How do waves and turbulence maintain the super-rotation of Venus' atmosphere – results from Akatsuki

Takeshi Horinouchi (Hokkaido University),
Yoshi-Yuki Hayashi, Shigeto Watanabe, Manabu Yamada, Atsushi Yamazaki, Toru Kouyama, Makoto Taguchi, Tetsuya Fukuhara, Masahiro Takagi, Kazunori Ogohara, Shin-ya Murakami, Javier Peralta, Sanjay S. Limaye, Takeshi Imamura, Masato Nakamura, Takao M. Sato, Takehiko Satoh
Background

• Hide’s theorem: Inviscid pure axial flow cannot **create** the maximum of angular momentum (AM) per unit mass inside the atmosphere. → It requires eddy AM transport.

• Also, AM transport is needed to **maintain** the AM maximum, if the meridional circulation passes through it (to wash it away).

→ AM budget is a key to approach the super-rotation (**SR**)
Past observational study of AM transport

- From VEx: no paper so far.

- **Problem**: AM flux is second order ($u'v'$): requires accuracy and good sampling.
Our strategy

• Improve automated cloud tracking (Ikegawa & Horinouchi 2016; Horinouchi et al 2017)
  • Better method; better error correction; sophisticated quality control (screening).
    • better than manual tracking not only in sampling density but also in accuracy
  • Actual error evaluation: see Horinouchi et al (2020; H20) online supplement

✓ Horinouchi et al (2020) *Science*. https://science.sciencemag.org/content/368/6489/405/ (DOI link is incorrect so far)
Data

• Period: Dec 2015 – Dec 2018
• Near cloud-top images from Akatsuki UVI (365 nm, 283 nm)
  • Used for cloud tracking
  • See Horinouchi et al (2018) for mean winds
• Thermal-infrared temperature from Akatsuki LIR
  • Limited to high-emission angles ➔ near cloud-top

Example: deviation from a rigid-body rotation (100 m/s at EQ; Derived from 3 images: 2017-01-01 12,14,16 UTC)
Introducing H20

Horinouchi et al (2020) *Science*. [https://science.sciencemag.org/content/368/6489/405/](https://science.sciencemag.org/content/368/6489/405/)  
(DOI link is incorrect so far)
Evaluation basis: Transformed Eulerian Mean (TEM) equation at steady state (TEM is a kind of zonal mean)

\[ \mathbf{v}^r \cdot \nabla M = \rho_0^{-1} \nabla \cdot \mathbf{F} \]

- \( M \equiv a \bar{u} \cos \varphi + a^2 \Omega \cos^2 \varphi \) (AM per unit mass)
- \( \mathbf{v}^r \equiv (0, v^r, w^r) \): zonal mean meridional circulation velocity (“residual”; incl. Stokes drift)
- \( \mathbf{F} \equiv (0, F_y, F_z) \): Eliassen-Palm (EP) flux: “eddy” AM flux (by waves and turbulence)

• Required eddy AM flux convergence (rhs) depends on the meridional circulation (lhs)
Crudely estimated the mean meridional circulation from old data (VIRA shortwave heating) with a simplest assumption → Order-estimation of required eddy acceleration

Here we used \( N^2 w^r \propto Q \) to get \( \mathbf{v}^r \). Introduced an idealized \( M \) distribution to get \( -(a \cos \varphi)^{-1} \mathbf{v}^r \cdot \nabla M \).

Acceleration needed to maintain \( M \)'s peak at ~equatorial cloud top (< ~1 m/s/day)

The mean meridional circulation we obtained is consistent with the satellite derived shortwave – longwave differences (supplement of H20)

part of Fig. 1 of H20
Example and spectra of wind disturbances (other than thermal tide)

Fig. 3 of H20
Latitudinal AM transport (A,B) and its convergence (C; acceleration at low lat) estimated from UVI images (dayside, near cloud-top). Red: 283 nm; Blue: 365 nm

by thermal tide

by other motions (waves & turbulence, resolution ~ 1000 km)

by ~5-day Rossby waves

by other motions (waves & turbulence): decelerating SR

Shading: inter-subperiod standard deviation

Effect of the error covariance has been subtracted

Caution: observations are available only on dayside

Caution: results are limited to low lat

part of Fig. 2 of H20
Vertical AM transport

- **Thermal tide** (estimated from UVI+LIR results & theoretical/observational vertical structure: Kouyama et al 2019): accelerates SR at magnitude comparable to its horizontal AM transport (previous page)

- Other sources: could not be estimated
AM balance suggested from observation by Akatsuki

