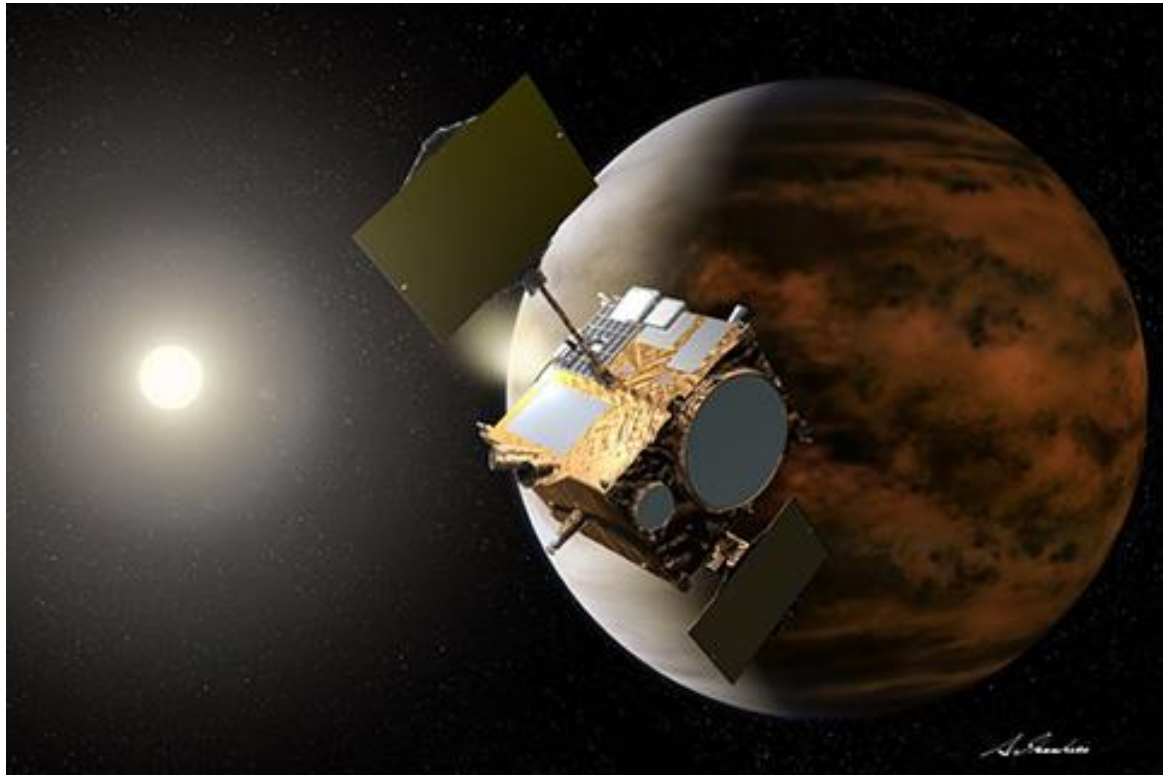
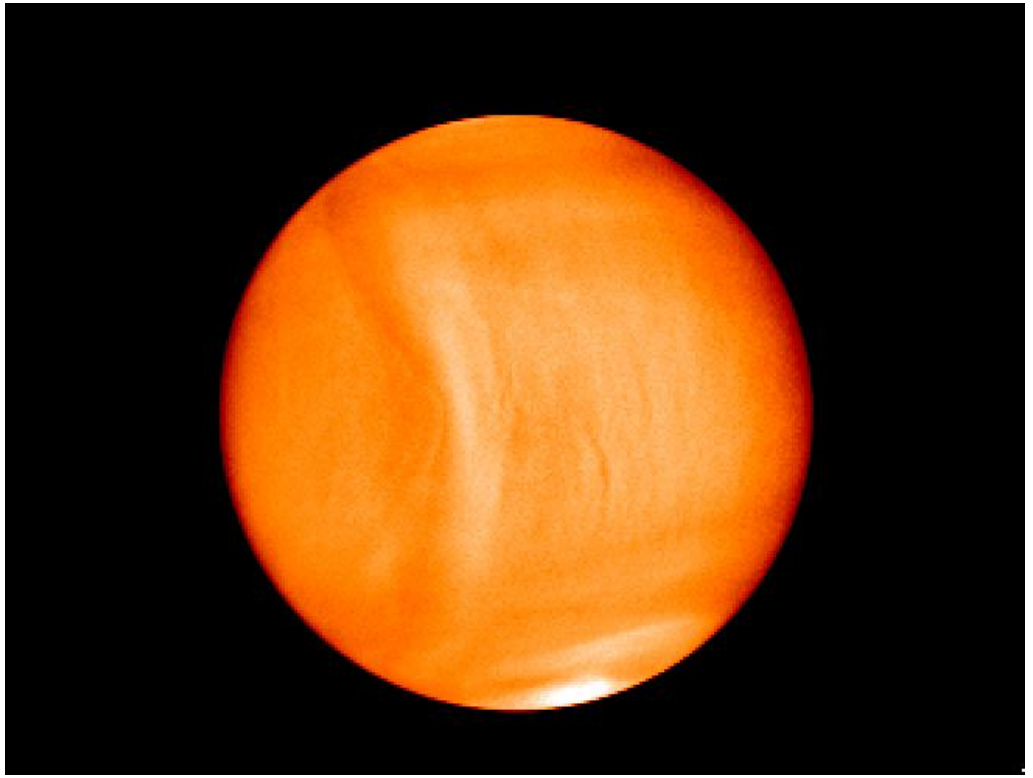
Detection of large stationary gravity waves over ten Venusian solar days seen in LIR images

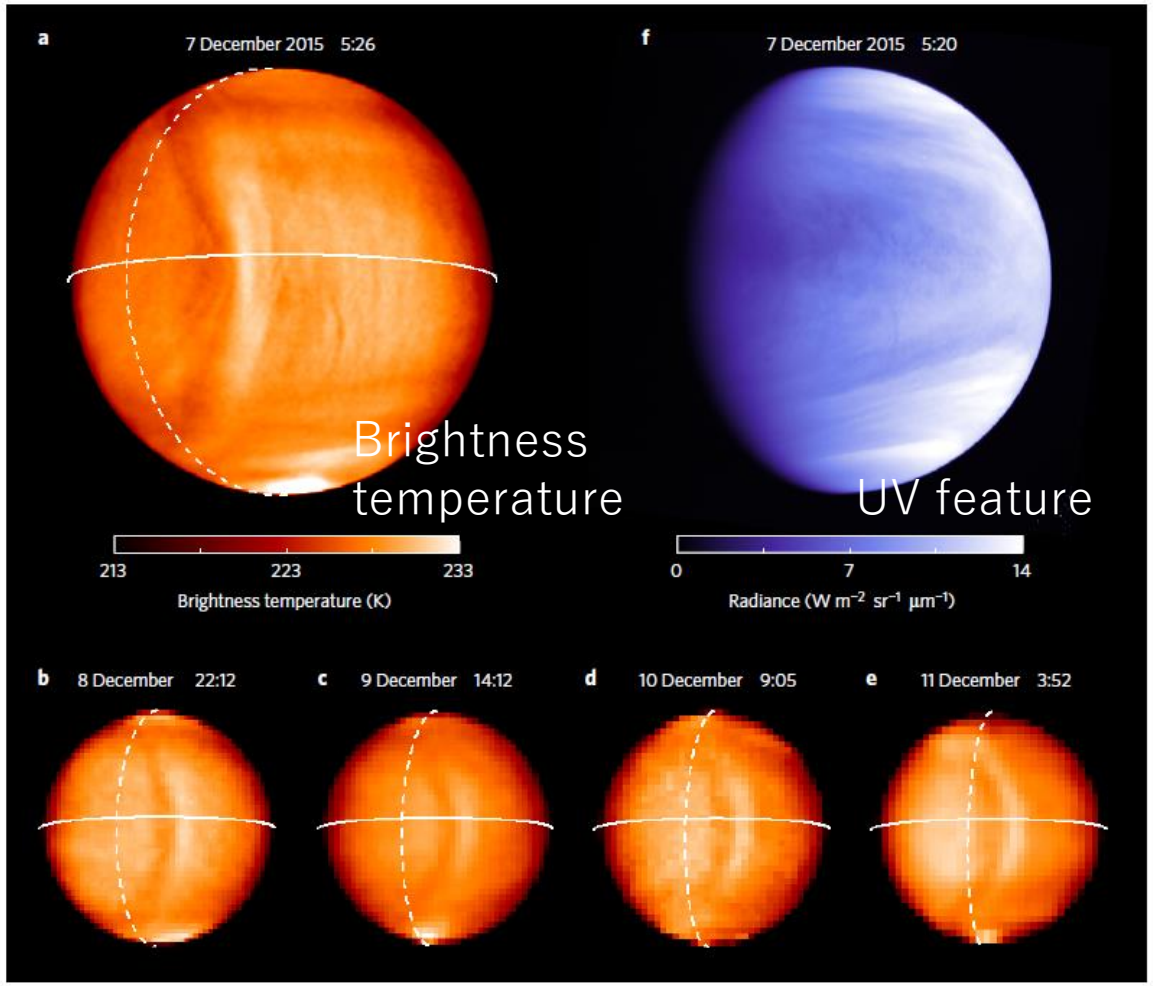




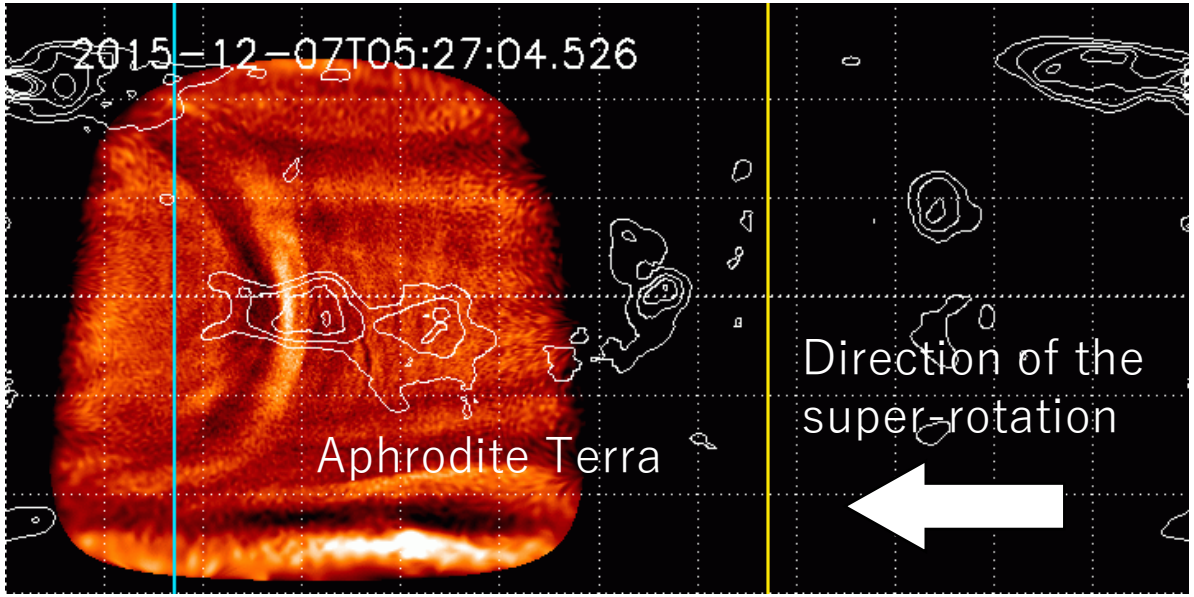
T. Kouyama (AIST), M. Taguchi, T. Fukuhara, T. Imamura, T. M. Sato, M. Futaguchi, T. Yamada, S. Murakami, G. L. Hashimoto, H. Sagawa, T. Satoh, and M. Nakamura
Akatsuki science team and LIR team.

Discovery of a large stationary gravity wave

2015.12.07



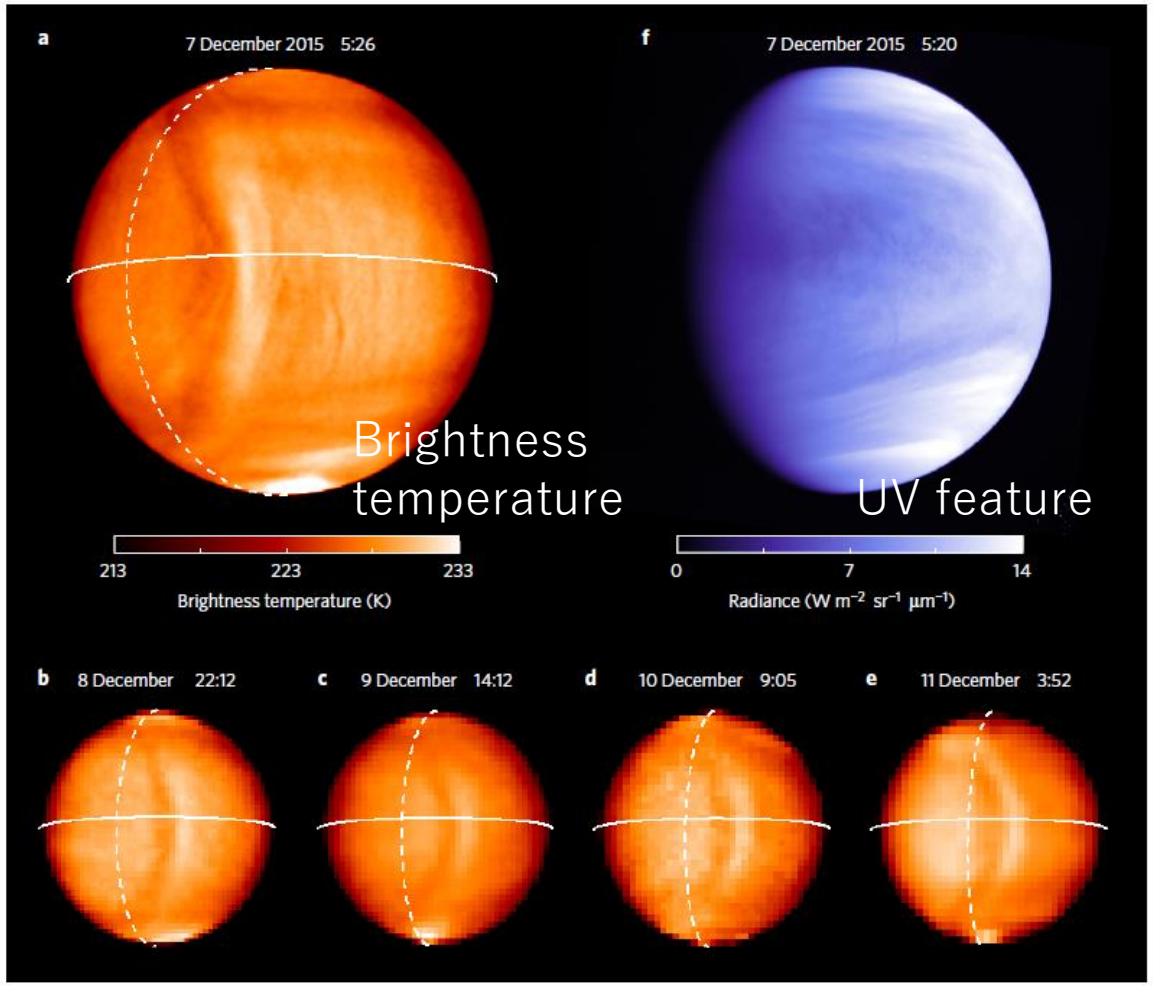
[Taguchi et al., 2016(DPS); Fukuhara et al., 2017]



- It stayed at almost same location (Aphrodite Terra) during the first observational sequence (5 days).
- This wave was absent in January 2016 and appeared again in July 2016 (lasted for ~one month).

Discovery of a large stationary gravity wave

2015.12.07

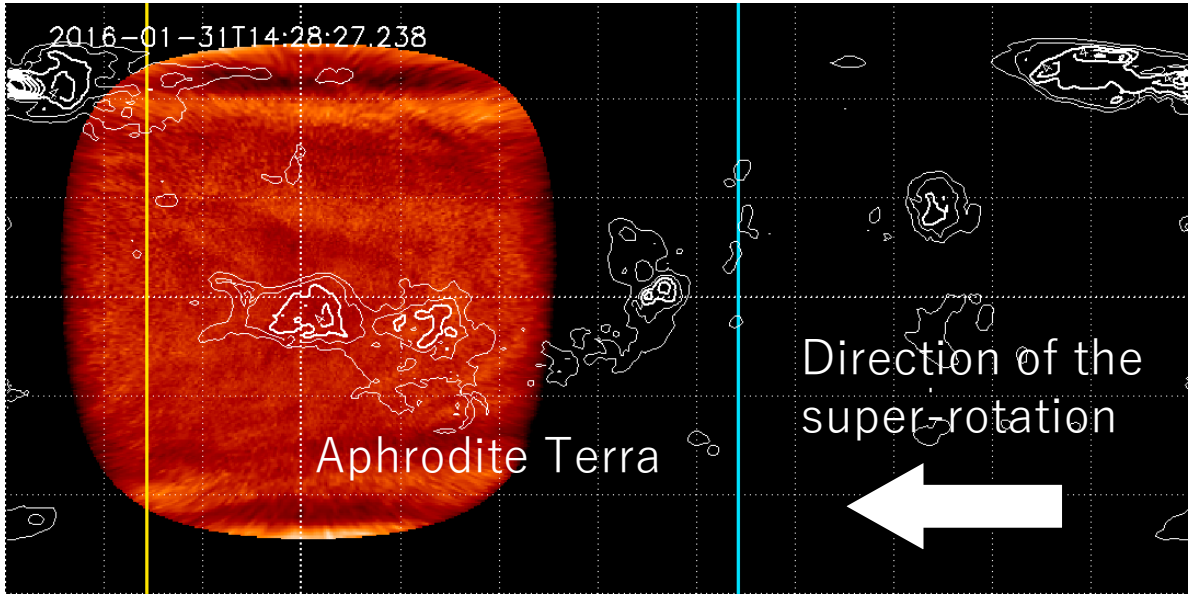


[Taguchi et al., 2016(DPS); Fukuhara et al., 2017]

The wave was absent in April 2016.

Morning terminator

Evening terminator



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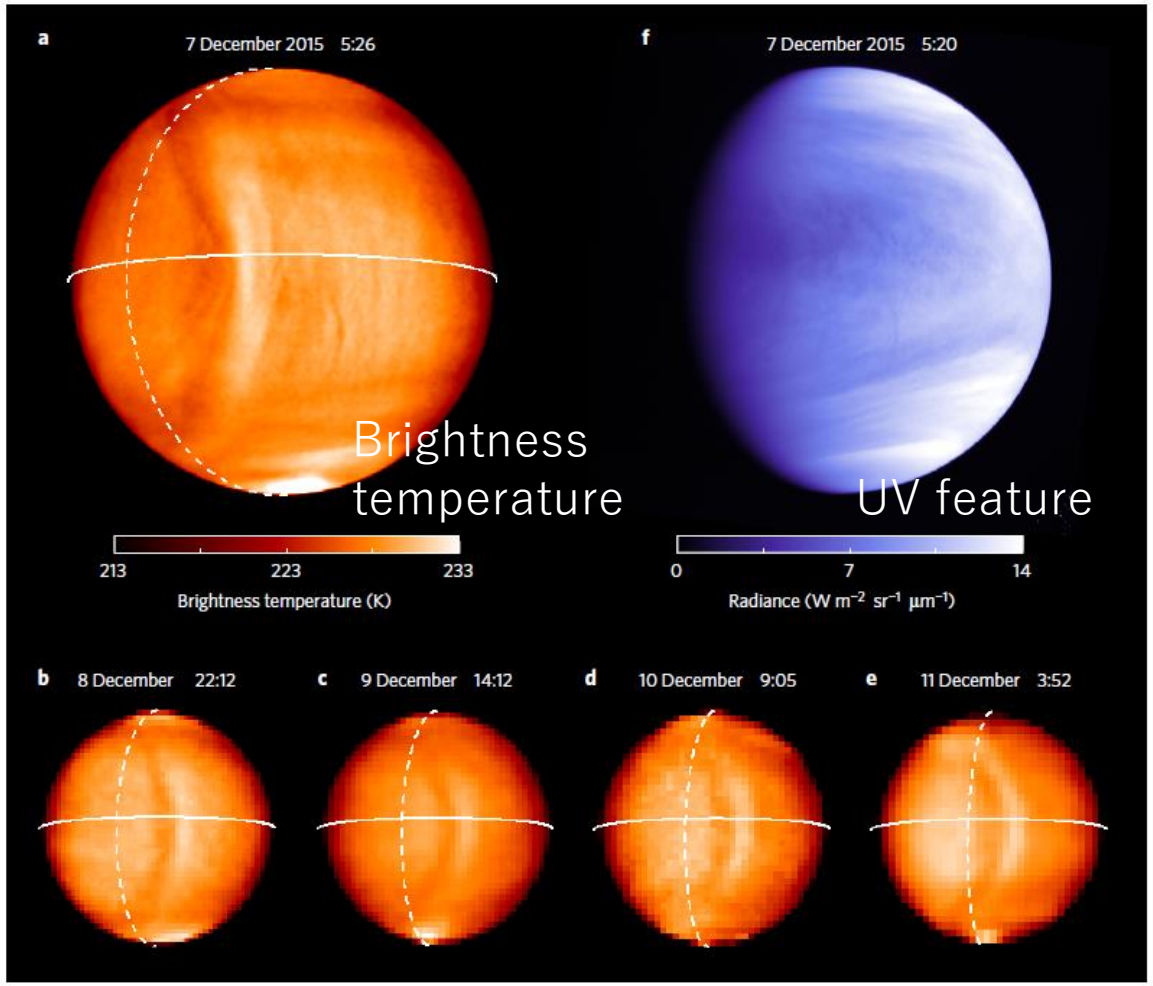
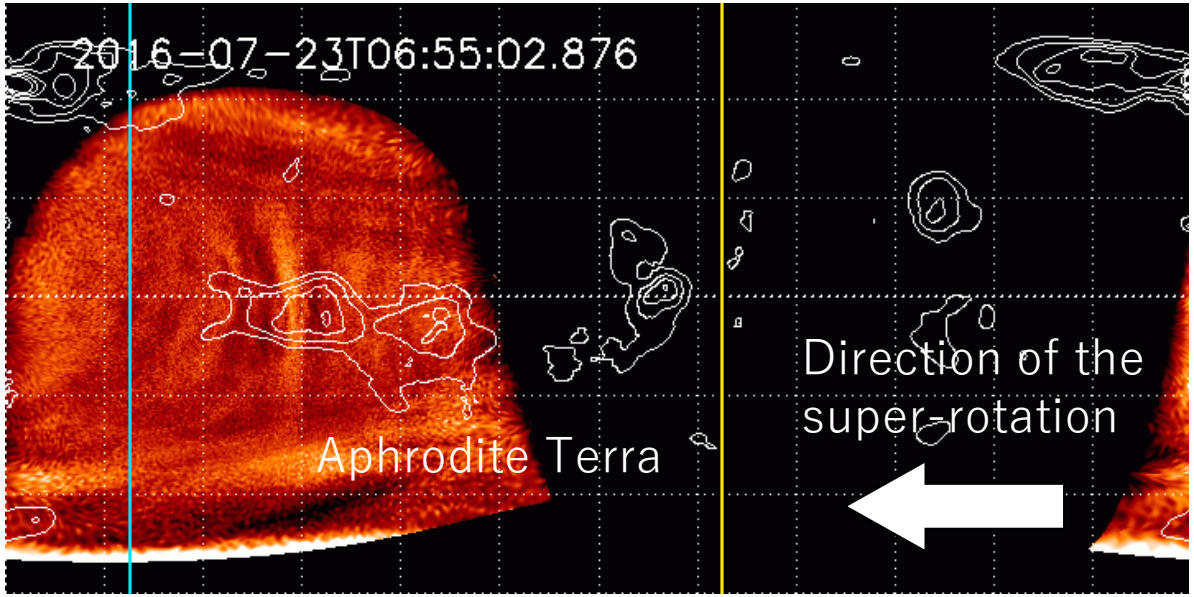
Discovery of a large stationary gravity wave

