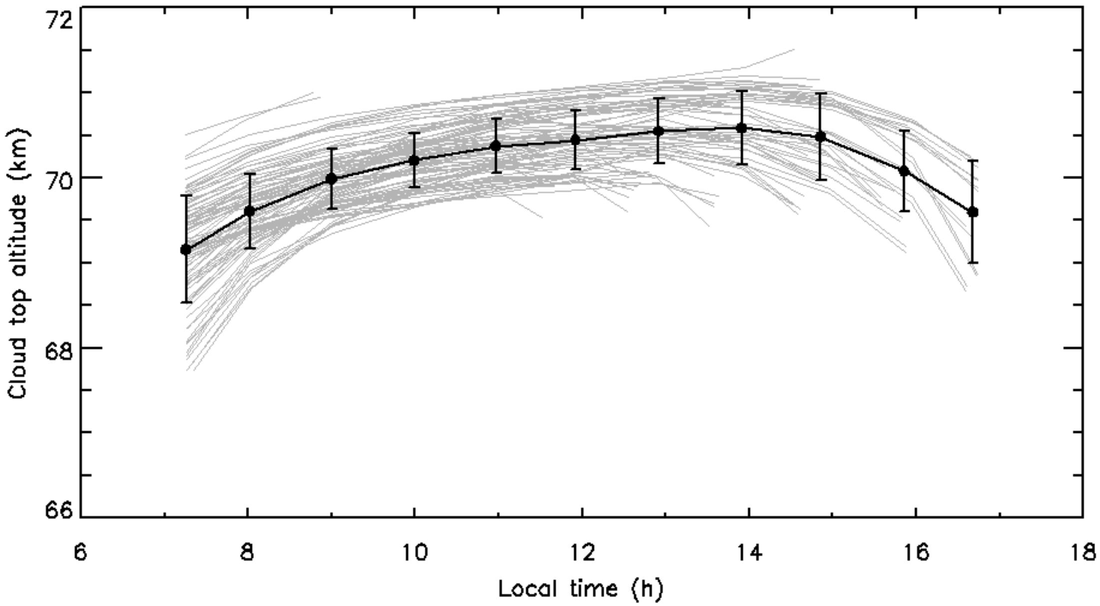
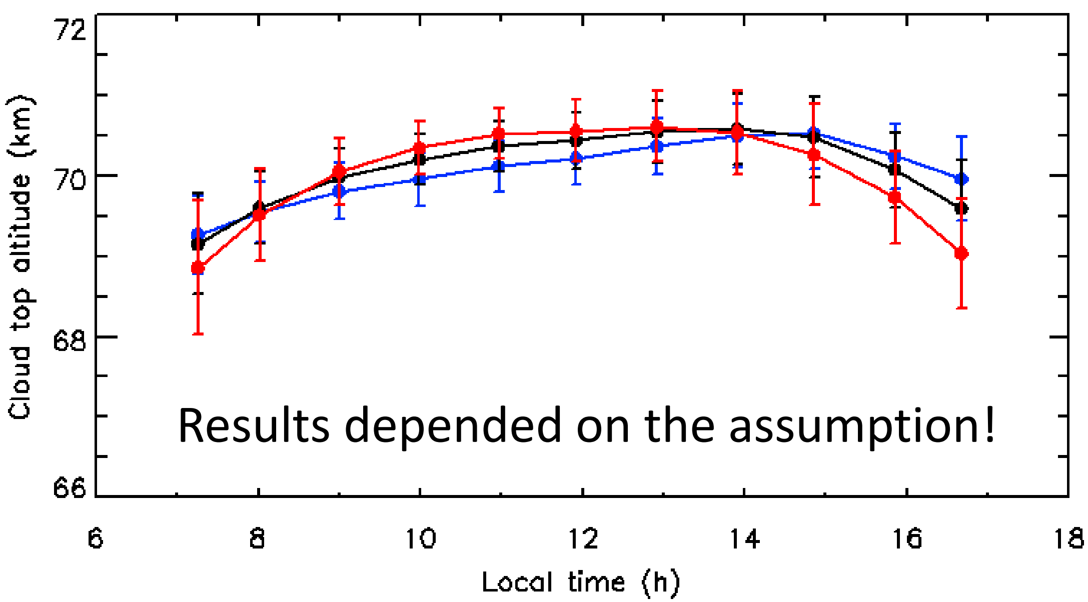


Fig. Local time dependence of cloud top in low latitudes.

- Tendency to increase from early morning (~7h) and reach a maximum in the early afternoon (~14 h) and decrease toward late afternoon (~17 h)
- The magnitude of increasing trend (~0.6 km) compared with the standard deviation (~0.4 km)



Best-fit
($\overline{r_2} = 1.07\ \mu m, \overline{H} = 5.1\ km$)

Two other combinations which gave cost function by 5% increase from the best fit value.
($\overline{r_2} = 0.97\ \mu m, \overline{H} = 4.7\ km$)
($\overline{r_2} = 1.17\ \mu m, \overline{H} = 5.6\ km$)

Summary

- We analyzed 93 Venus' dayside images acquired at a wide variety of solar phase angles (0-120°) by the 2.02-μm channel of Akatsuki/IR2, between April 4 and May 25, 2016, for the purpose of mapping cloud top altitude.

- The observed solar phase angle dependence, and the center-to-limb variation of reflected sunlight at low latitudes were used to derive a spatially-averaged cloud top structure characterized by mode 2 particle radius $\overline{r_2}$, cloud scale height $\overline{H}$, and cloud top altitude $\overline{z_c}$. The best-fit model is obtained at the combination of $\overline{r_2}$=1.07 μm, $\overline{H}$=5.1 km, and $\overline{z_c}$=70.3 km. The obtained $\overline{r_2}$ and $\overline{H}$ are in agreement with previous studies.

- Cloud top altitudes at individual locations were retrieved with the best-fit values of $\overline{r_2}$ and $\overline{H}$. The average of zonally-averaged cloud top profiles was symmetric to the equator. The averaged cloud top in low and middle latitudes was in the range 68-70 km. It rapidly decreased in higher latitudes of 50-60° and was 61 km in high latitudes of 70-75°. This global pattern is qualitatively in agreement with previous results by Ignatiev et al. (2009), Haus et al. (2014), Cottini et al. (2015), and Fedorova et al. (2016). The cloud top averaged in low latitudes showed no significant local time dependence with the exception that the magnitude of the change was 1 km at most.