Fig. 4A of H20

Schematic illustration of suggested AM balance in the cloud layer of Venus. A: those quantified or order-estimated in this study; Wavy arrows indicate eddy transports of SR’s negative AM; items with “tr” represent transports quantified (black, blue) or order-estimated (gray) in this study.
AM balance suggested from observation plus physical considerations

Fig. 4B of H20

Schematic illustration of suggested AM balance in the cloud layer of Venus. B: A plus speculation. Wavy arrows indicate eddy transports of SR’s negative AM; items with “tr” represent transports quantified (black, blue) or order-estimated (gray) in this study, and those with “tr?” (in B) represent suggested ones.
Discussion: super-rotation as a day-night heat transporter

• Radiative time scale in the upper cloud layer: $\sim 10$ days $< \text{solar day}$ $\Rightarrow$ day-night heat transport needed

• Zonal flow such as super-rotation does that, but it alone cannot transport heat poleward (problem).

• **Solution**: to allow both super-rotation & meridional circulation by having AM transport by thermal tide (and other kinds of eddy motion)

• Remark: pure axi-symmetric framework (like Gieracsh 1975) is inadequate in the sense that it does not require day-night heat transport (but it’s OK for near surface where radiative time scale is $\sim 10^4$ days)
Conclusions

• We have successfully quantified the AM transport near the cloud top at low-to-mid latitude
  • Also quantified spectral features; found turbulent motions

• The AM peak around the equatorial cloud top is maintained by the AM transport by thermal tide (against run off by meridional circulation)
  • Turbulence and other waves act oppositely there, but they should be important for the AM redistribution at mid-latitude

• Proposed a thermo-dynamic view of the SR:
  • Heat transport system by SR and meridional circulation mediated by thermal tide and/or other kind waves & turbulence
    • Remark: Atmospheric general circulation should be told in terms of how the non-uniform absorbed solar energy is circulated.
  • Possible application to exo-planets: might be ubiquitous
Fig. S1. A vertical distribution of static energy. It is obtained from the VIRA data (39), and is expressed as the difference from the surface value, \( s \equiv s - s(z=0\,\text{km}) \). This profile was used to compute the meridional heat transport shown in subsection S13. Its theoretical basis is found in (54).
Thermal tide: $T \sim$ cloud top from LIR (high emission angle observation)

Fig. S11 of H20（あかつきの熱赤外カメラLIRによる雲頂付近の潮汐の温度場）
Fig. S9 of H20

365 nm

Fig. S10. Illustration of the sensitivity test to investigate the dependence of tidal angular momentum flux on the assumption of $u_0$. A–H: mean zonal wind $\bar{u}$ obtained from the three-year period (black curves) at latitudes shown on their upper-right corners. The red lines indicate the values of $u_0$ obtained by the least-square fitting of the wavenumber-2 sinusoidal curve. I, $\langle u_t v_t \rangle \cos \varphi$ obtained from this assumption (red curve), which is the same as the thin solid blue curve in Fig. 2A. All panels: the green and cyan lines (A–H) and curves (I) show the cases in which $u_0$ defined this way is shifted by ±0.3 times the fitting-based tidal amplitude (green: the faster; cyan: the slower). The blue lines (A–H) and curve (I) show the case in which $u_0$ is defined as the center in between the maximum and the minimum of $\bar{u}$. 
Yamamoto et al (2019) Venus GCM results

(c) $4.54 \times 10^3$ Pa (~69 km)

Dashed: true zonal mean
Solid: mean over dayside
$u'v'$: major contribution is from tides
Cloud top wind (traditional UV obs., but highly improved)

Motion relative to a representative rotation

$[U+90\cos\varphi, V]$ & radiance
U averaged over 20°S-20°N

Super-rotation + tide

365 nm  slower

283 nm  faster
$V$ averaged over $20^\circ - 35^\circ$ N

Poleward dayside tidal wind

365 nm  slightly slower

283 nm  slightly faster
U 365nm 11-13LT

Dotted bars: standard deviation w/ t

Red: mean over 201512 – 201812

least mid-lat diff btw 365&283: a matter of z-distribution of SO2 and the unknown absorber?
U 283nm 11-13LT

Dotted bars: standard deviation w/ t

Red: mean over 201512 – 201812

least mid-lat diff btwn 365&283: a matter of z-distribution of SO2 and the unknown absorber?
Ref: Kouyama et al (2012) from Galileo SSI

Simple CC

Corrected by relaxation labeling (w/ formulation having problems: see Horinouchi et al 2017)