2015.12.07

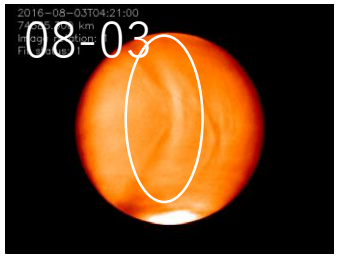


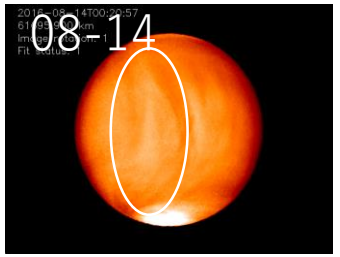
[Taguchi et al., 2016(DPS); Fukuhara et al., 2017]

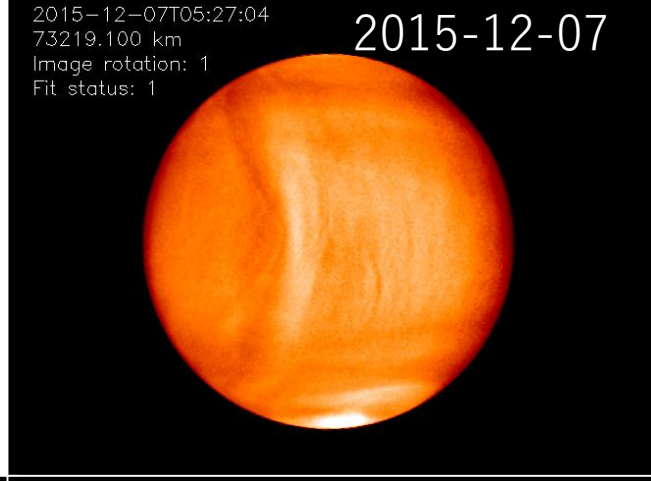


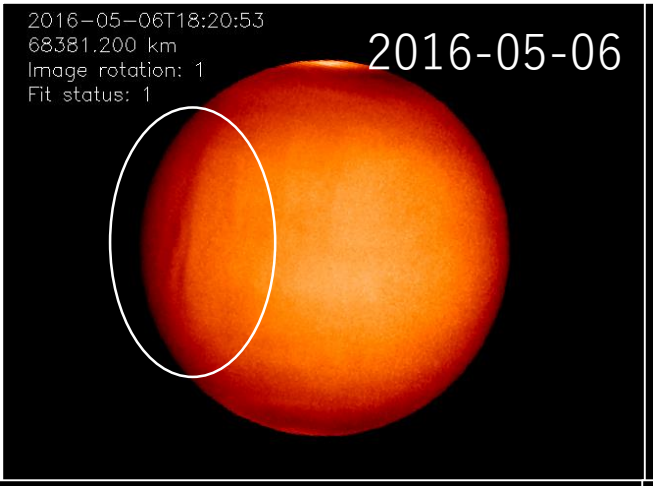
- It stayed at almost same location (Aphrodite Terra) during the first observational sequence (5 days).
- This wave was absent in January 2016 and appeared again in July 2016 (lasted for ~one month).

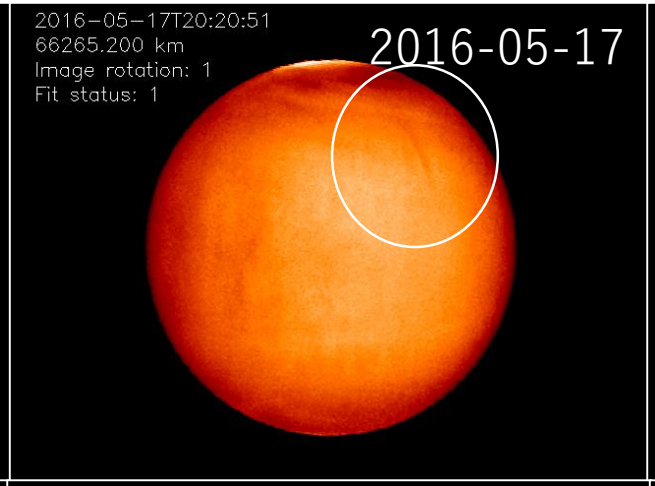
Many stationary wave events seen in LIR images
- some wave events lasted several weeks.

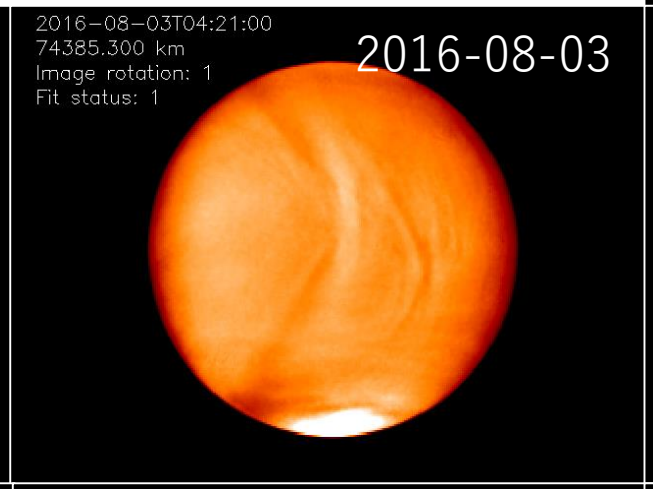


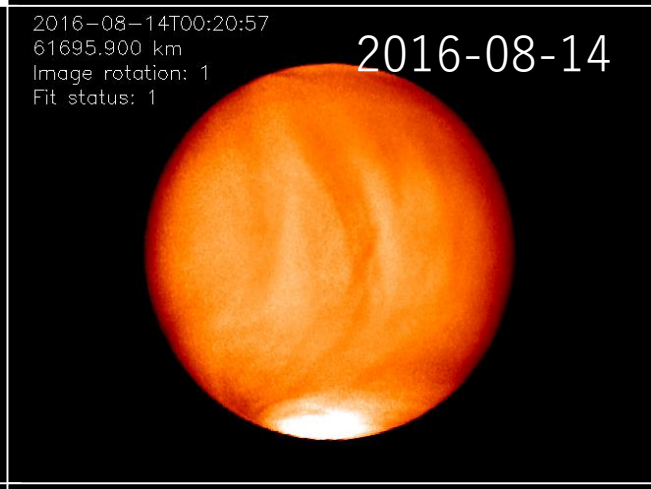


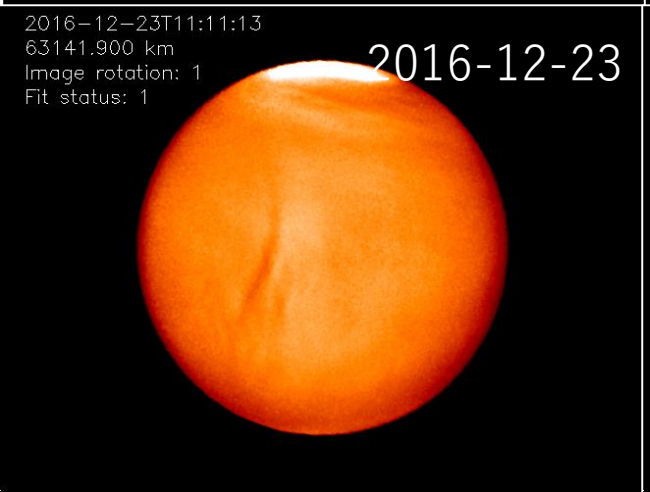


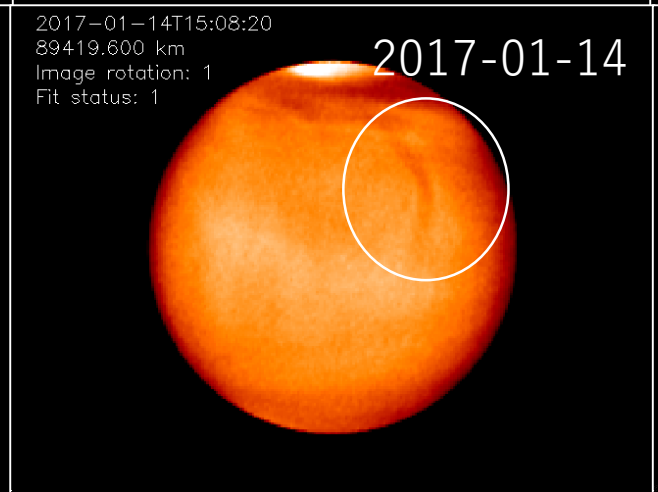


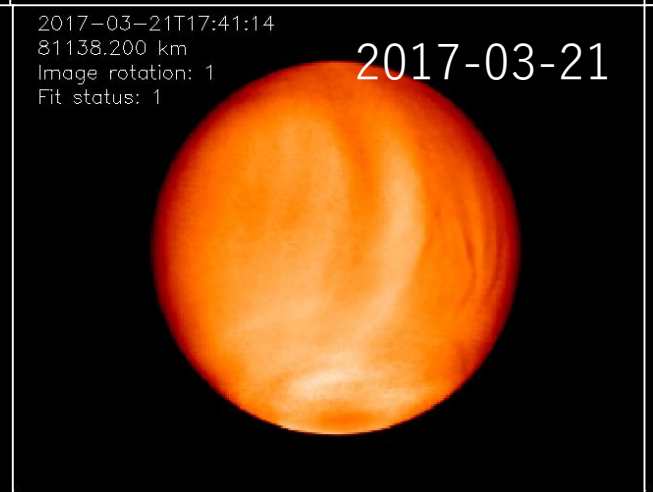


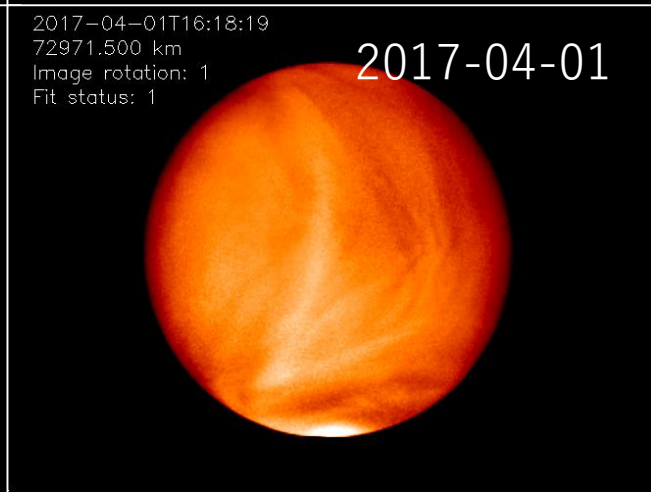




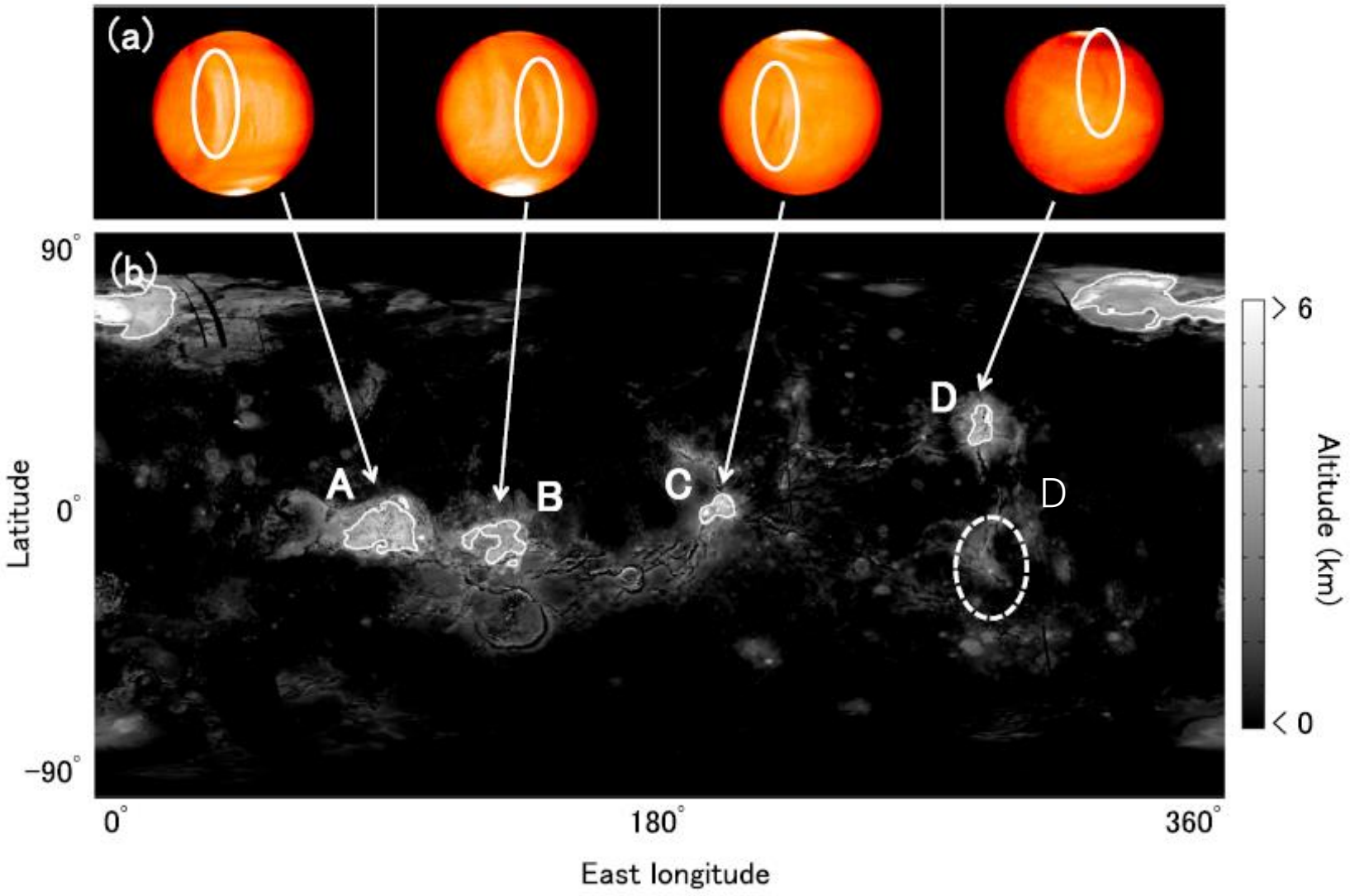








Topographical dependence:
Clear, large stationary waves appeared above **highlands in low latitudes**



The four highlands are
- widely higher than 3 km
- in low latitudes (< 35˚)

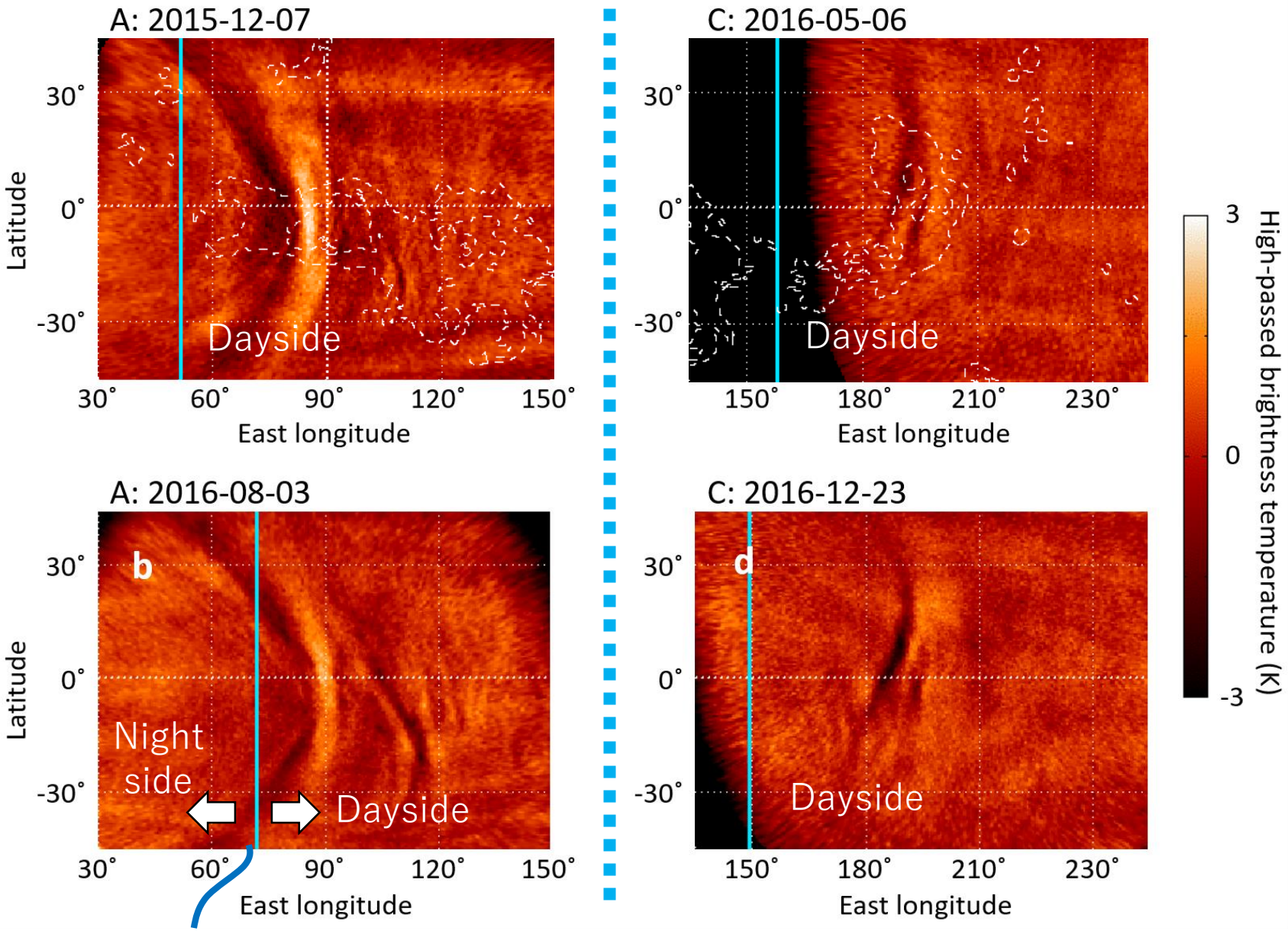
Maxwell Mon (60˚N) has never shown a stationary feature

High altitude and **low latitudes** are key parameters for large stationary features

[Kouyama et al., 2017]

Aphrodite Terra (west part)

Atla Regio



- Similar appearance above a same region
- Different shapes at the different locations

