Mesoscale modeling of Venus' bow-shape waves

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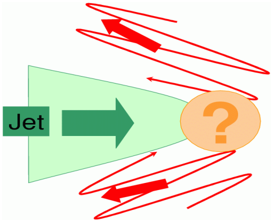
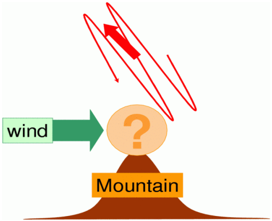
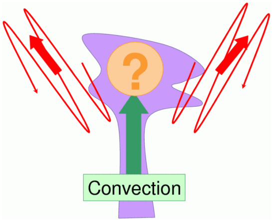
International Venus Conference // June 3, 2019

Gravity waves in planetary atmospheres

Gravity waves: atmospheric waves which restoring force is buoyancy







Why study gravity waves?

- ☞ Link to characteristics of underlying flow
- ☞ Momentum transfer to large-scale flow
- ☞ Torque on surface and change of rotation rate
- ☞ Influence on tracer transport

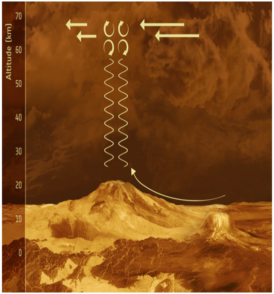
Venus' clouds' gravity waves and topography

VEGA balloons

- ✎ Impact of surface topography on cloud dynamics [Blamont et al. Science 1986]
- ✎ Modeling orographic GW propagate to cloud top [Young et al. JAS 1987 and 1994]

Venus Express

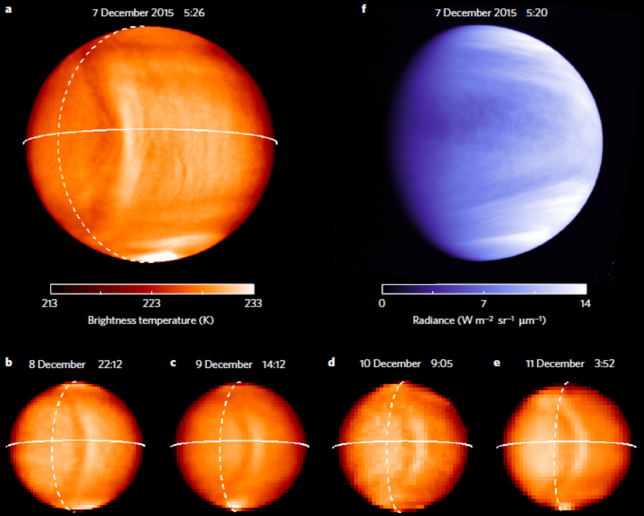
- ✎ Correlation topography ↔ top of the cloud's zonal wind [Bertaux et al. JGR 2016]
- ✎ Water minimum at cloud top above Aphrodite Terra [Fedorova et al. Icarus 2016]
- ✎ Nighttime stationary features above topography [Peralta et al. Nature Astronomy 2017]



[Credits: ESA]

Bow-shaped patterns in Venus' cloud top

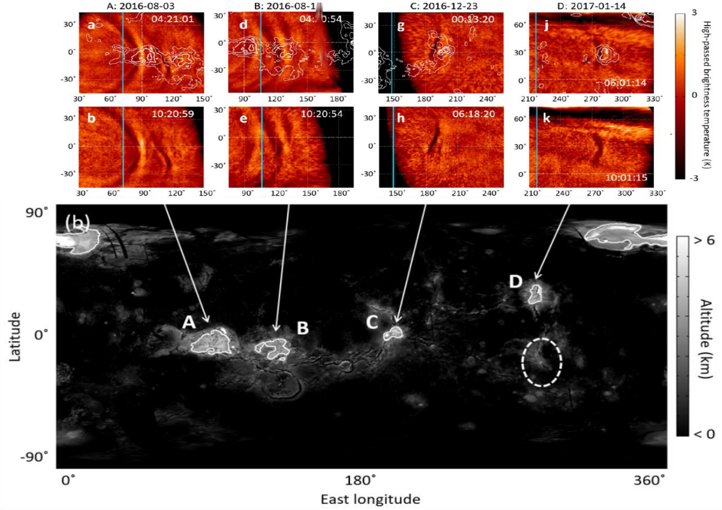
Revealed by Akatsuki LIR and UV



[Fukuhara et al. Nature Geoscience 2017]