⬇

Surface topography should affect the wave shape at each location

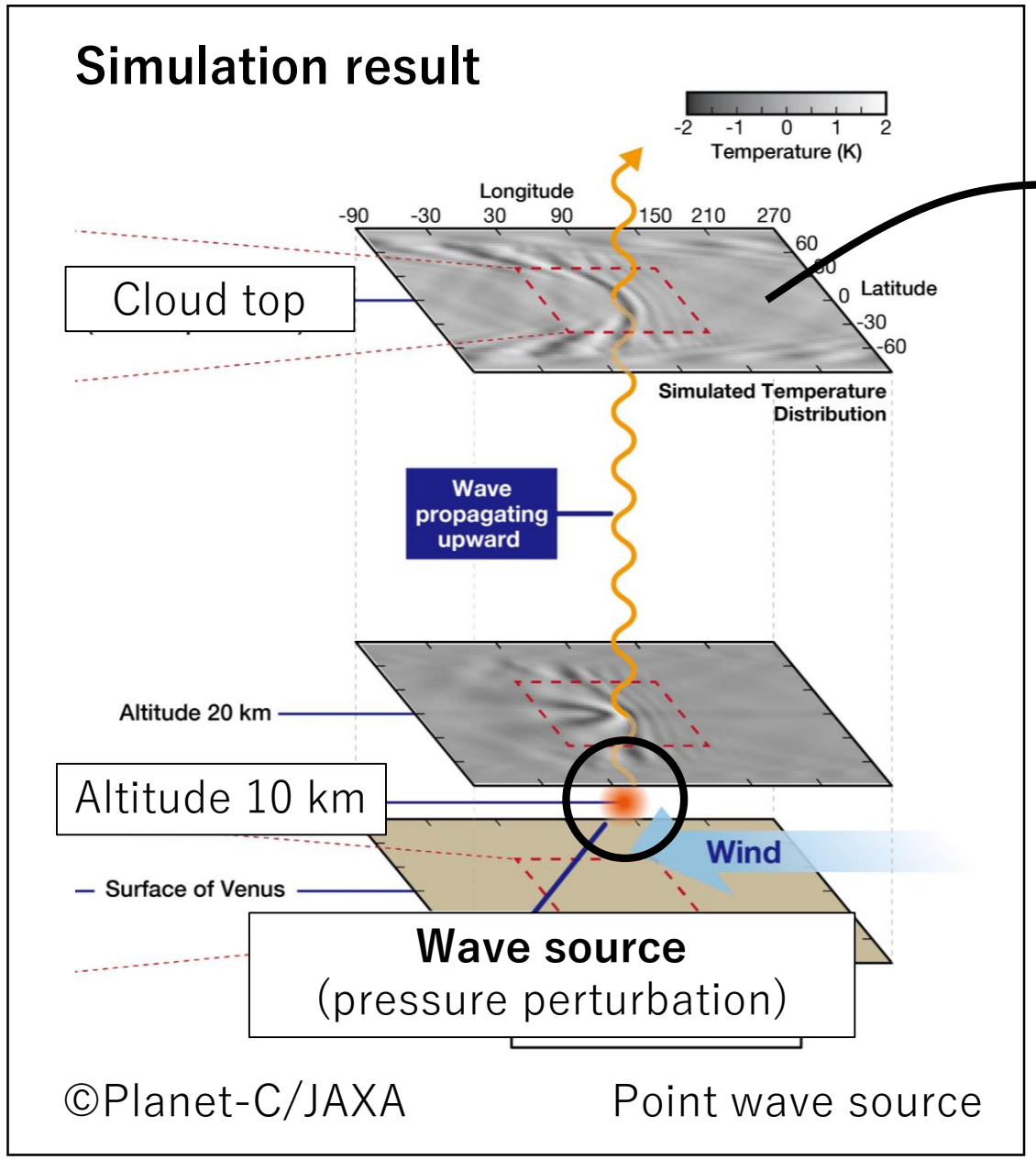
---

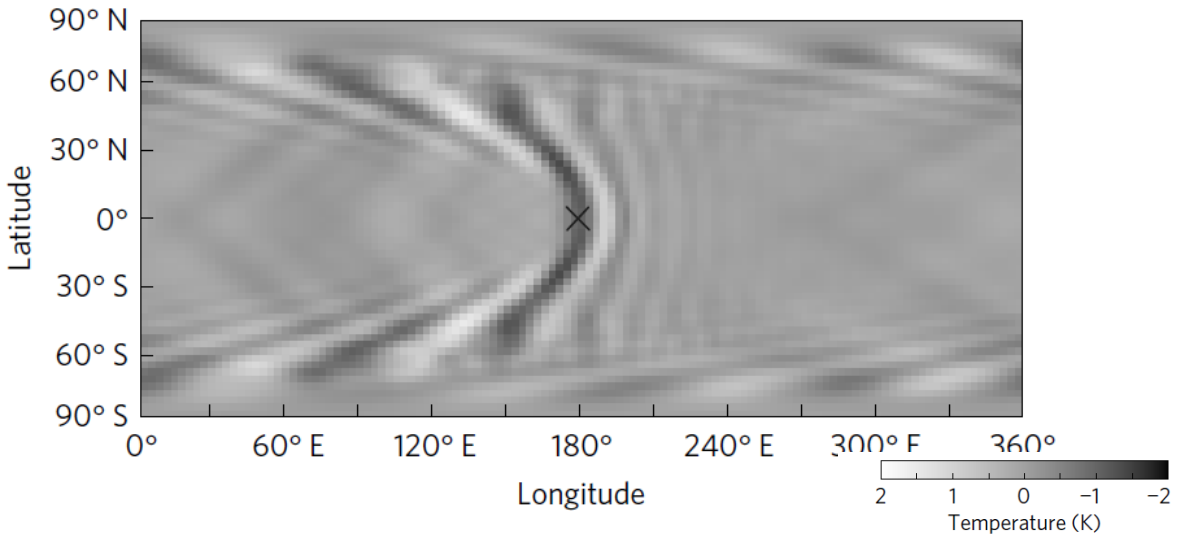
Significant every when they approach **evening terminator**.

⬇

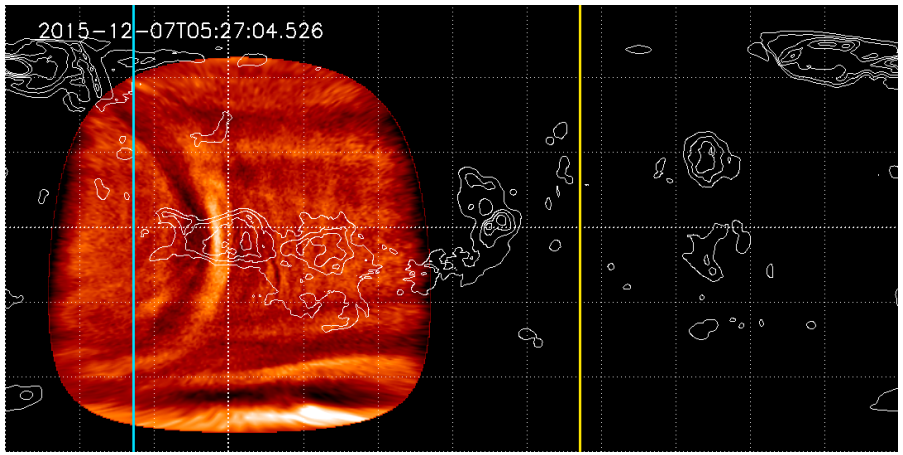
Local time dependence!

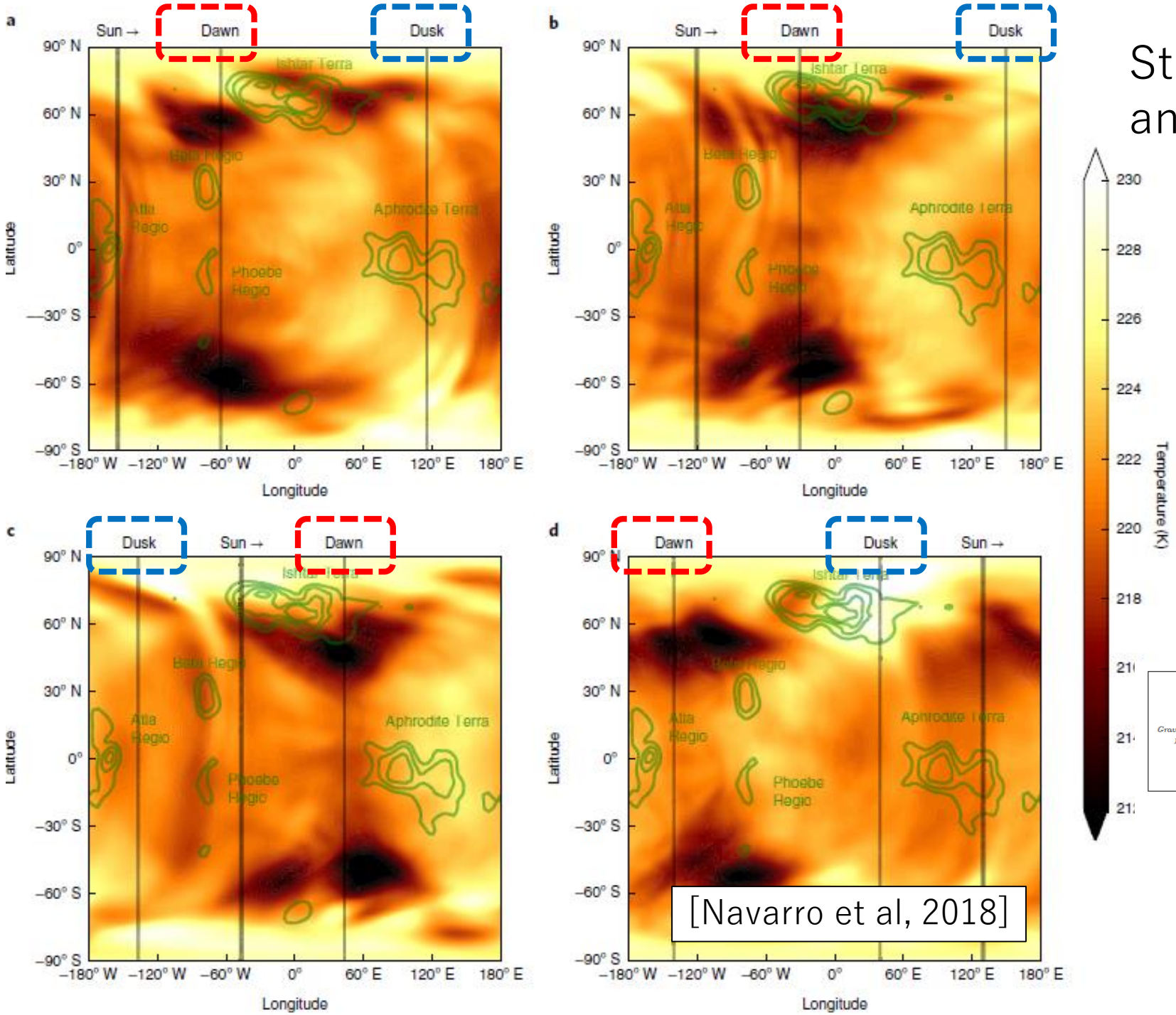
Perturbation at lower altitudes can make the bow-shape structure





[Fukuhara et al., 2017]

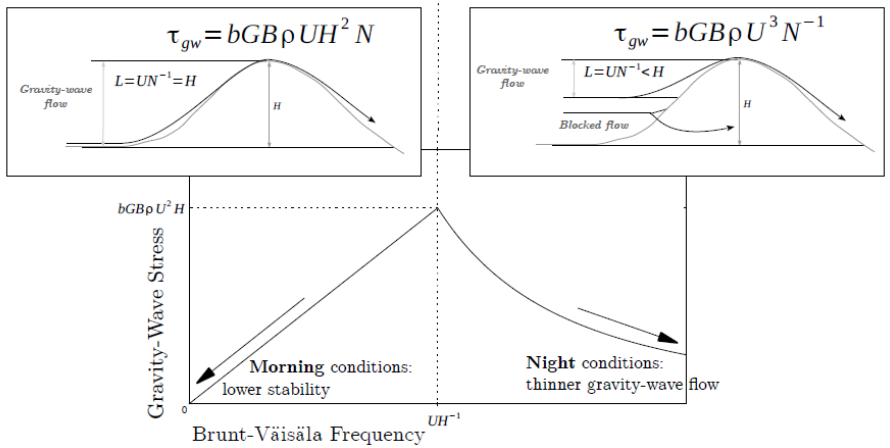




Stationary features in GCM and mesoscale model

[Navarro et al, 2018]
[Lefevre et al., 2019]

Topographical and local time dependence were well reproduced!



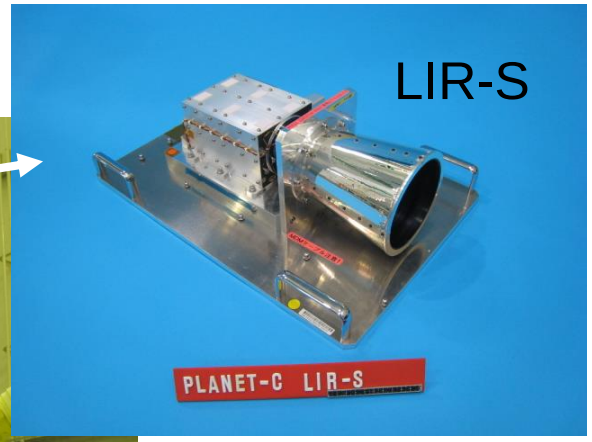
In this presentation

- Further detections of stationary waves in LIR images
- Mean temperature maps and their standard deviations
  - Local time – Latitude (i.e. thermal tides)
  - Longitude – Latitude (i.e. topography dependence)

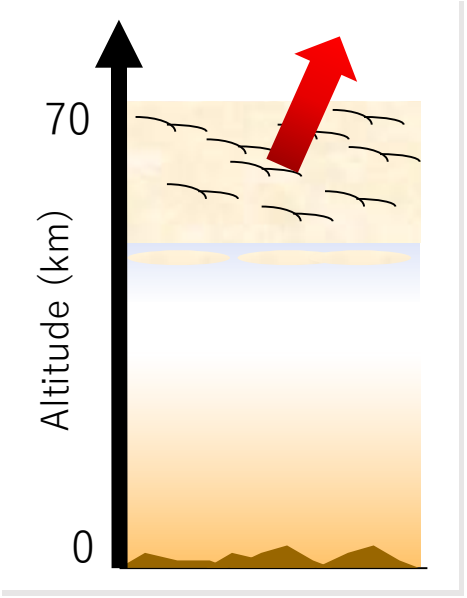
Data

Longwave Infrared Camera (LIR) / Akatsuki

Akatsuki in Final Test



[Fukuhara et al., 2011]



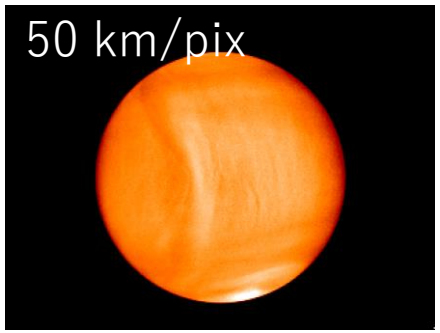
Wavelength: **8-12 μm**

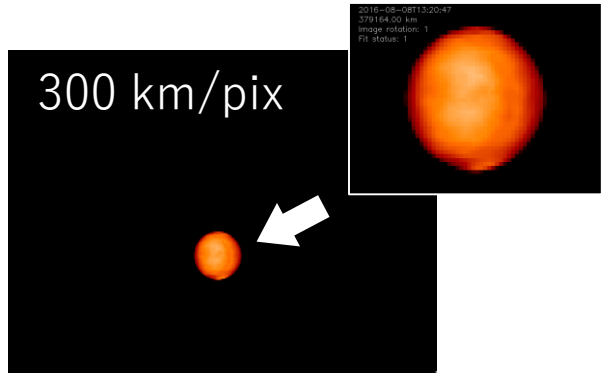
- Thermal emission from upper cloud layer (65-75 km)
- Both dayside and night side of Venus

[Taguchi et al., 2007]

Spatial Resolution:

up to 300 km/pix





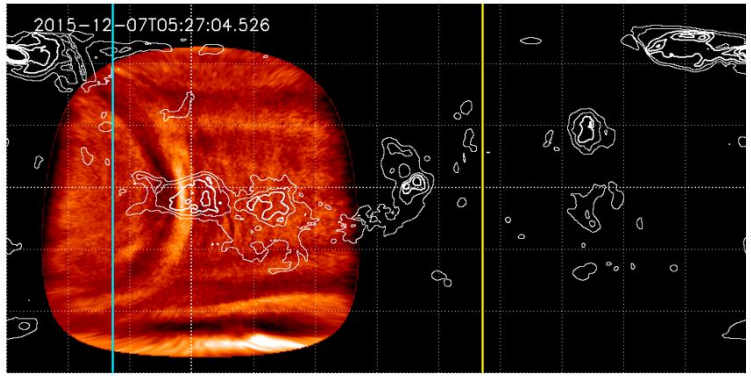
Data period in this study:

2015. 12 (VOI) ~ 2019.03

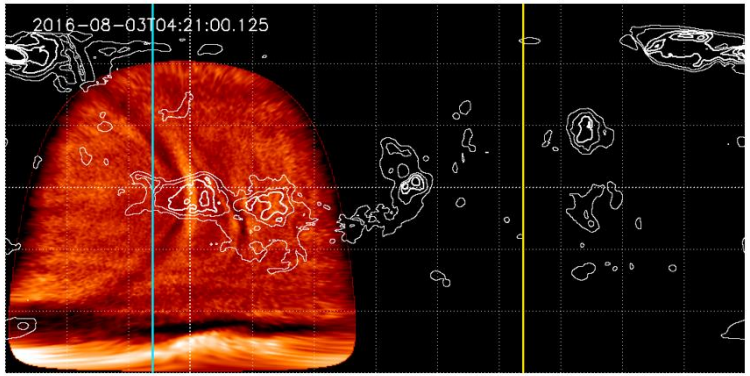
~5 Venus years (224 Earth days)
or more than **10 Venus solar days** (117 Earth days)

Stationary features above Aphrodite Terra

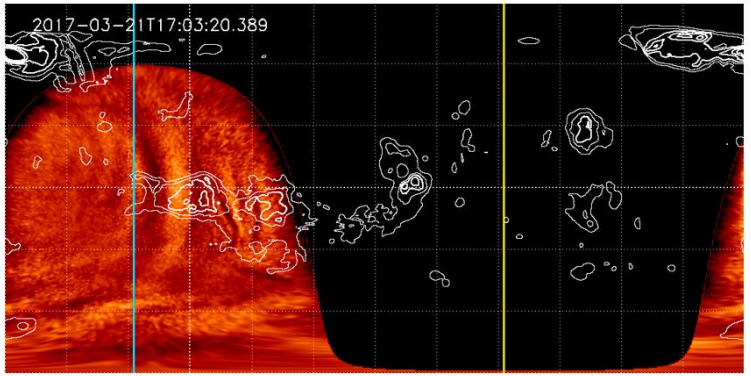
(a) 2015-12-07



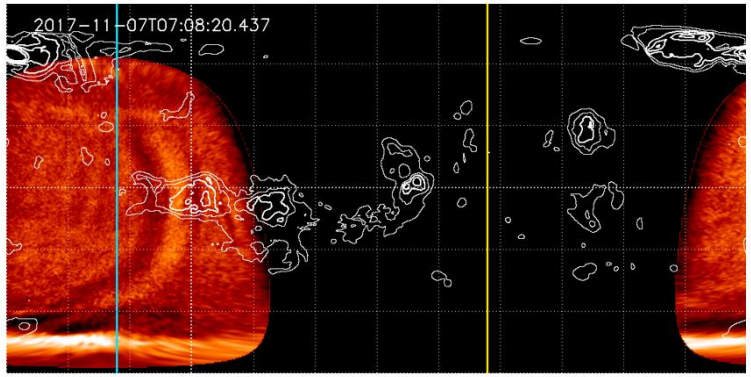
(b) 2016-08-03



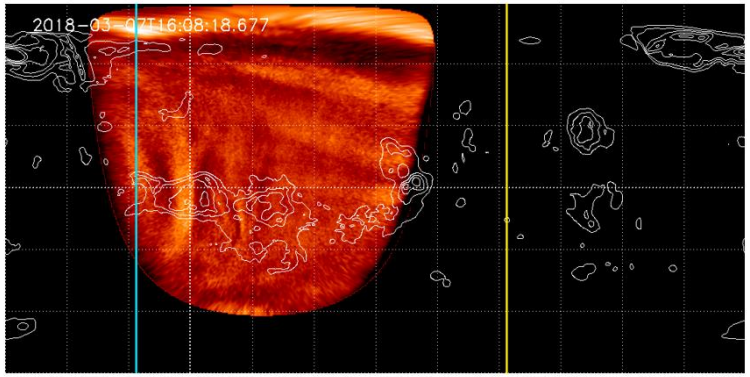
(c) 2017-03-21



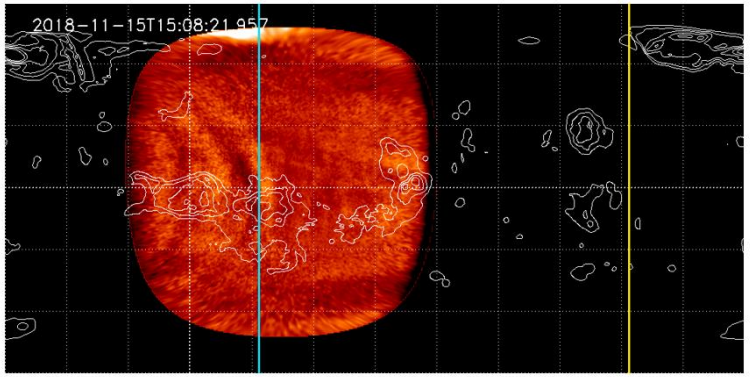
(d) 2017-11-07



(e) 2018-03-07



(f) 2018-11-15



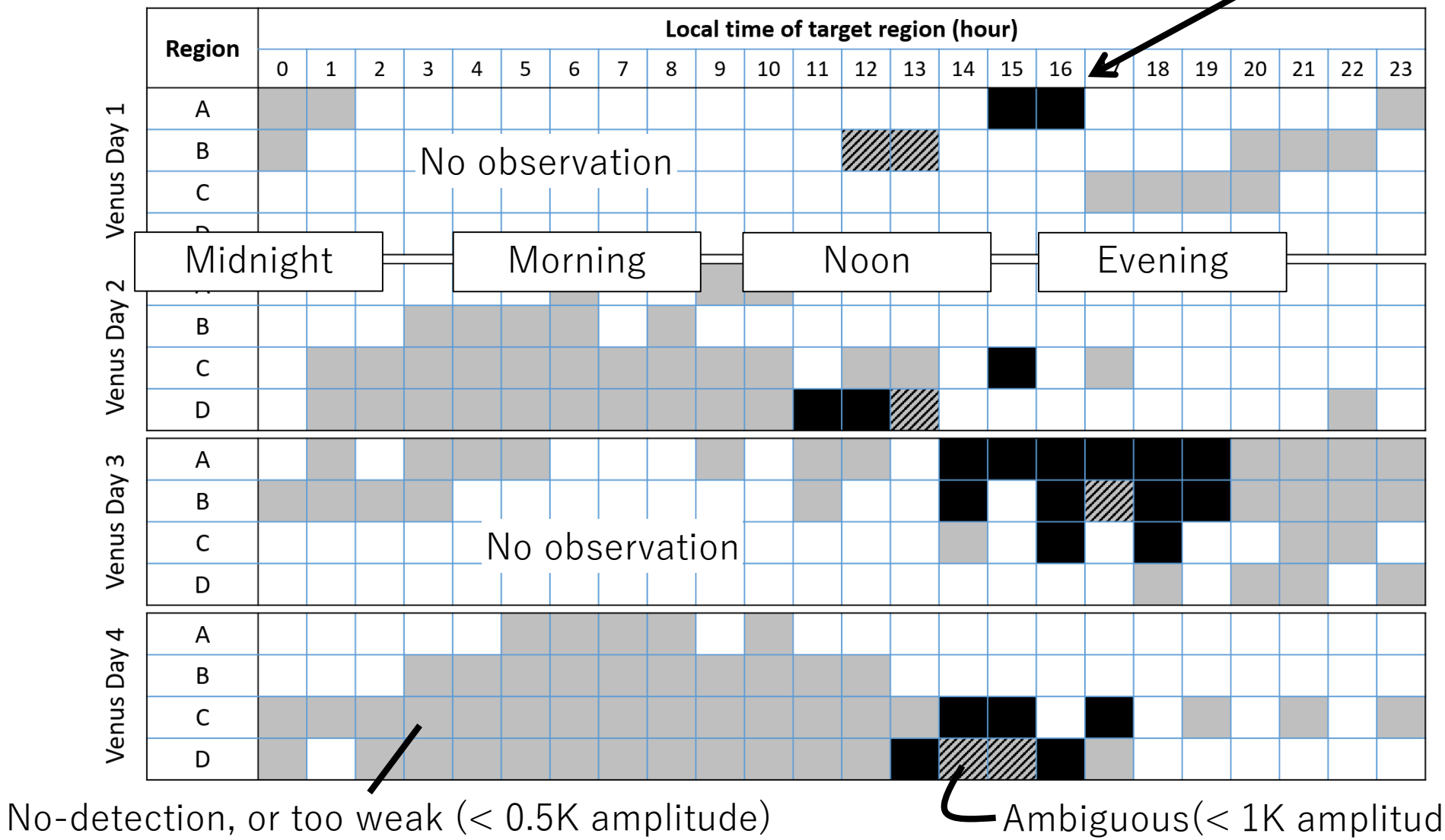
7 events were detected almost every Venusian solar day (VOI-R = 1st Venusian day)

1. 2015-12-07 (VOI-R)
2. 2016-04-02 (out of FOV)
3. 2016-07-27
4. 2016-11-22 (out of FOV)
5. 2017-03-18
6. 2017-07-13 (out of FOV)
7. 2017-11-06
8. 2018-03-04
9. 2018-06-28
10. 2018-10-23
11. 2019-02-16 (out of FOV)
(12. 2019-06-14)

Quite regular event!

Local time dependence

[Kouyama et al., 2017]

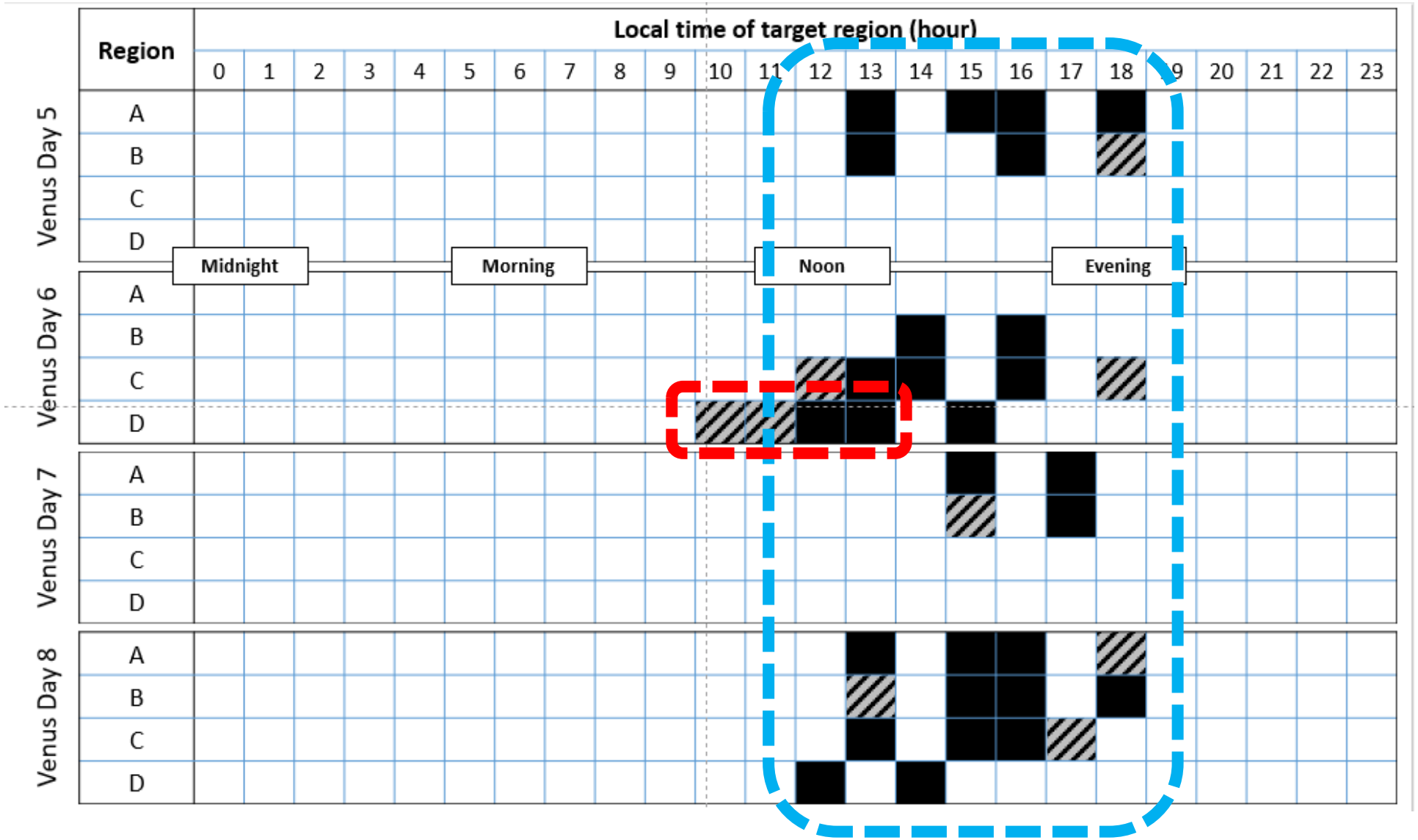


A: Aphrodite Terra (West), B: Aphrodite Terra (East), C: Atla Regio, D: Beta Regio

Local time dependence

2017/2 – 2018/4

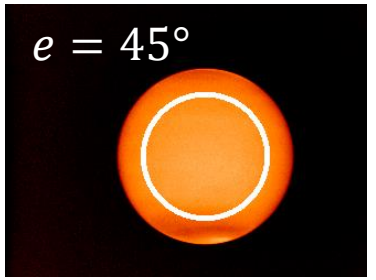
Afternoon ~ Evening

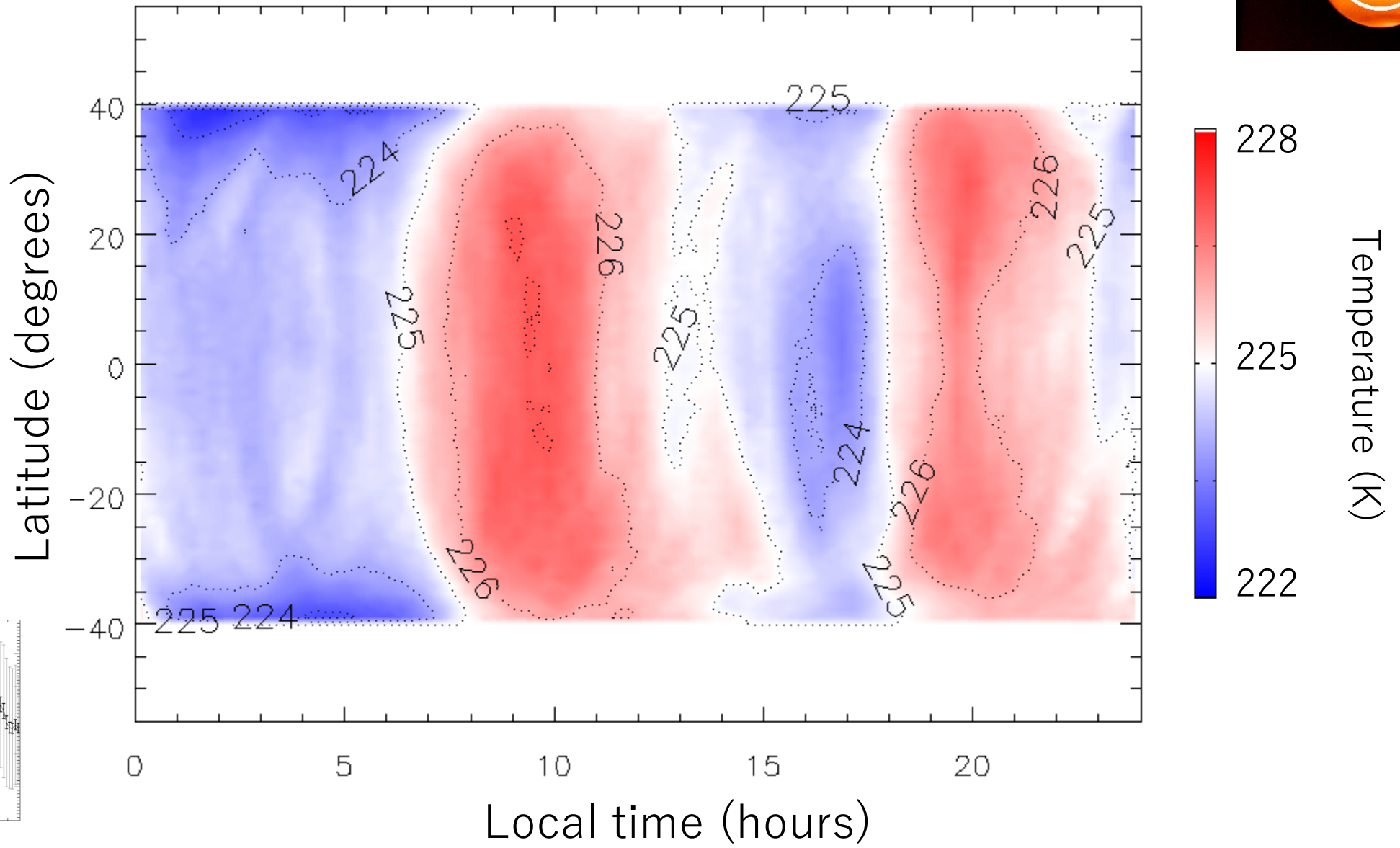


A: Aphrodite Terra (West), B: Aphrodite Terra (East), C: Atla Regio, D: Beta Regio

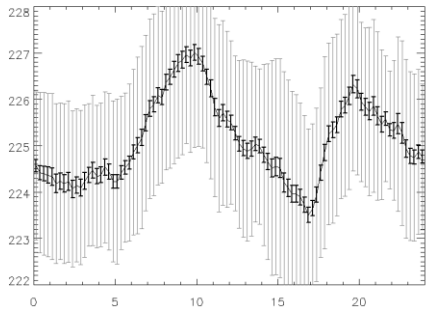
Averaged temperature: emission angle =45°

In local time-latitude (i.e. Thermal tides)



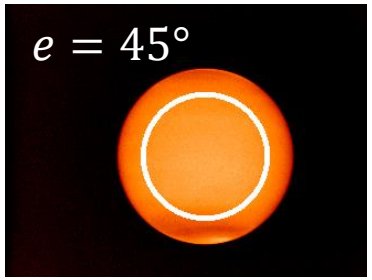


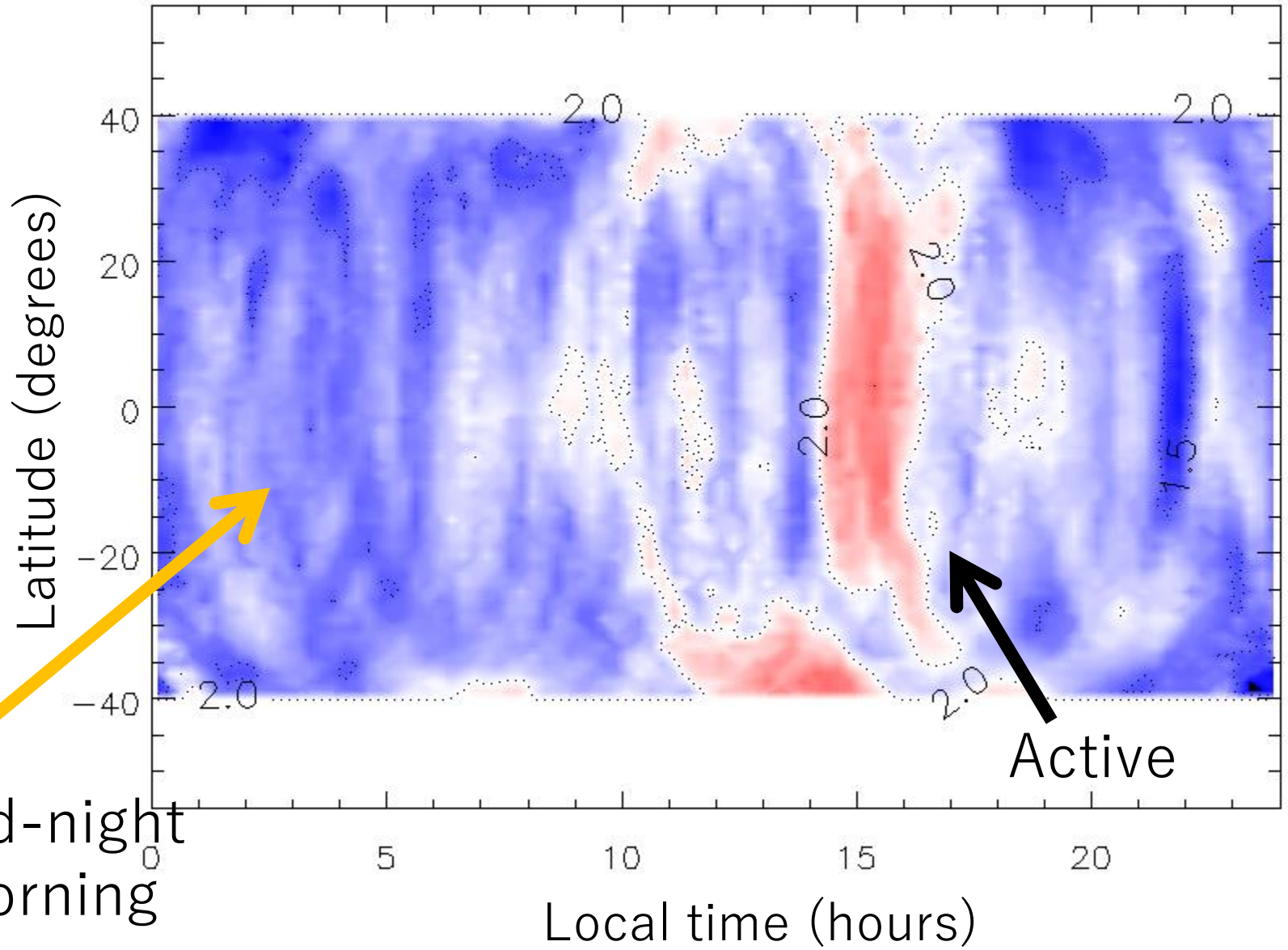
@ equator

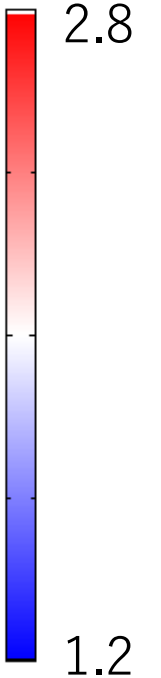


Standard deviation (= where the wave is more active)

In local time-latitude





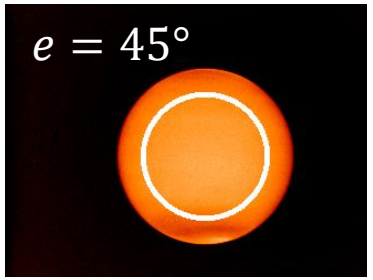


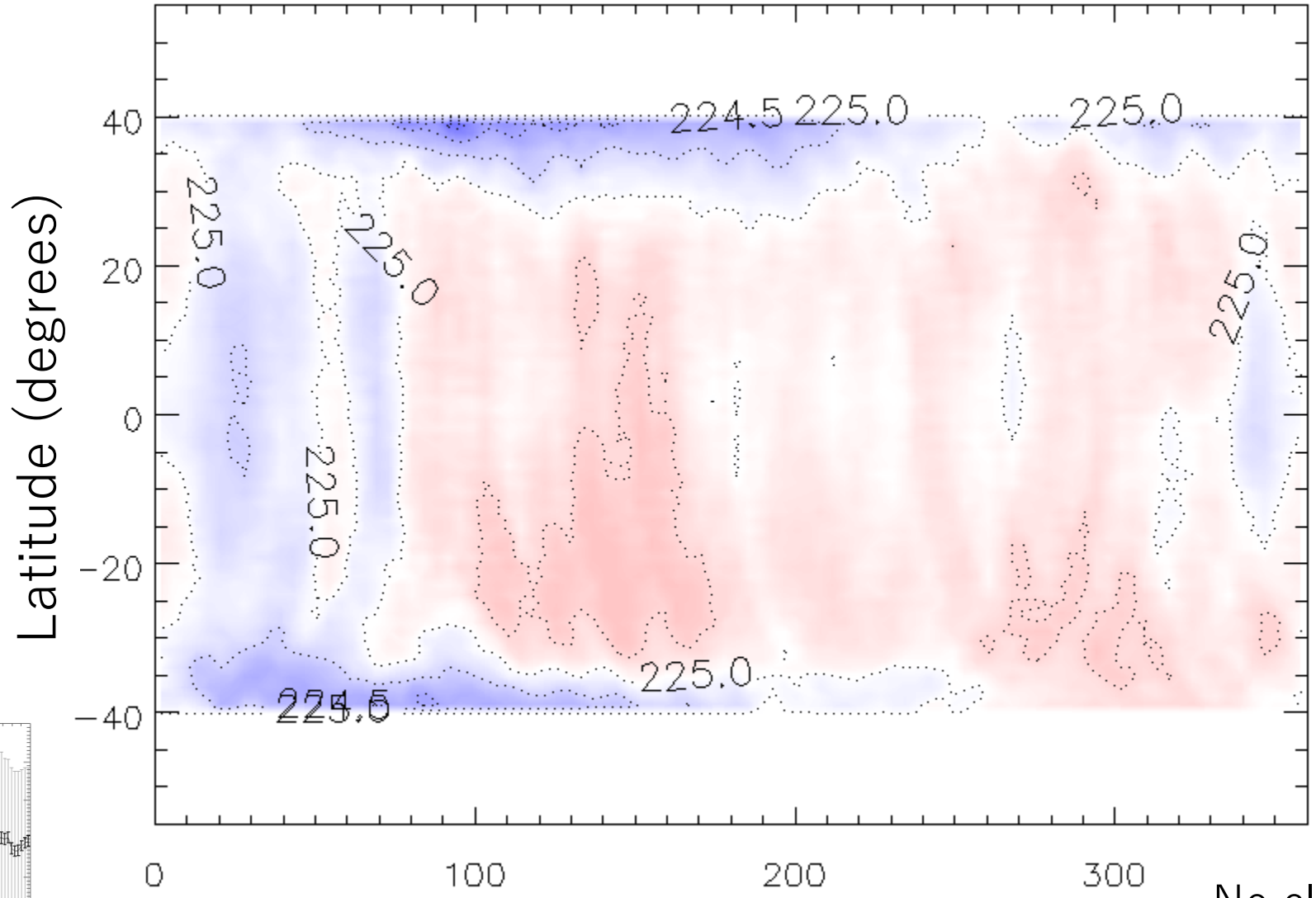
Quiet in mid-night to early morning

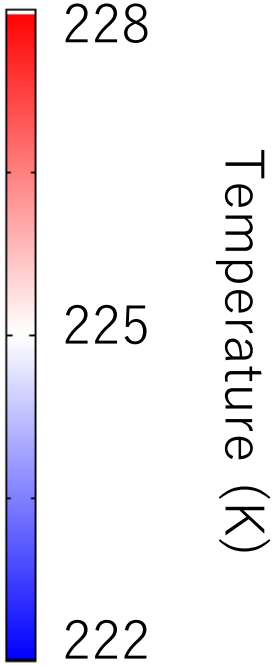
Active

Averaged temperature: emission angle =45°

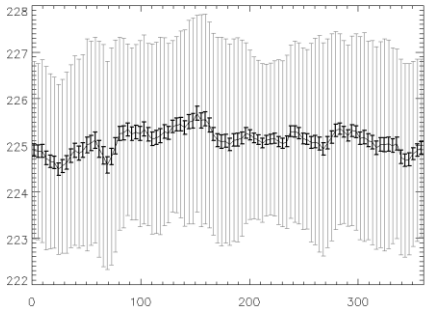
In longitude-latitude (i.e. Topography dependence)