Bow-shaped patterns in Venus' cloud top

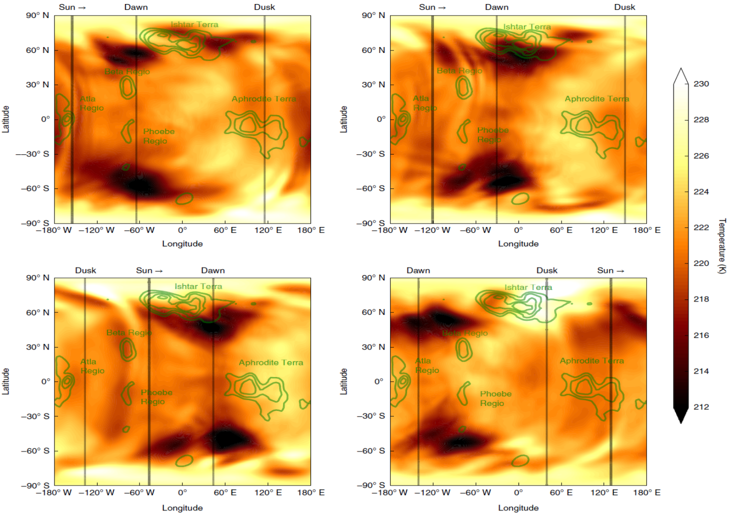
Revealed by Akatsuki LIR



[Kouyama et al. GRL 2018]

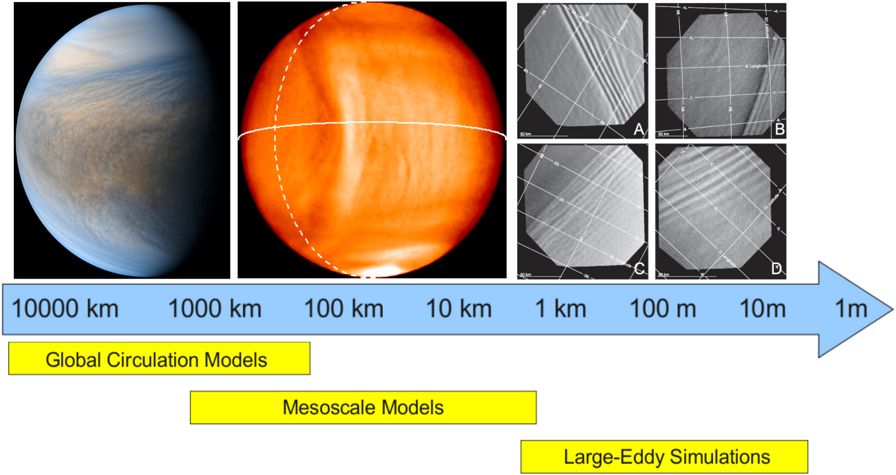
Bow-shape waves in a Venus GCM

Adopting a semi-parameterized approach: GW momentum deposited at $z = 35$ km



[Navarro et al. Nature Astronomy 2018]

Atmospheric modeling for Venus



Venus Mesoscale Model: LMD-VMM

Limited aread, grid spacing $\sim 50 - 5$ km

WRF dynamical core

integration of conservation laws for momentum, mass, energy, tracers

LMD Venus physics

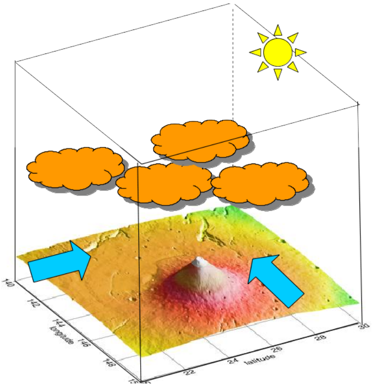
radiative transfer (CO_2 + H_2SO_4 clouds), soil model, vertical mixing, microphysics (not tested), photochemistry (not tested)