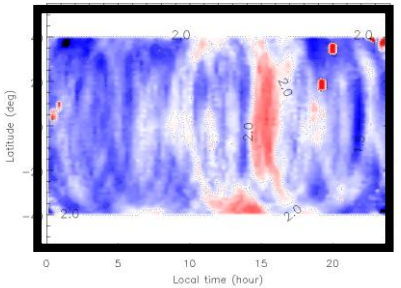
@ equator



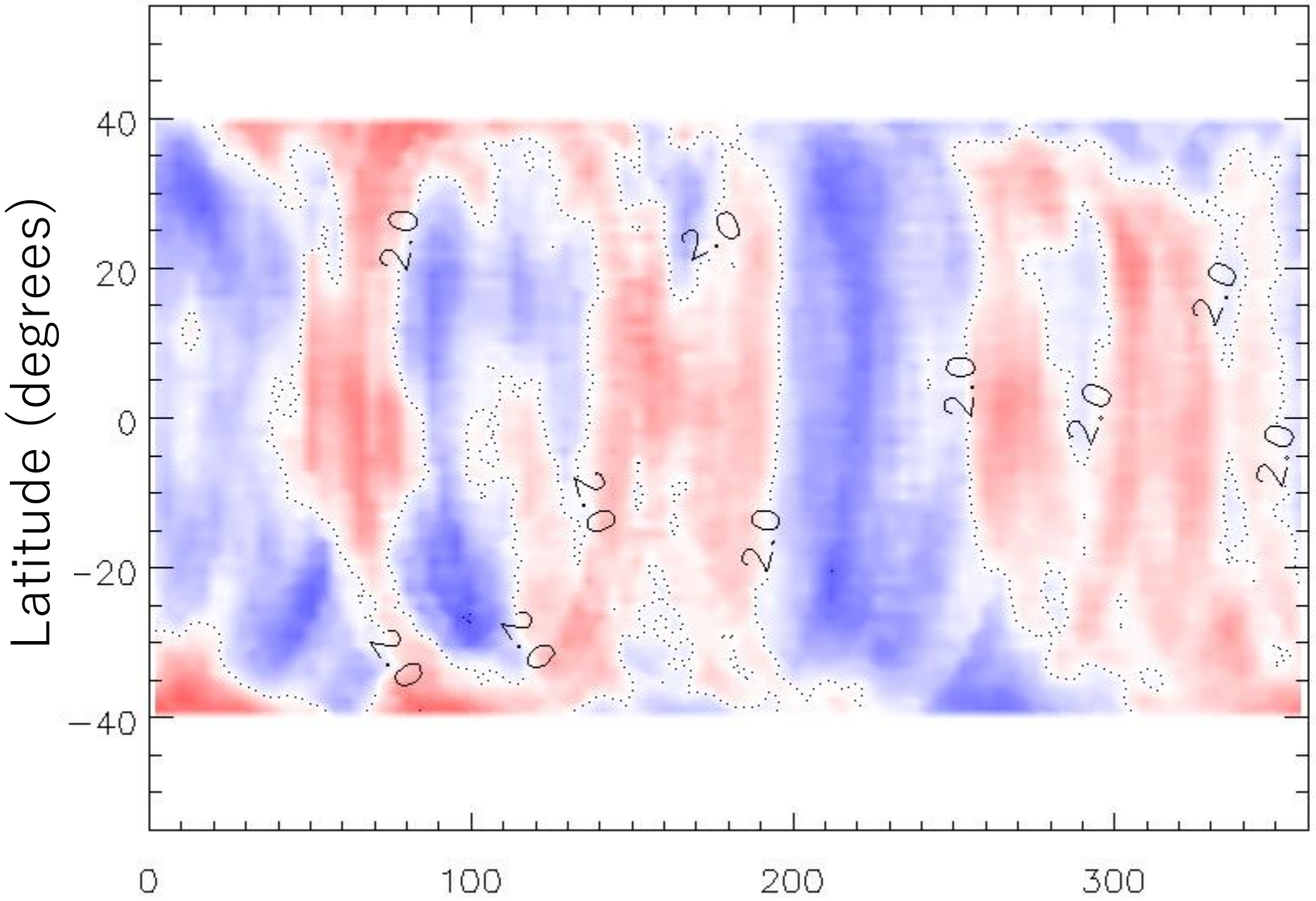
No clear topographical dependence

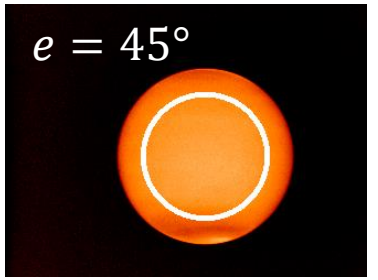
Standard deviation (= where the wave is more active)

In longitude-latitude (i.e. Topography dependence)



Local time
0 – 24 h

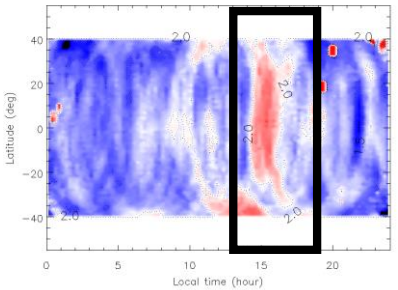




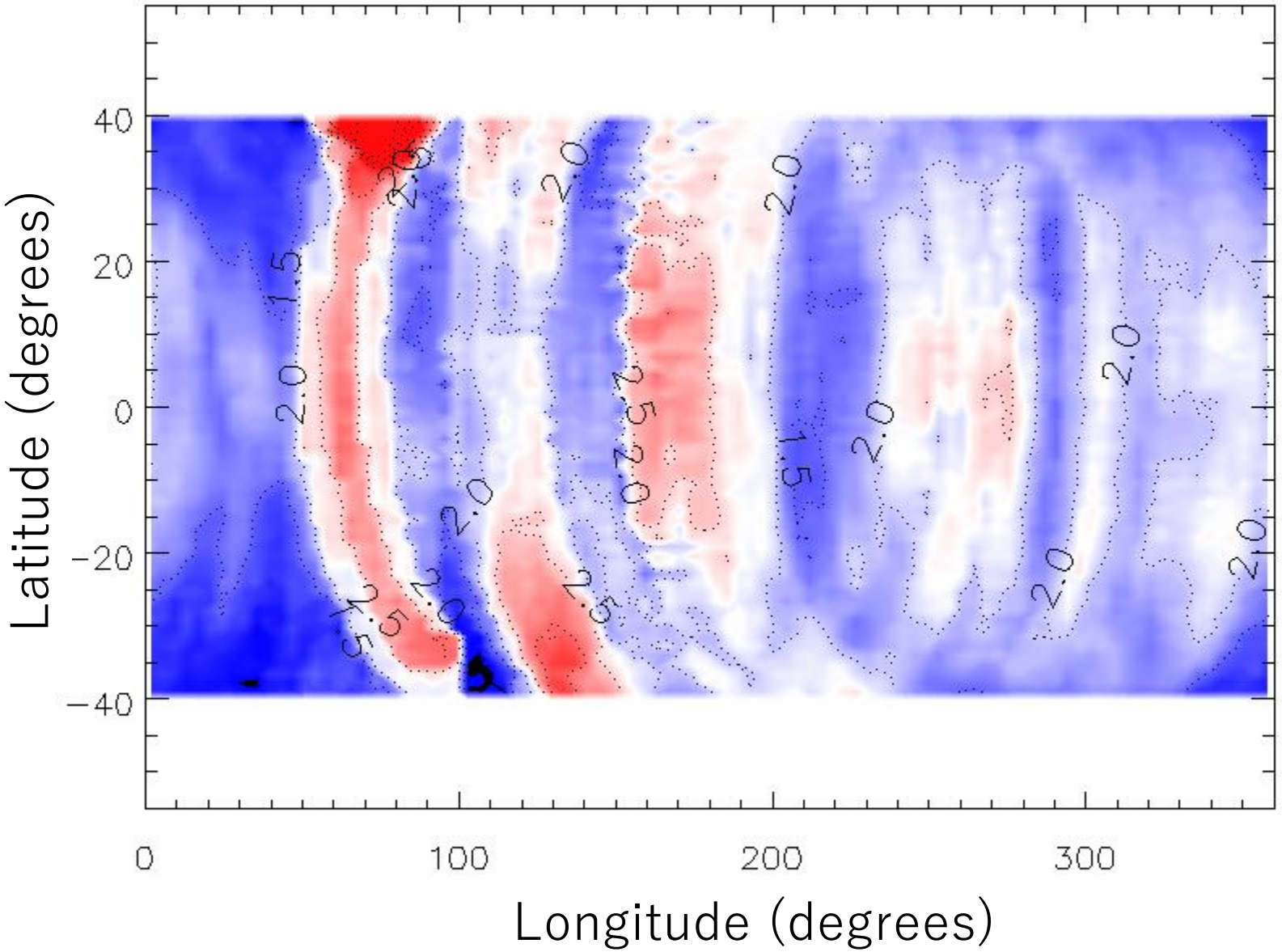
Thermal-tide components contaminate?

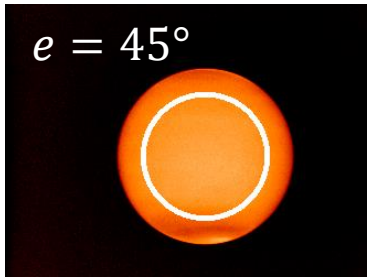
Standard deviation (= where the wave is more active)

In longitude-latitude (i.e. Topography dependence)



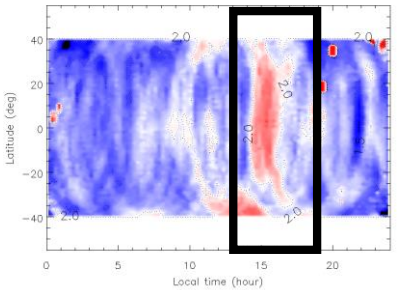
Local time
13 – 19 h



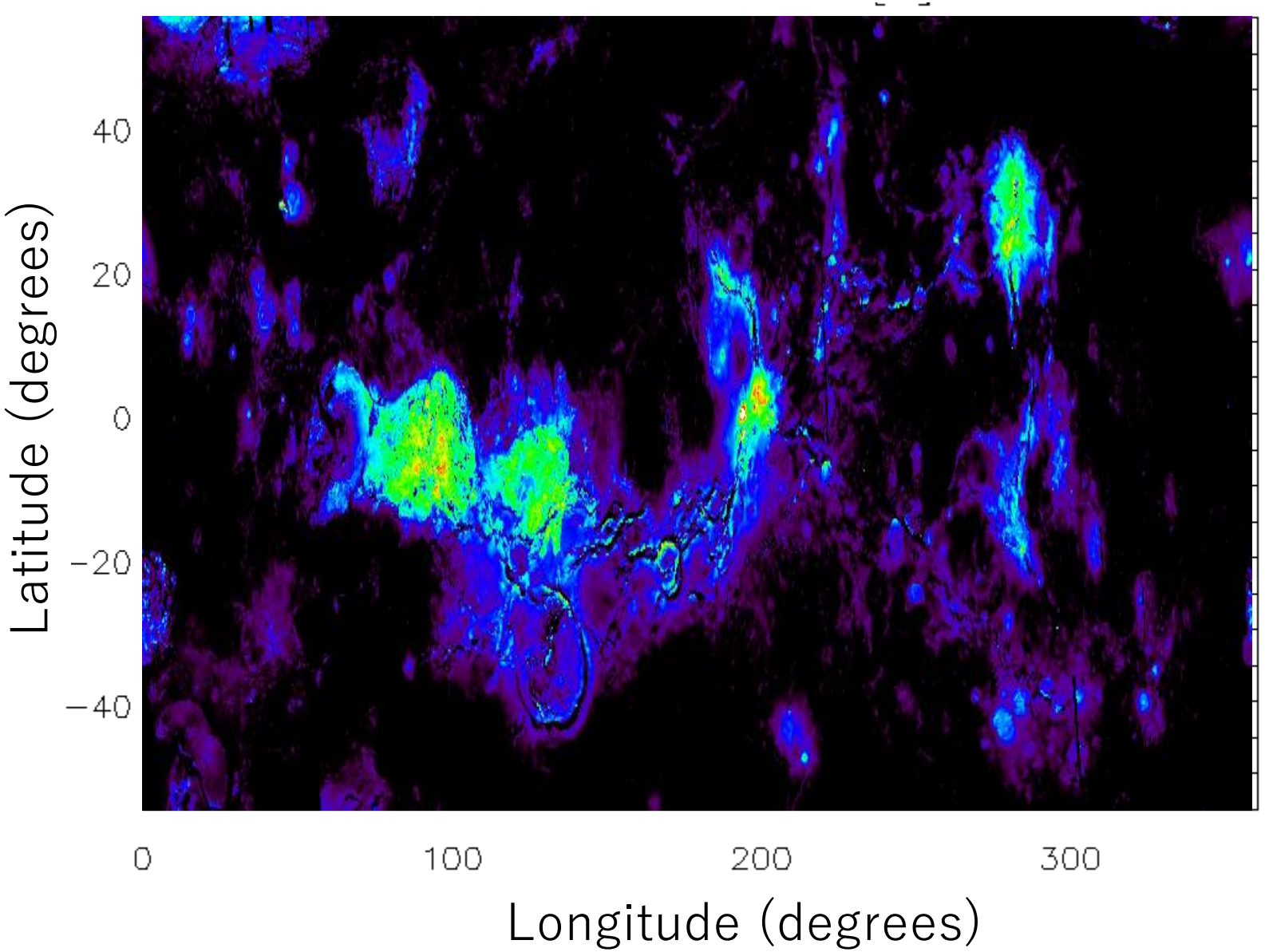


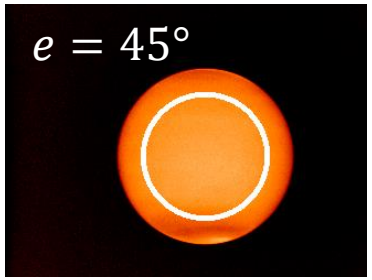
Standard deviation (= where the wave is more active)

In longitude-latitude (i.e. Topography dependence)



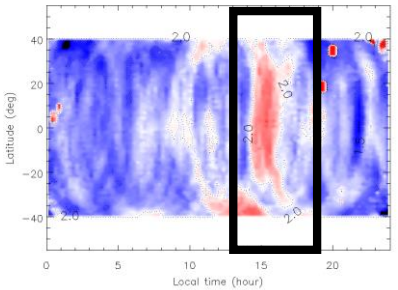
Local time
13 – 19 h



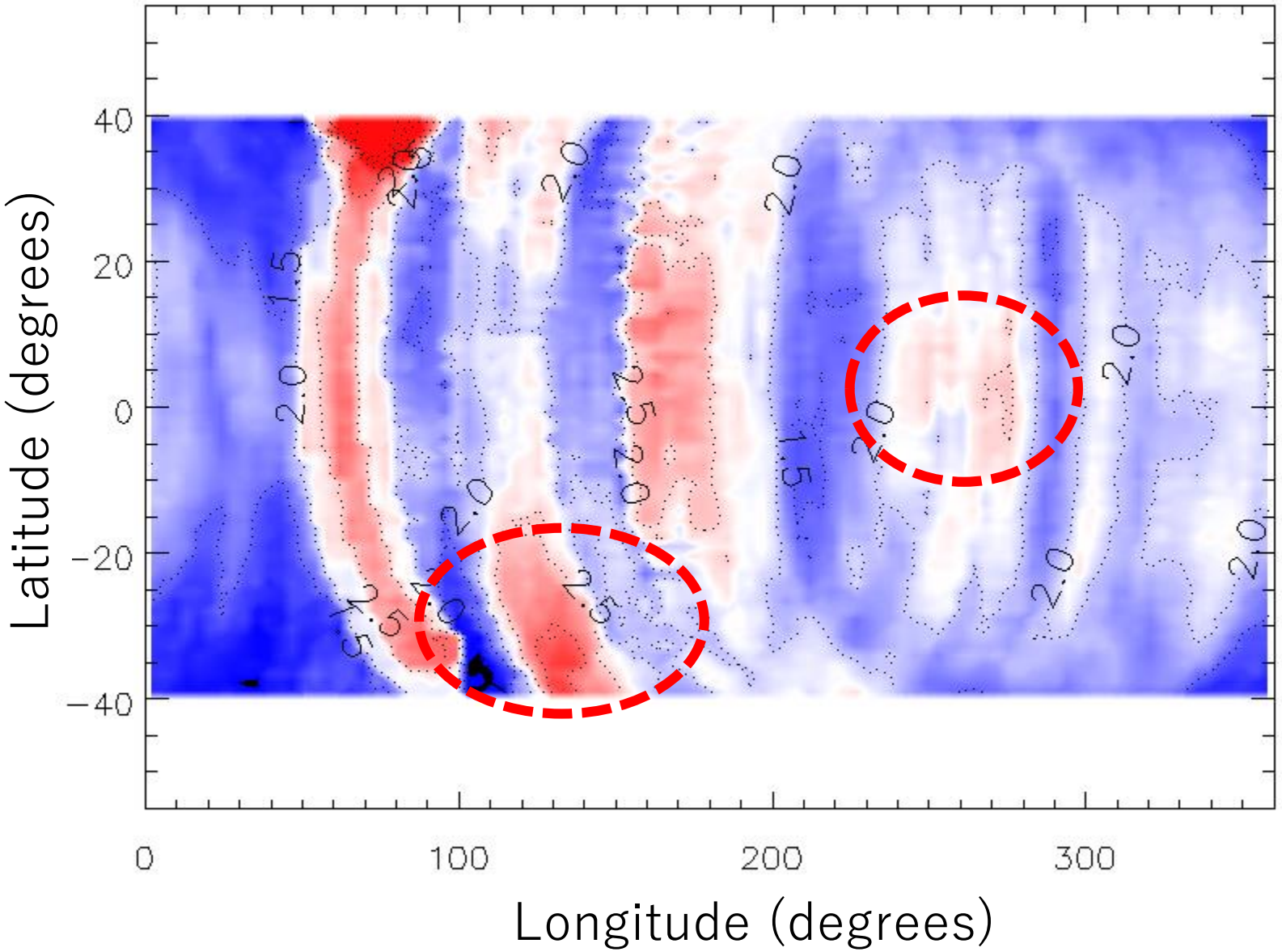


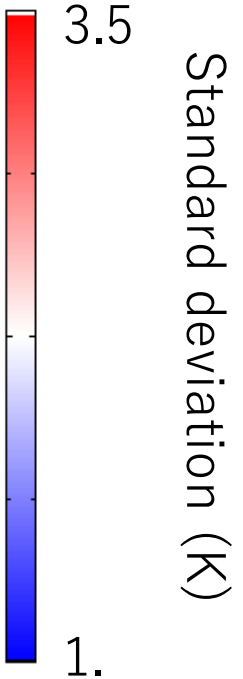
Standard deviation (= where the wave is more active)

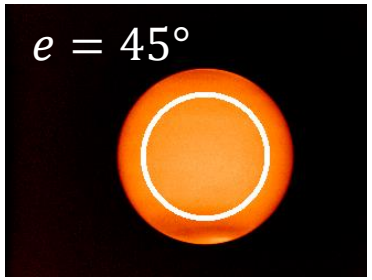
In longitude-latitude (i.e. Topography dependence)



Local time
13 – 19 h







Small but many stationary features (from Fukuya's study, P50)

Averaging several images
taken within a short period
to enhance S/N ratio

Smaller features are clearly identified

Wavelength: 500-1500km
Amplitude: > 1.5K
No detection at high latitudes (< 40 deg)

Summary & Discussion

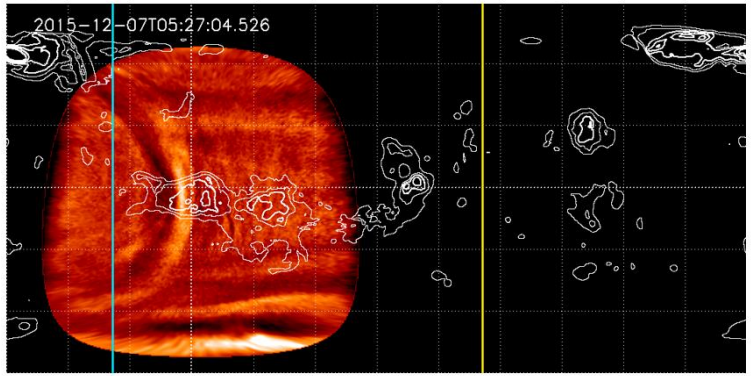
- Many large stationary waves have been confirmed, and their appearances are quite regular.
  => We can predict when they will appear in advance.
  (Today: Aphrodite Terra)

- The large stationary waves appeared above **huge highlands in low latitudes**, while the wave has not been confirmed above Maxwell Mons (60°N).
- The stationary waves showed **clear local time dependence.**

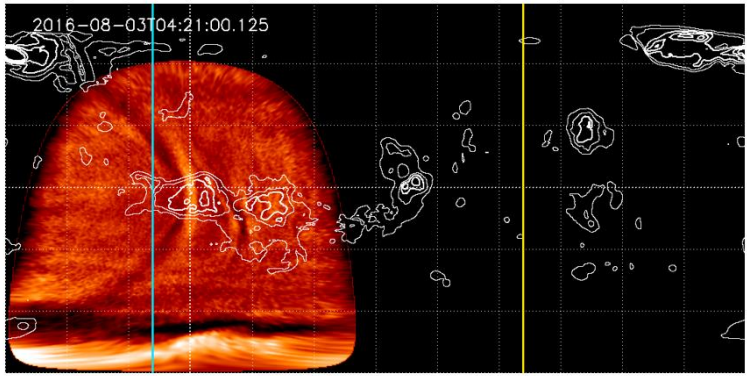
- From Fukuya's study, much smaller stationary features have been identified above even small highlands/peaks (as reported in Peralta et al, 2017).