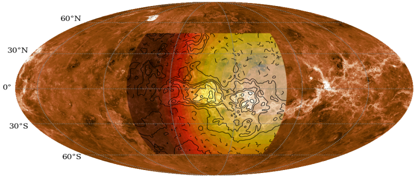
LMD Venus GCM fields

initial and boundary conditions

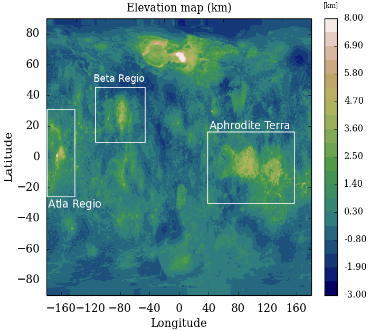
Surface properties

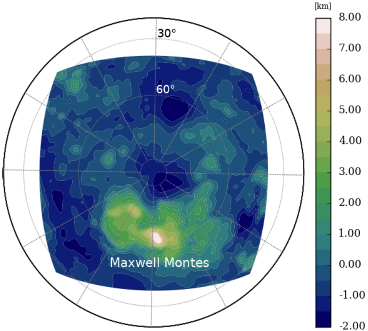
Magellan high-resolution topography





Venus mesoscale simulations for gravity waves





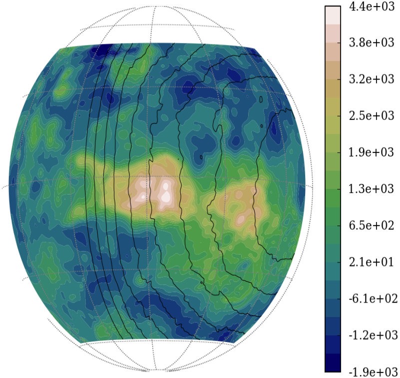
- GCM initial and boundary conditions: Garate-Lopez and Lebonnois 2018
- Boundaries updated every 1/100 Vd; Relaxation zone 5 grid points

- Vertical grid: 150 levels from the ground to 100 km altitude
- 5-km-deep Rayleigh-damping layer at model top

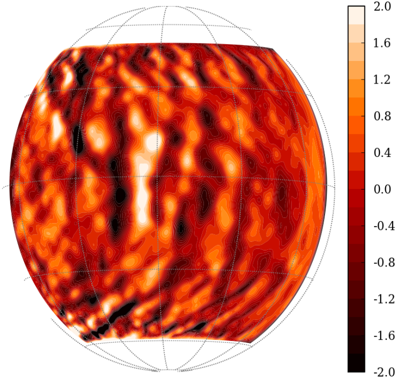
	Aphrodite Terra	Beta Regio	Atla Regio	Maxwell
Horizontal resolution (km)	40	30	15	40
Map projection	Mercator	Mercator	Mercator	Stereographic

Aphrodite Terra mesoscale simulation

Topography & sunlight



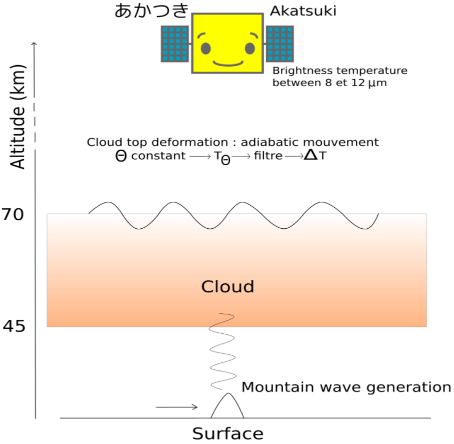
HP-filtered T_b at cloud top



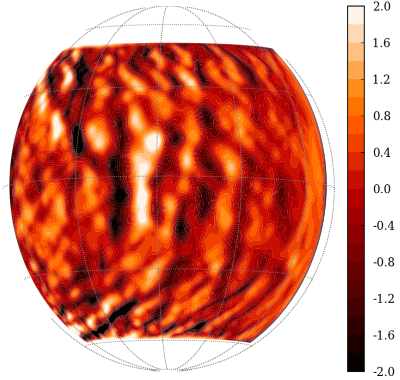
[Lefèvre, Spiga and Lebonnois, submitted to Icarus, arxiv 1902.07010]

Aphrodite Terra mesoscale simulation

Methodology



HP-filtered T_b at cloud top



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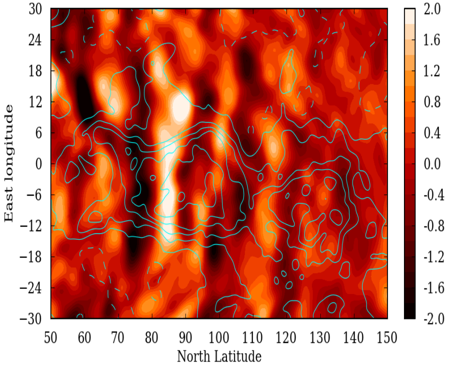
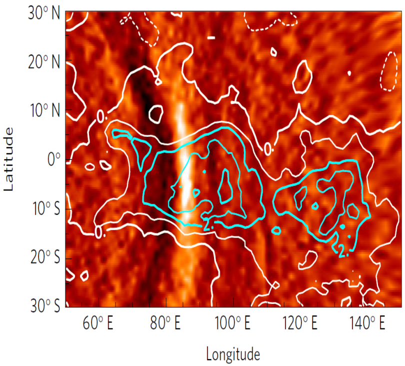
Aphrodite Terra bow-shape at cloud top

LMD Venus mesoscale simulation



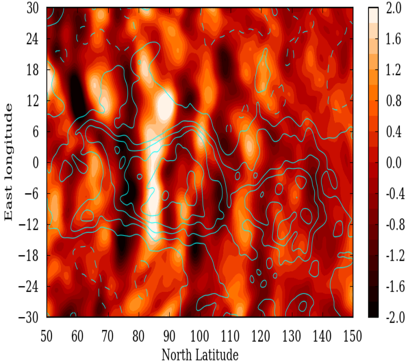
Akatsuki



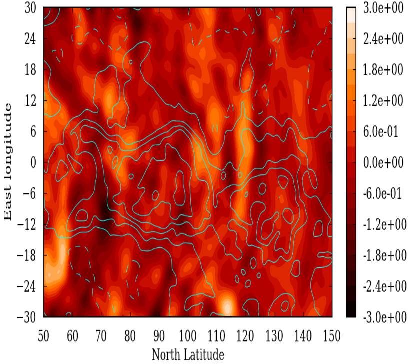
[Lefèvre, Spiga and Lebonnois, submitted to Icarus, arxiv 1902.07010 // Fukuhara et al. Nature Geoscience 2017]

Aphrodite Terra bow-shape: local time

Reference (afternoon)



Later (night)

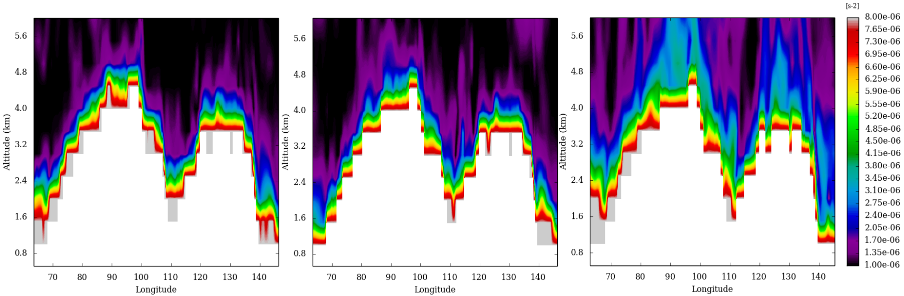


[Lefèvre, Spiga and Lebonnois, submitted to Icarus, arxiv 1902.07010]

Local time of bow-shaped waves: why?