Stationary features above Aphrodite Terra

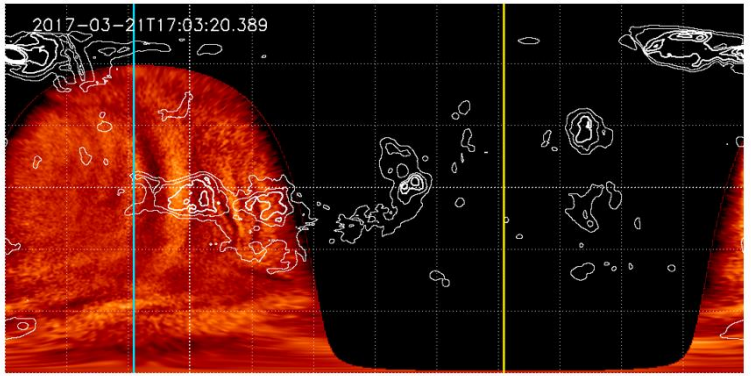
(a) 2015-12-07



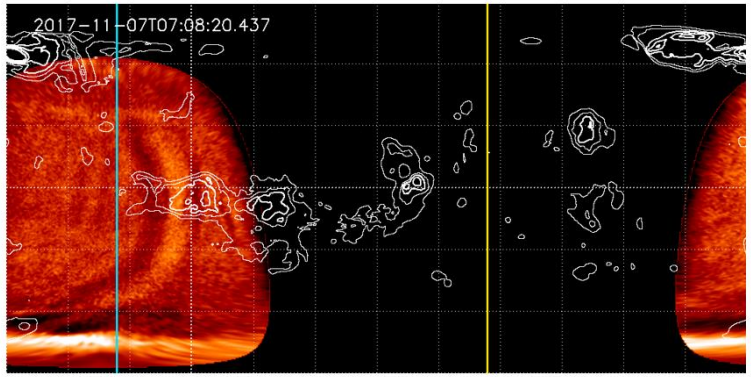
(b) 2016-08-03



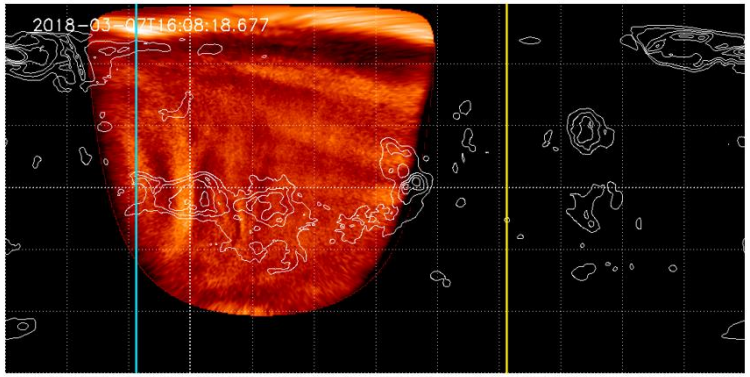
(c) 2017-03-21



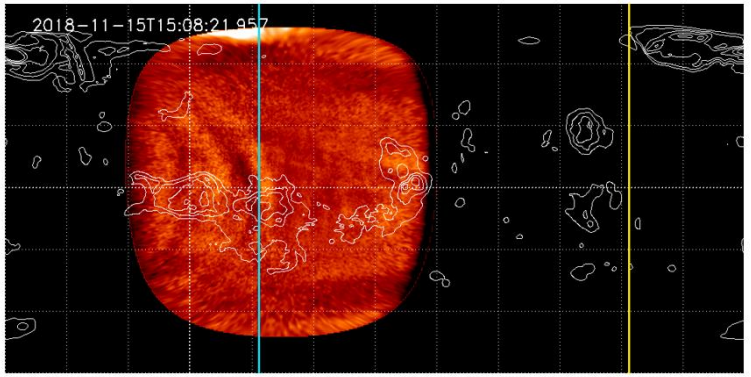
(d) 2017-11-07



(e) 2018-03-07



(f) 2018-11-15

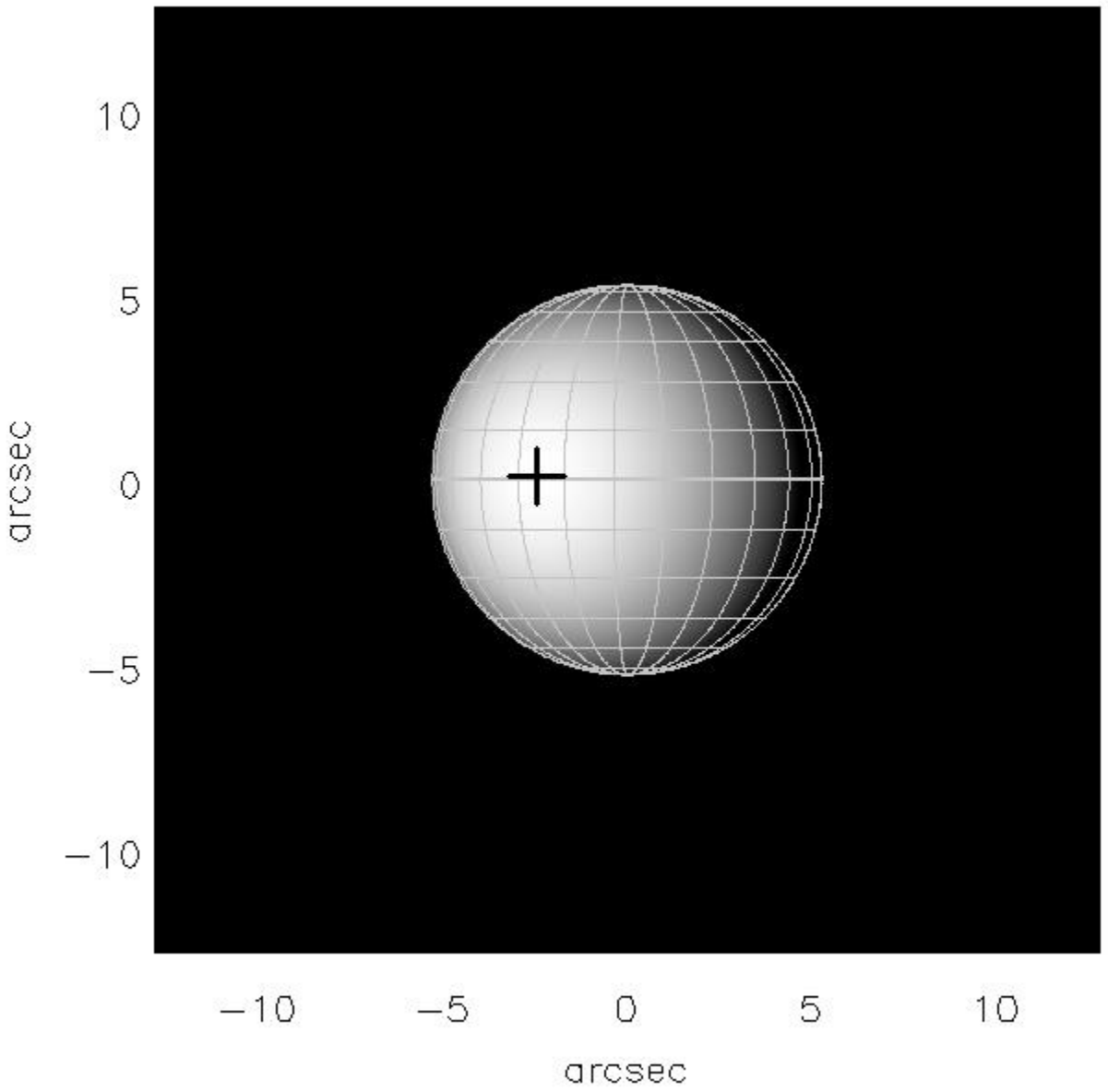


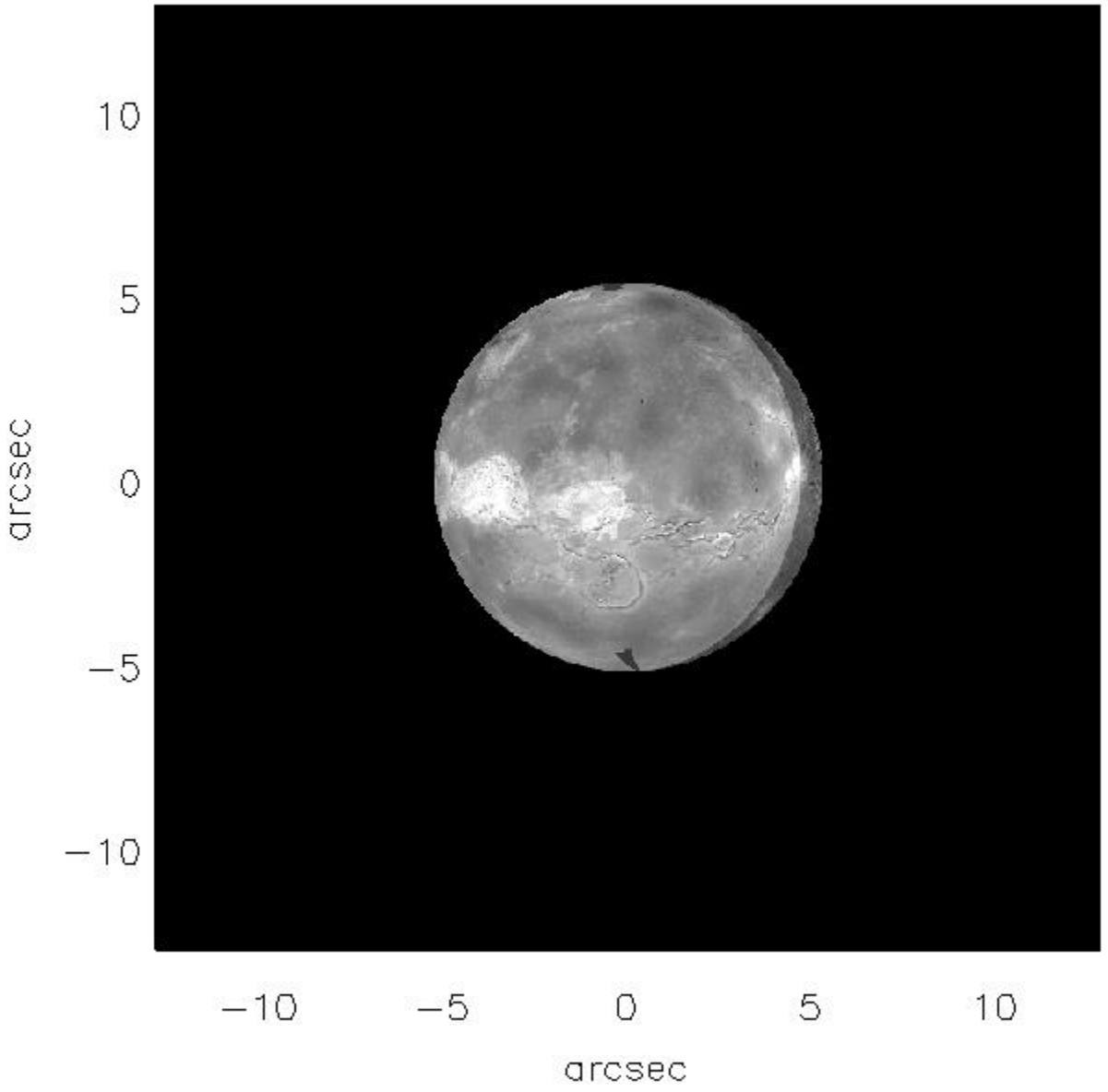
Detected Venusian Solar day (VOI-R = 1st day)

1. 2015-12-07 (VOI-R)
2. 2016-04-02
3. 2016-07-27
4. 2016-11-22
5. 2017-03-18
6. 2017-07-13
7. 2017-11-06
8. 2018-03-04
9. 2018-06-28
10. 2018-10-23
11. 2019-02-16
12. **2019-06-14**
13. 2019-10-08
14. 2020-02-02
15. 2020-05-28
16. 2020-09-23
17. 2021-01-17
18. 2021-05-14
19. 2021-09-07
20. 2022-01-03

Today's Venus (seen from Earth)

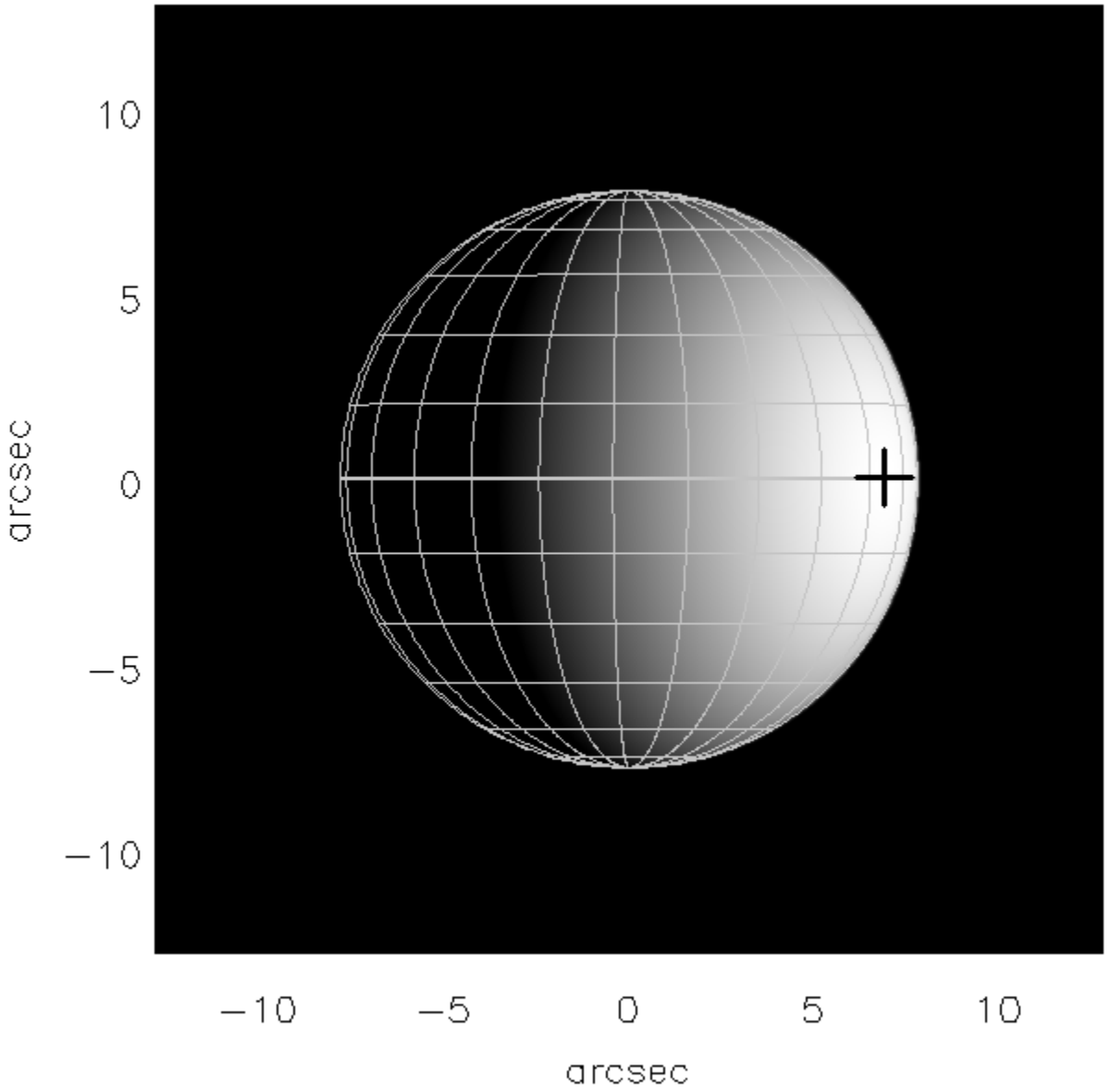
2019-06-04T00:00:00 (UTC)

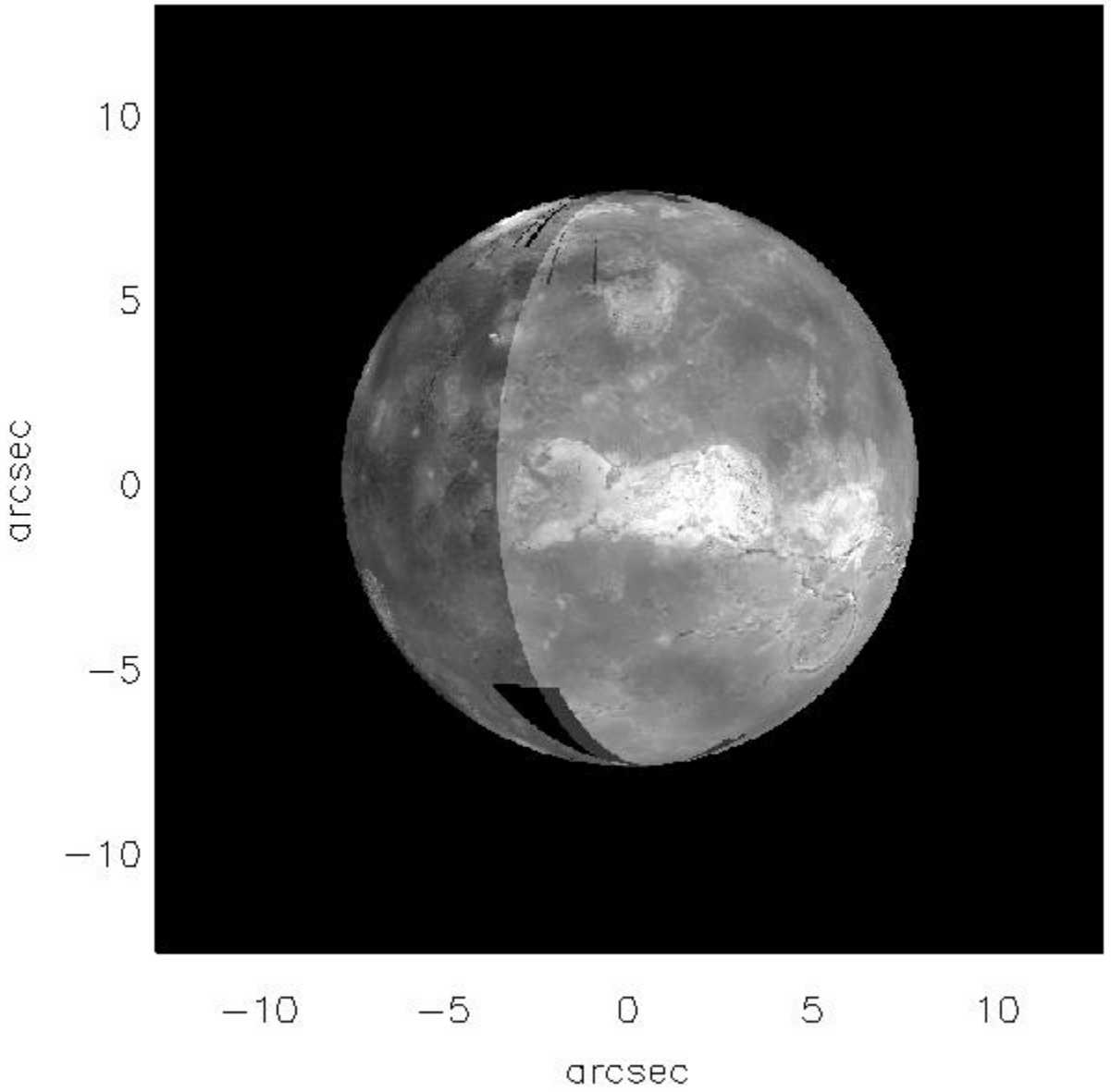




Venus (seen from Earth)

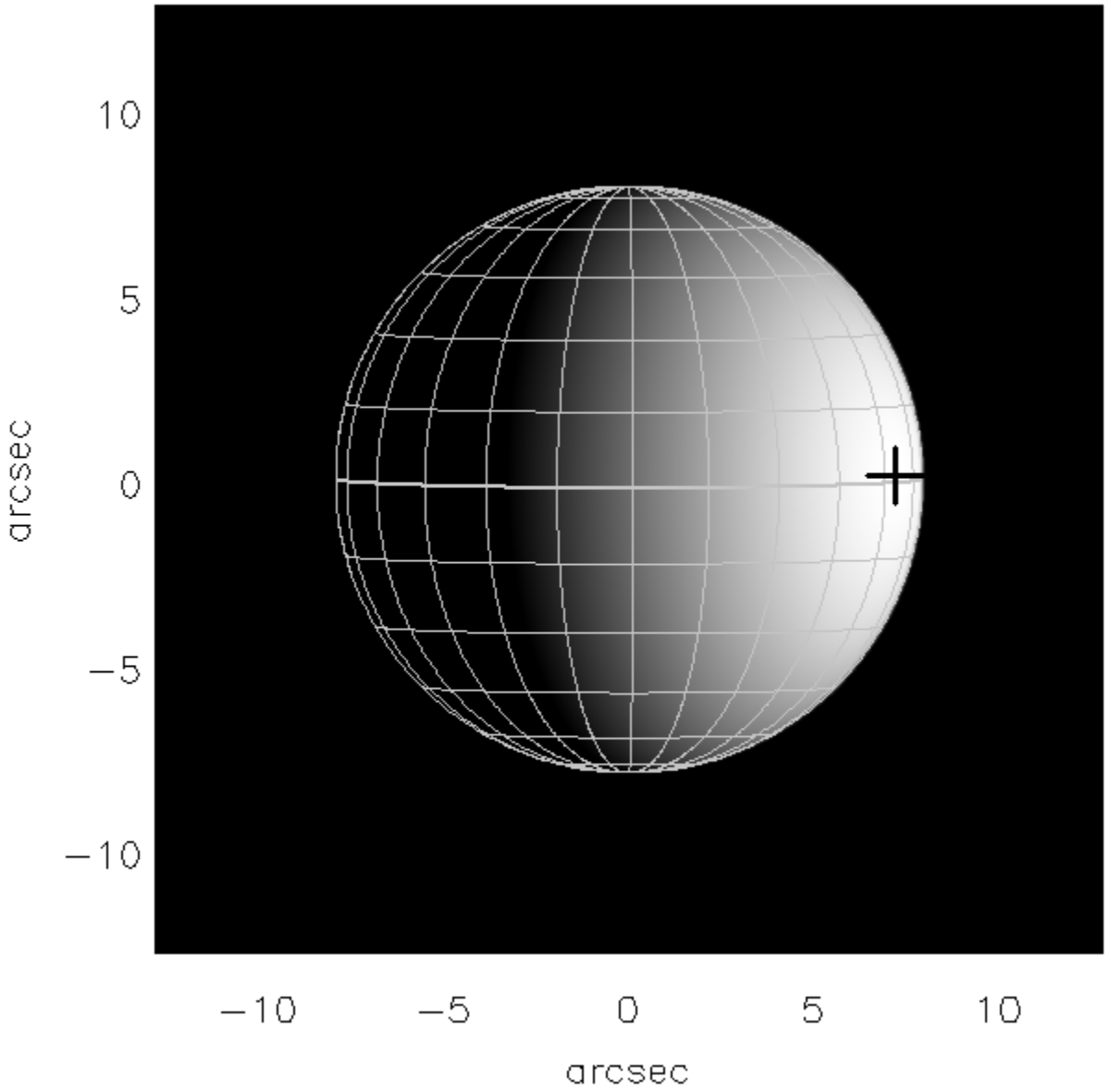
2020-02-02T00:00:00 (UTC)