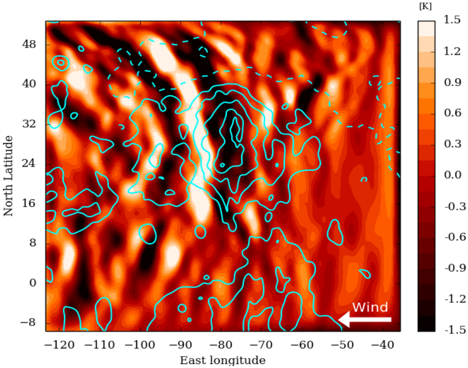
- ☞ Propagation: critical levels? ✗ ($c \sim 0$ vs. super-rotation)
- ☞ Source: low-atmosphere wind? ✗ (little diurnal cycle)
- ☞ Source: low-atmosphere static stability? ✓

midnight ⇒ noon ⇒ late afternoon

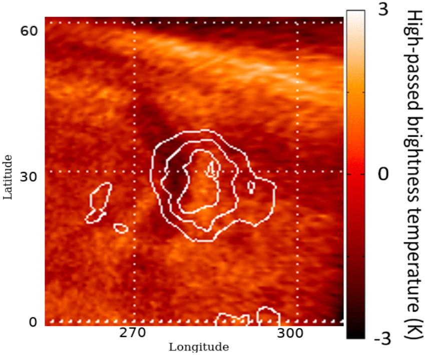


Beta Regio bow-shape at cloud top

LMD Venus mesoscale simulation



Akatsuki



[Lefèvre, Spiga and Lebonnois, submitted to Icarus, arxiv 1902.07010 // Kouyama et al. Icarus 2017]

How waves propagate through two mixed layers?

Tunneling effects

Gravity waves are evanescent in neutral-stability layers, in which the energy of the waves decrease exponentially with altitude. However, if the vertical extension of the neutral region is not too large, it is possible for a significant fraction of the incident wave energy to pass through the neutral stability region, via wave tunneling.

Computations [Sutherland and Yewchuk 2004]

From a region with a Brunt-Väisälä frequency N through a barrier of height H of $N \sim 0$, the transmission of energy $\mathcal{T}$ is

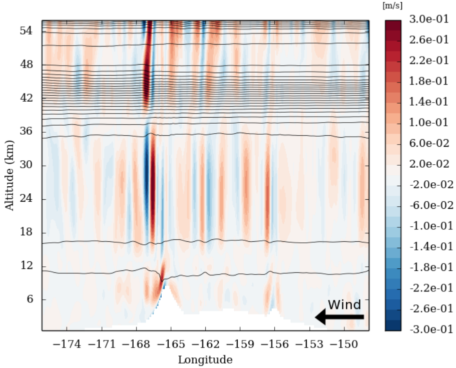
$$\mathcal{T} = \left[1 + \left(\frac{\sinh(k_x H)}{\sin 2\theta}\right)^2\right]^{-1} \qquad \theta = \cos(\omega / N)$$

with k_x the horizontal wavenumber and ω the frequency of the wave.

Vertical propagation of bow-shaped waves

From the surface to cloud top

Vertical wind (colors)
Potential temperature (contours)



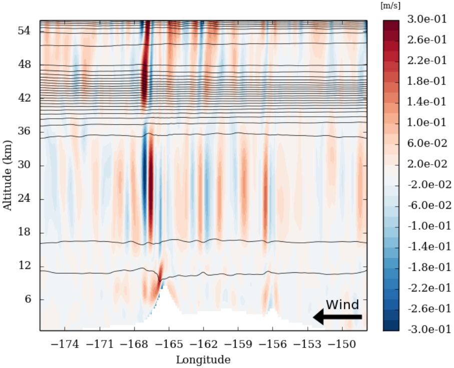
Vertical propagation of bow-shaped waves

From the surface to cloud top

⥀⥁ Cloud convective layer ⥀⥁

↶↷ Large-scale mixing ↶↷

Vertical wind (colors)
Potential temperature (contours)



Vertical propagation of bow-shaped waves

From the surface to cloud top

⇑ 18%

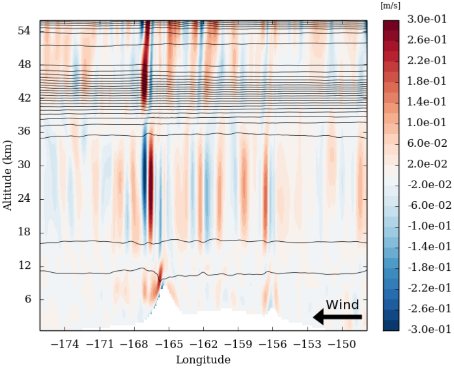
⥀⥁ Cloud convective layer ⥀⥁

⇑ 21%

↶↷ Large-scale mixing ↶↷

⇑ 100%

Vertical wind (colors)
Potential temperature (contours)

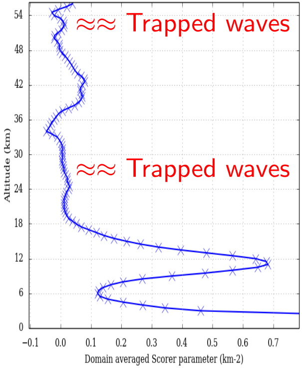


Vertical propagation of bow-shaped waves

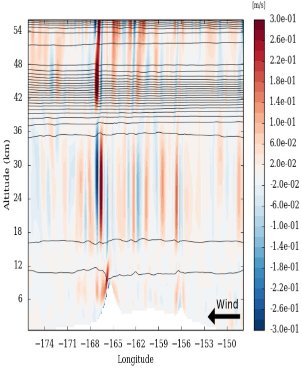
From the surface to cloud top

Scorer parameter

$$\frac{N^2}{U^2} - \frac{1}{U}\frac{\mathrm{d}U}{\mathrm{d}z}$$

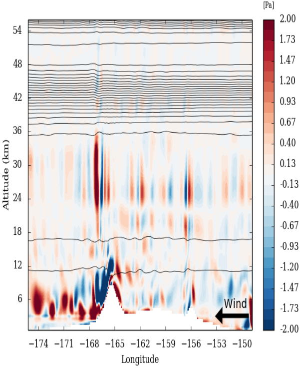


Vertical wind and potential temperature



EP (momentum) flux

$$-\rho u' v'$$



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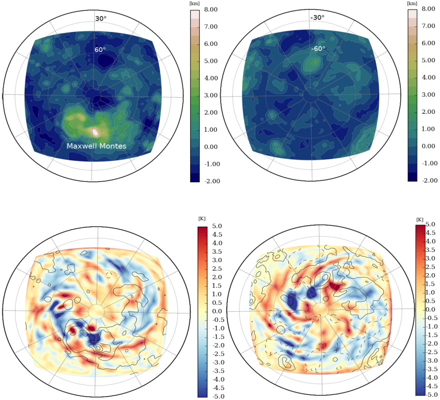
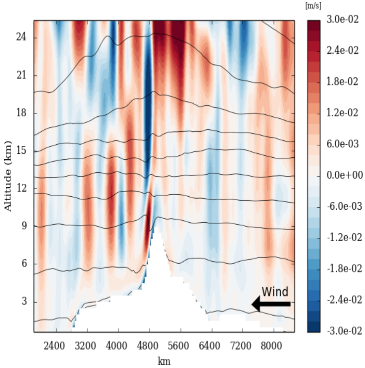
Orographic gravity waves in polar regions?





Mixed (near-neutral) layers	18-35 km	48-52 km	$\simeq$ total
$\mathcal{T}$ (low-latitude mountains)	21%	84 %	18 %
$\mathcal{T}$ (polar mountains)	13%	63%	8%

Summary [Lefèvre, Spiga, Lebonnois revised for Icarus (arxiv 1902.07010)]

- ✎ A versatile mesoscale model for Venus with full physics
- ✎ Reproduced amplitude + morphology of Akatsuki's gravity waves
- ✎ Studied tunneling effects through the mixed layers
- ✎ Explained variability with local time
- ✎ Validated Navarro et al.'s semi-parameterized approach

Perspectives for mesoscale modeling

- ☞ near-surface slope winds [Lebonnois et al. 2018]
- ☞ polar meteorology [Garate-Lopez et al. 2015]
- ☞ mesoscale structures near jets [Horinouchi et al. 2017]
- ☞ nighttime stationary waves [Peralta et al. 2017]
- ☞ mesoscale cyclones [McGouldrick, Limaye, this conference]