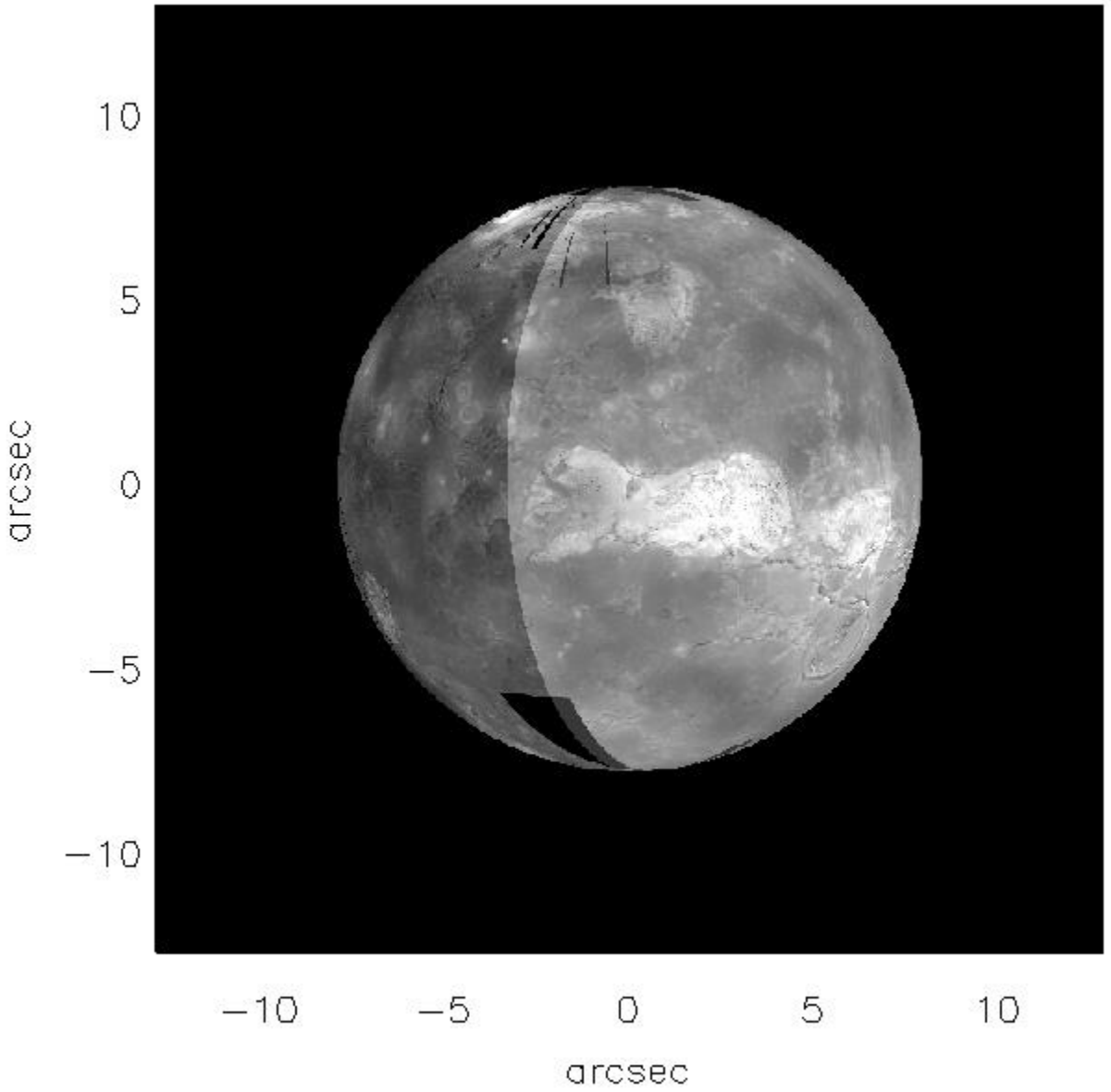




Venus (seen from Earth)

2021-09-07T00:00:00 (UTC)





Aphrodite Terra (west)	Atla Regio	Beta Regio	
1 2015-12-07	1 2016-01-10	1 2016-02-08	
2 2016-04-02	2 2016-05-06	2 2016-06-04	
3 2016-07-27	3 2016-08-30	3 2016-09-29	
4 2016-11-22	4 2016-12-26	4 2017-01-24	
5 2017-03-18	5 2017-04-21	5 2017-05-20	
6 2017-07-13	6 2017-08-16	6 2017-09-14	
7 2017-11-06	7 2017-12-10	7 2018-01-09	
8 2018-03-04	8 2018-04-07	8 2018-05-06	Released
9 2018-06-28	9 2018-08-01	9 2018-08-30	
10 2018-10-23	10 2018-11-26	10 2018-12-25	
11 2019-02-16	11 2019-03-23	11 2019-04-21	
12 2019-06-14	12 2019-07-18	12 2019-08-16	
13 2019-10-08	13 2019-11-11	13 2019-12-10	
14 2020-02-02	14 2020-03-07	14 2020-04-05	
15 2020-05-28	15 2020-07-02	15 2020-07-31	
16 2020-09-23	16 2020-10-26	16 2020-11-24	
17 2021-01-17	17 2021-02-20	17 2021-03-22	
18 2021-05-14	18 2021-06-17	18 2021-07-16	
19 2021-09-07	19 2021-10-12	19 2021-11-10	
20 2022-01-03	20 2022-02-05	20 2022-03-06	
21 2022-04-29	21 2022-06-02	21 2022-07-02	

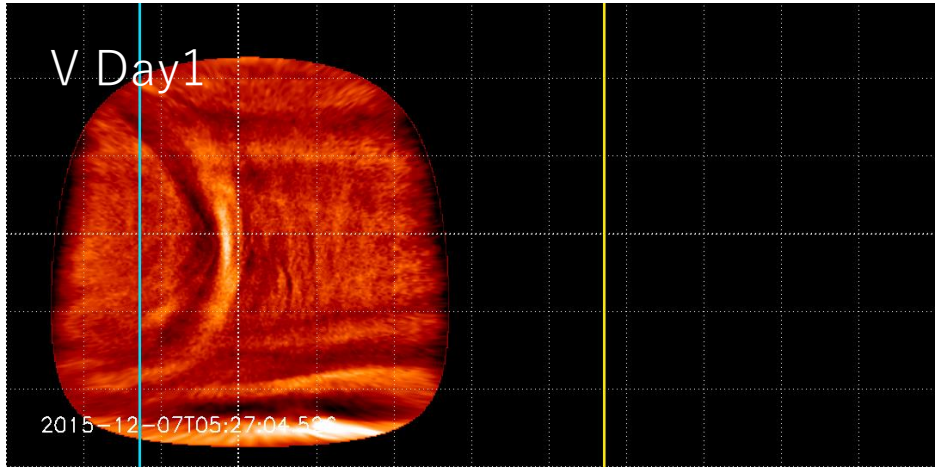
(LT = 15.5)

Backup slides

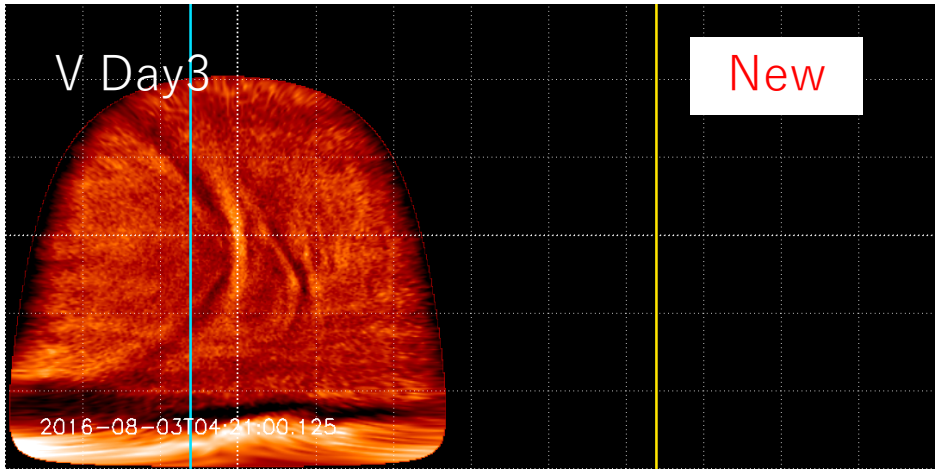
Periodically appearing

Above Aphrodite Terra

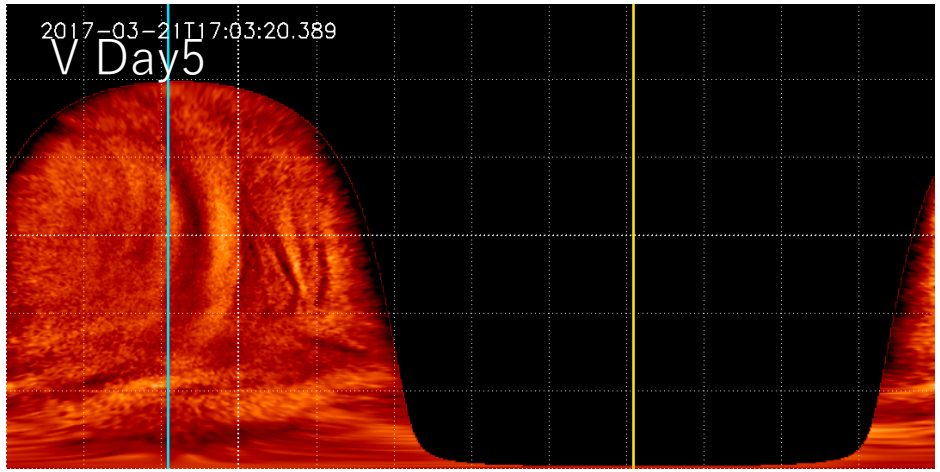
A: 2015-12-07



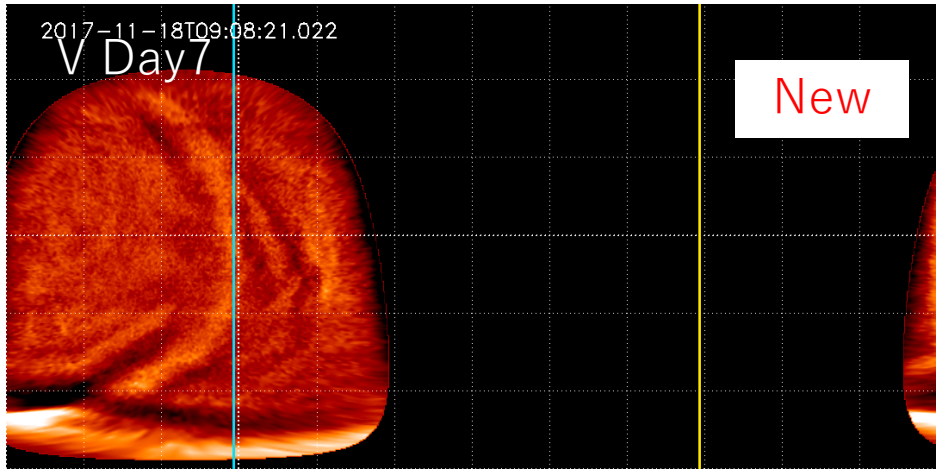
A: 2016-08-03



A: 2017-03-21



A: 2017-11-18



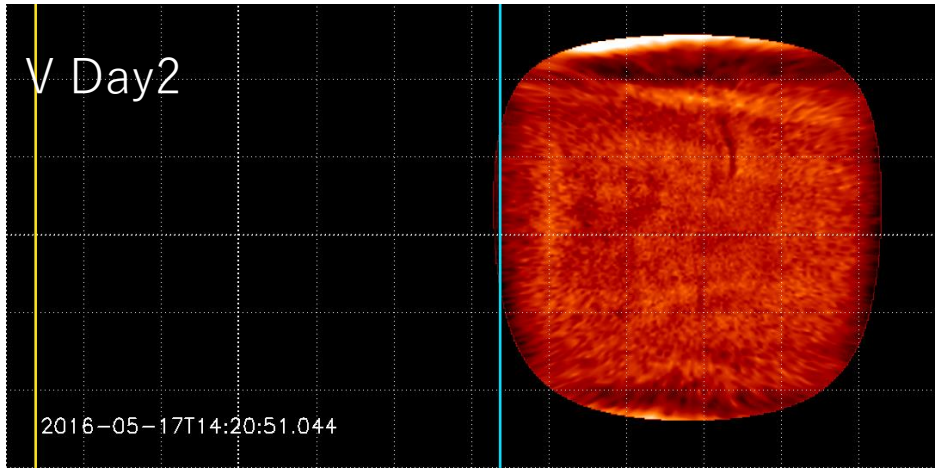
Evening

Morning

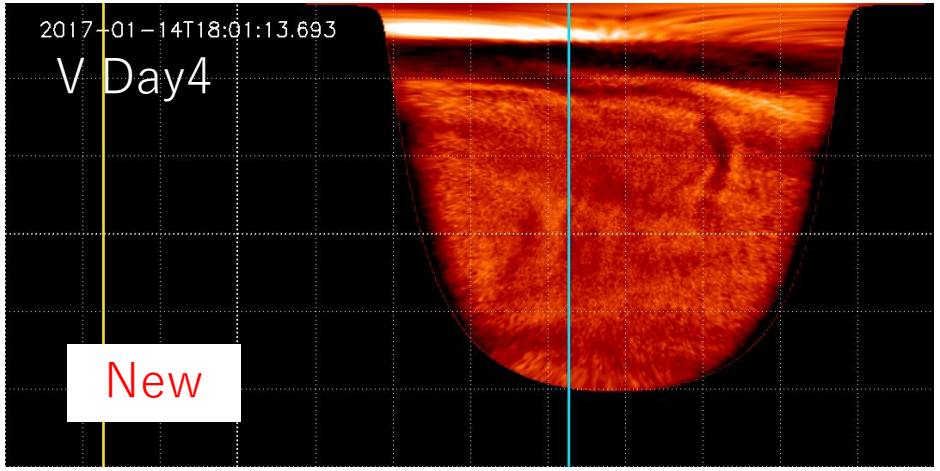
Periodically appearing

Above Beta Regio

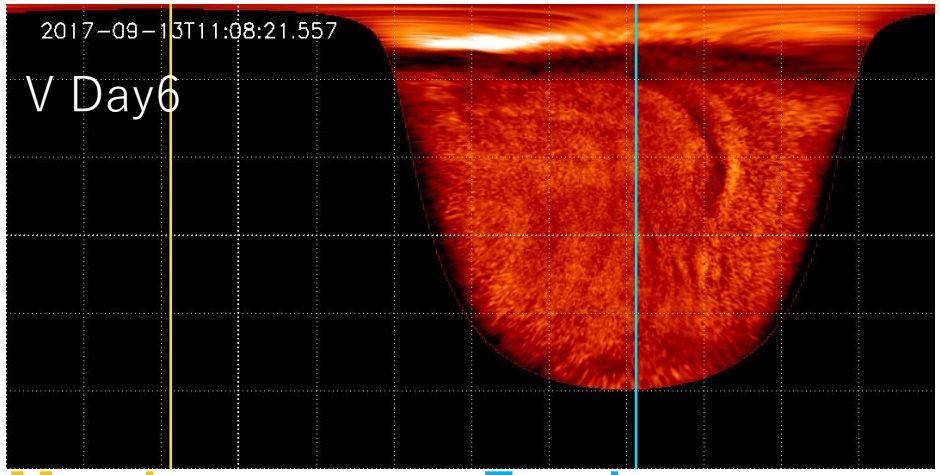
D: 2016-05-17



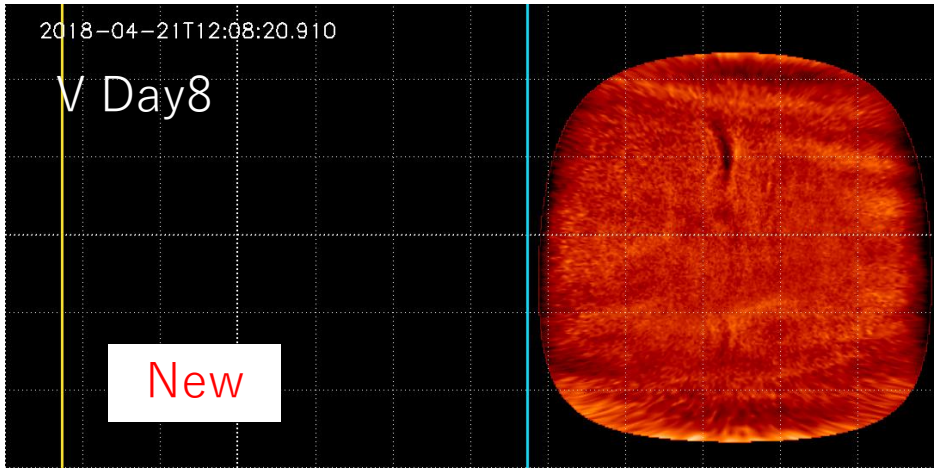
D: 2017-01-14



D: 2017-09-13



D: 2018-04-21

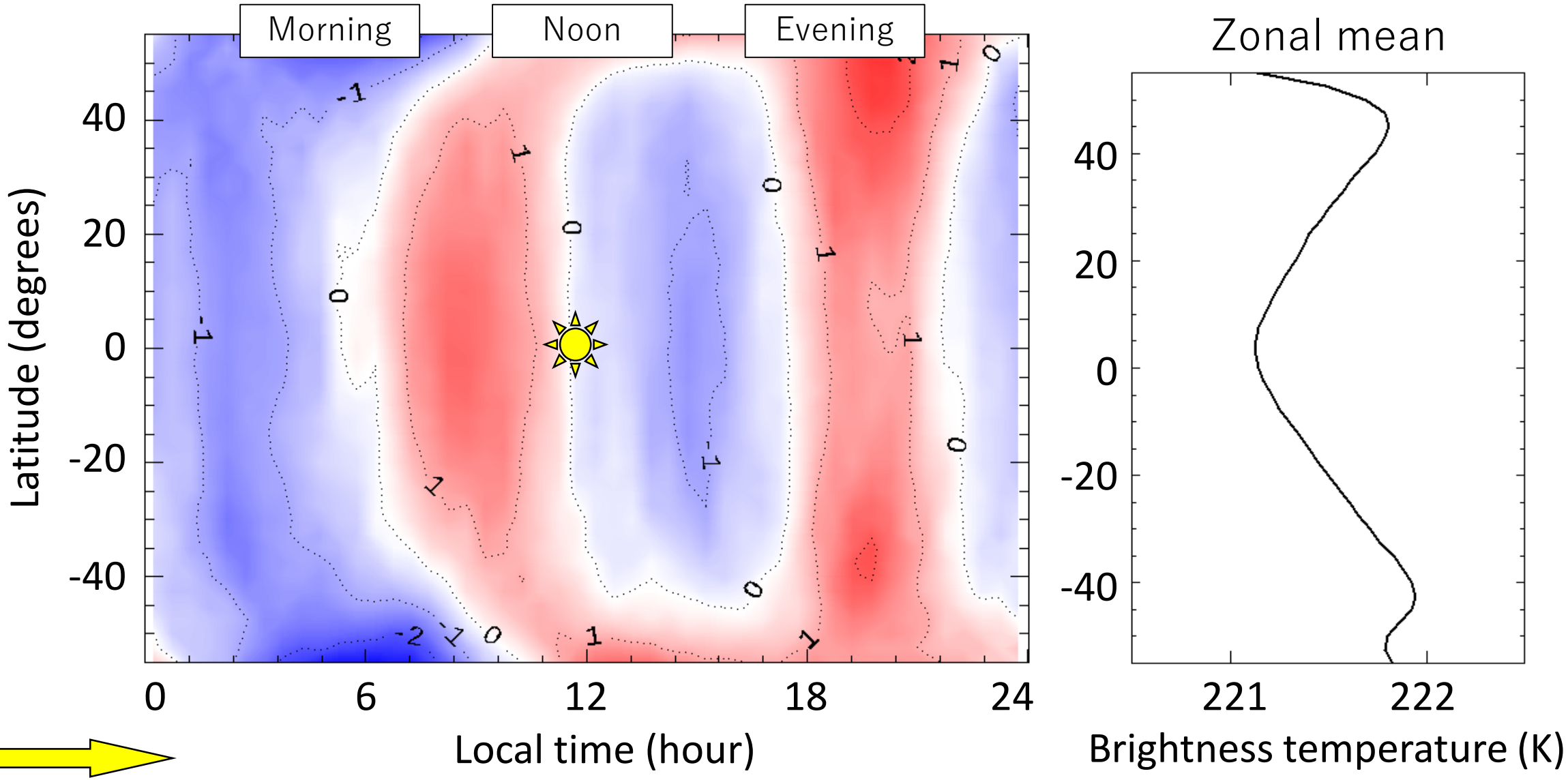


Morning

Evening

The stationary waves are quite regular events in Venus atmosphere

Tidal component (residual from zonal mean), e = **60 deg** (~69 km)



Standard error: ~0.1 K

[Kouyama et al., submitted]

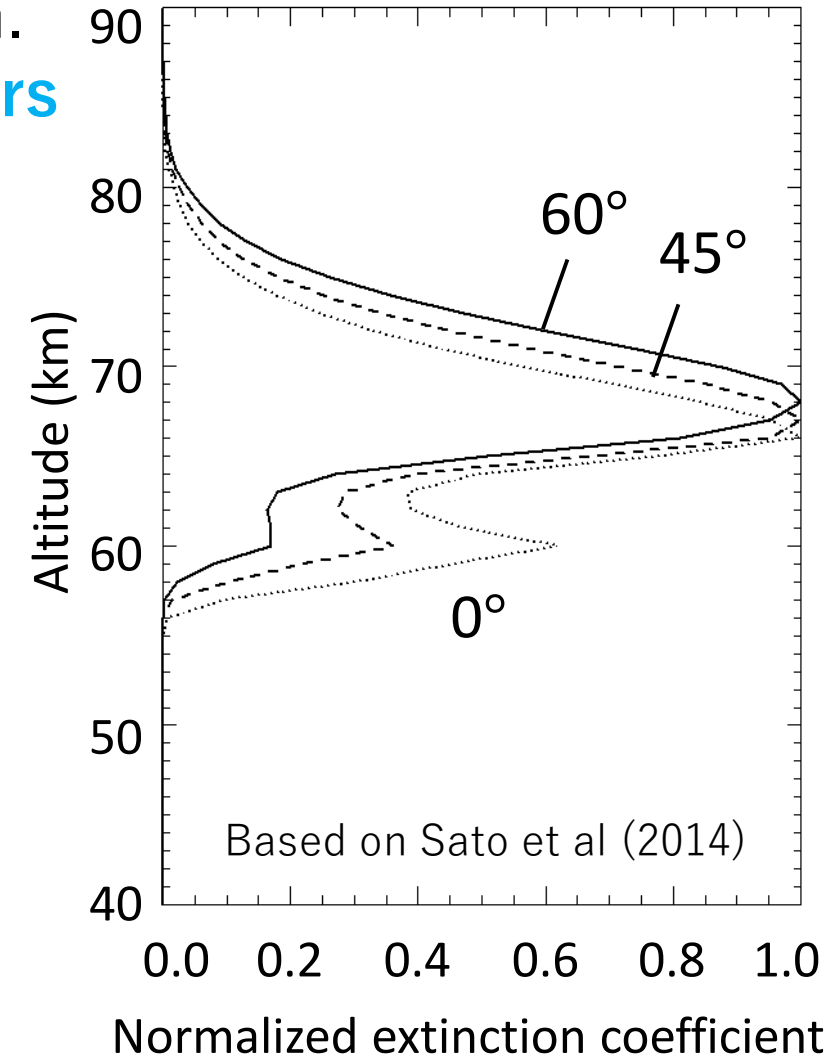
Data period and LIR's sensing altitudes

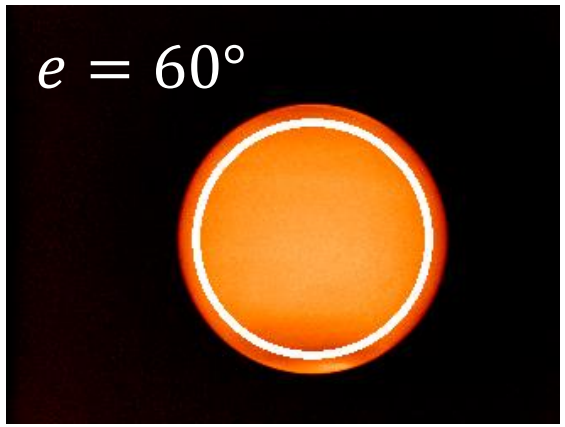
- Data period: 2016 Oct. – 2019 Jan.
  = more than **three Venusian years**
  (22,000 images)

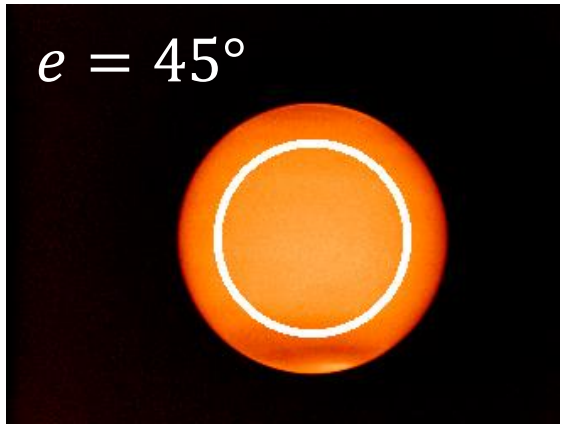
- Wavelength: 8-12 μ m
  Thermal emission

- Upper cloud layer (65-75 km)

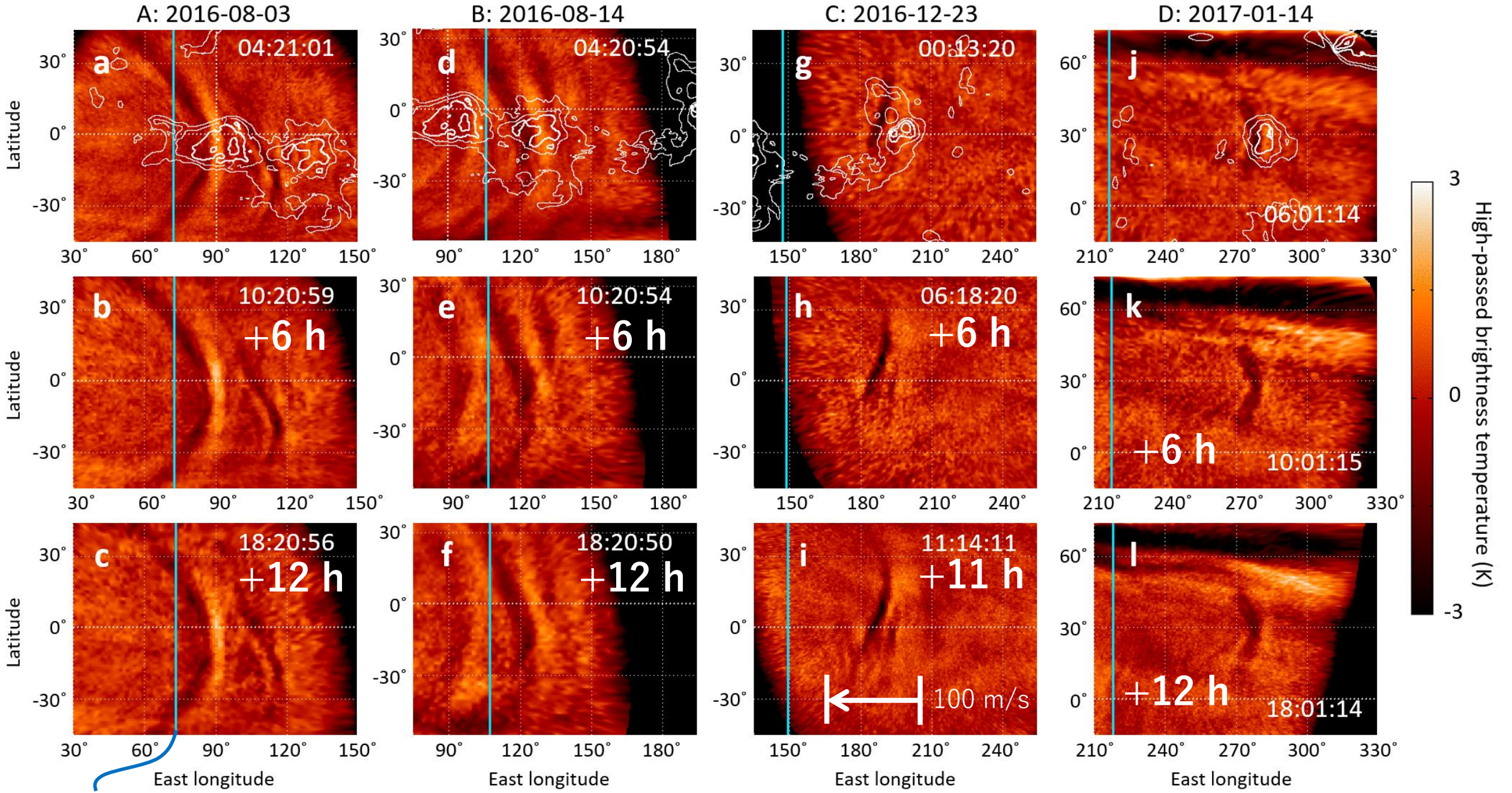
- Observing altitude
  Emission angle dependence:
  $e = 60°$: 68.9 km
  $e = 45°$: 67.3 km (1.6 km lower)
  → Vertical structure of the tides can be investigated



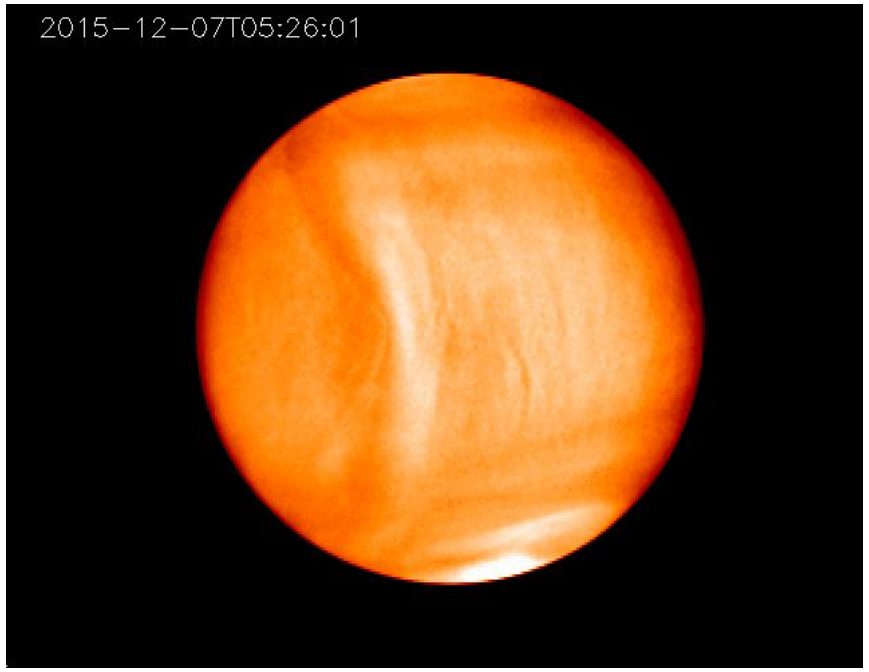




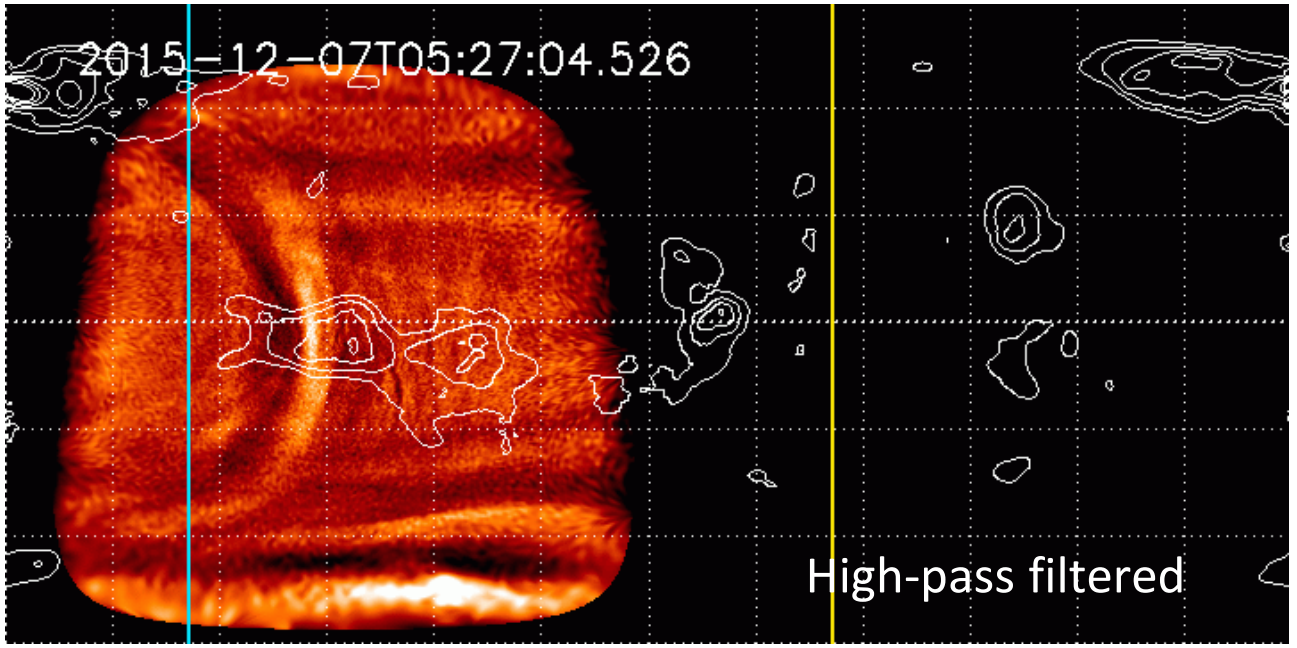
[Kouyama et al., submitted]


A: 2016-08-03
B: 2016-08-14
C: 2016-12-23
D: 2017-01-14
a
04:21:01
b
10:20:59
+6 h
c
18:20:56
+12 h
d
04:20:54
e
10:20:54
+6 h
f
18:20:50
+12 h
g
00:13:20
h
06:18:20
+6 h
i
11:14:11
+11 h
100 m/s
j
06:01:14
k
+6 h
10:01:15
l
+12 h
18:01:14
Latitude
East longitude
High-passed brightness temperature (K)
3
0
-3
Blue line: evening terminator

Stationary gravity wave



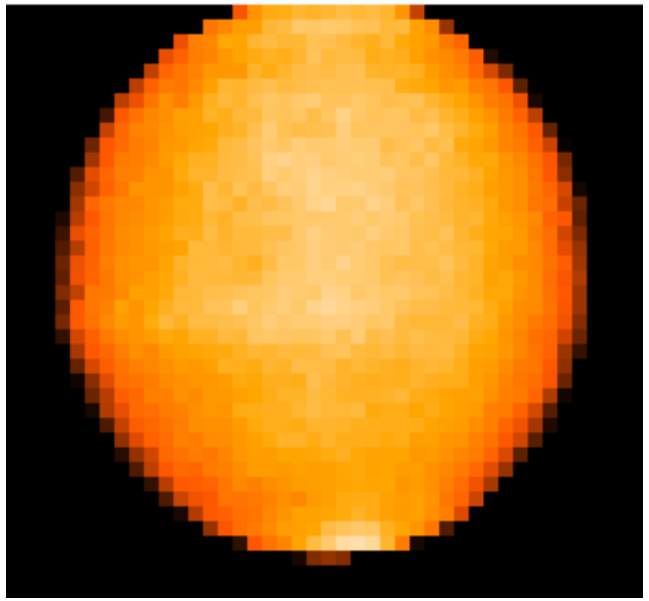
Blue line: evening terminator Yellow line: morning terminator

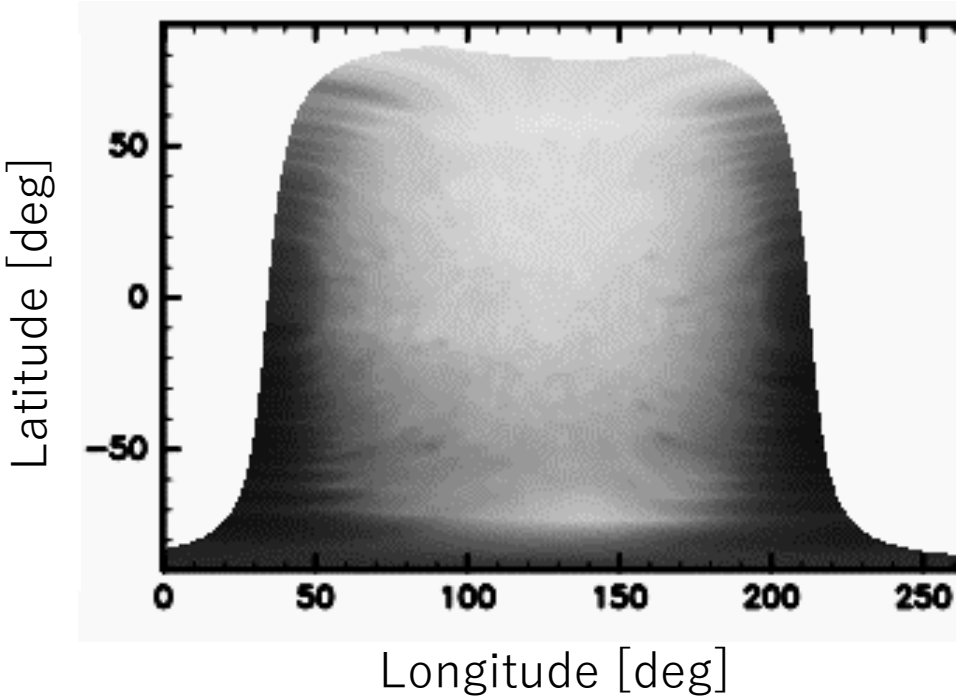


- Longitude of the boundary between high and low temperature regions of the bow shape at the equator: $\lambda_B \approx 80^\circ \sim 84^\circ$
- Angular velocity of the boundary: $\omega_B \approx -1 \sim 0\,[\mathrm{deg/day}]$
- Rotation speed of Venus to the Sun: $\omega_R \approx -3.1\,[\mathrm{deg/day}]$
- The bow-shaped structure looks to be fixed not to local time but on the ground.

The Bow-Shaped Structure

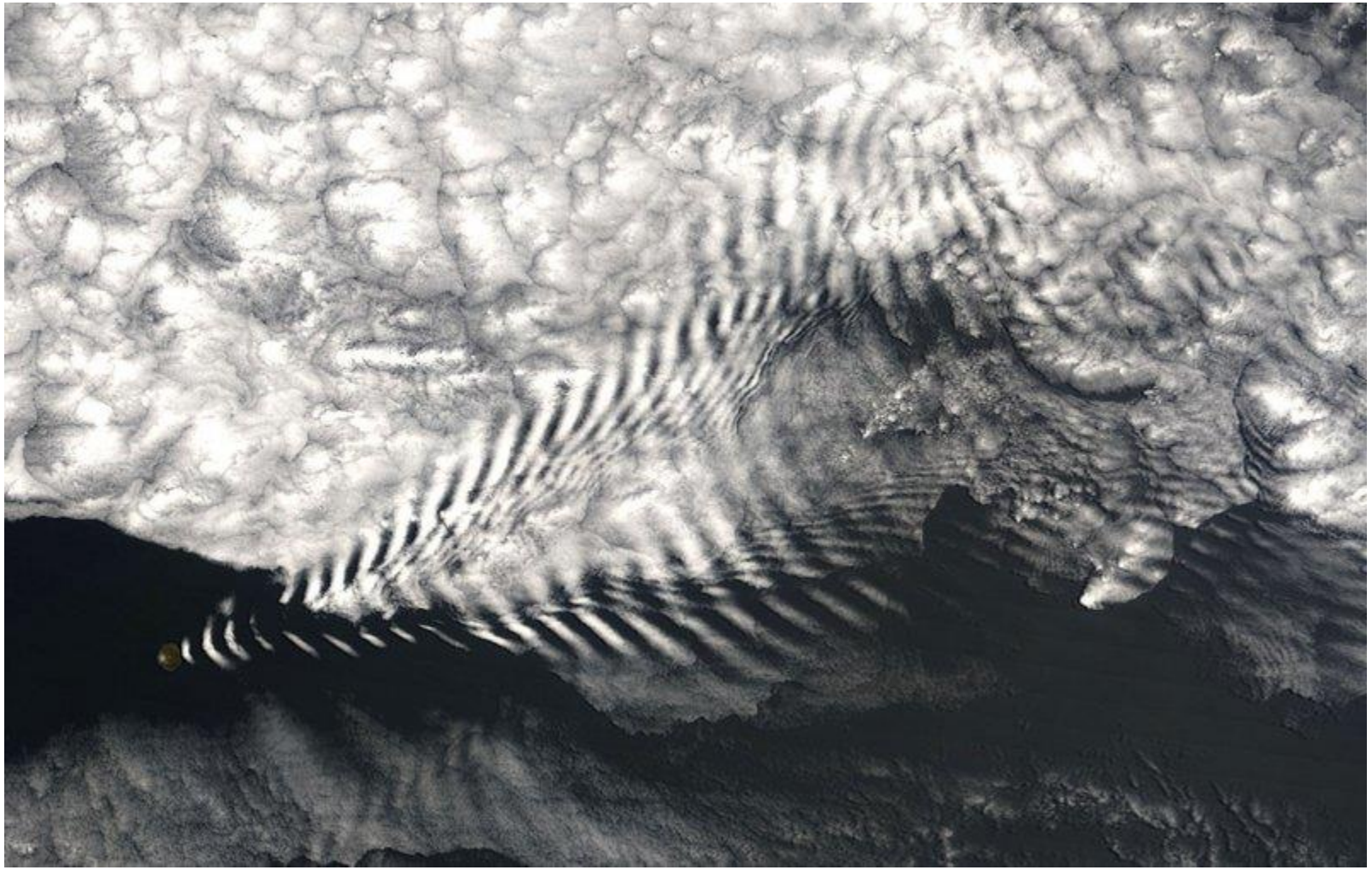
2016-01-15 10:45:22 UT
Sub S/C LT 21.3h





■The bow-shaped structure disappeared when LIR observed the same longitude and local time region at the earliest opportunity of observation on January 15, 2016.

ship wave, sailing wave, wake



NASA satellite image (MODIS imager on board the Terra satellite) of a wave cloud forming off of Amsterdam Island in the far southern Indian Ocean. Image taken on December 19, 2005. (Wikipedia)