金星のような惑星大気超回転の
ロスビー数依存性

山本勝(九大応力研)
角田裕穂(九大総理工)
高橋正明(国立環境研究所)

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金星のような惑星大気超回転のロスビー数依存性

＜今日の話の内容＞
超回転について
雲で覆われた惑星について
高Rossby数(>1)の雲に覆われた惑星の超回転のメカニズム（Tsunoda et al. 2021）
帯状流が、全球にわたって惑星個体部の回転（自転）よりも早く回転する現象。例）金星大気は、雲頂で自転（243日）の60倍の高速回転（4日循環）している。

超回転は様々な天体で観測されている。これらの惑星の間の超回転の相似性や違いは、十分に理解されていない。
超回転について（地球型惑星）

帯状流が、全球にわたって惑星個体部の回転（自転）よりも早く回転する現象。例）金星大気は、雲頂で自転（243日）の60倍の高速回転（4日循環）している。

地球型惑星の場合

惑星個体部の回転が、大気超回転の角運動量のソース。どのように角運動量が大気超回転に供給されるのか？
Motionless atmosphere adhered to the surface by the frictional drag

Specific angular momentum
\[ m = r \cos \varphi (\Omega r \cos \varphi) = m_0 \]

where \( \Omega \) : Planetary rotation rate
\( r \) : Planetary radius, \( \varphi \) : latitude
\( m_0 \) : Specific angular momentum at the planet’s surface

Surface = angular momentum source
Super- vs Sub-rotation

Specific angular momentum

\[ m = m_0 + u r \cos \varphi \]

where \( \Omega \): Planetary rotation rate
\( r \): Planetary radius, \( \varphi \): latitude,
\( u \): zonal-mean zonal flow

\( m > m_0 \): super-rotation
\( m < m_0 \): sub-rotation

On the sub-rotating surface \((u<0)\), the angular momentum is supplied by the frictional drag from the surface.

⇒ The sub-rotating surface is needed to drive the SR during the spin-up.
Hadley Circulation removes angular momentum in the tropics.

⇒ Equatorial zonal flow is decelerated
Super-rotation in the tropics because of equatorial zonal-flow deceleration
Super-rotation in the extratropics because of poleward angular momentum flux of Hadley cell

Some zonal-flow acceleration is required to produce “equatorial SR”
Gierasch–Rossow–Williams mechanism ➔ SRing regime

Equatorial SR

Equatorward momentum flux of eddies

Equatorward momentum flux of eddies

Sub-rotation

Hadley Circulation

pole
tropics
pole

surface = angular momentum source

(Giersch 1975 JAS; Rossow & Williams 1979 JAS)

Equatorward momentum flux of eddies accelerates the equatorial SR
雲で覆われた惑星について

＜Venus-type＞
太陽放射の大部分が上層の雲で吸収され、その雲による加熱が大循環を駆動する。

Stratospheric clouds and aerosols

＜Earth-type＞
太陽放射の大部分が地表面で吸収され、その地表面加熱が大循環を駆動する。
雲で覆われた惑星について

＜Venus-type＞
太陽放射の大部分が上層の雲で吸収され、その雲による加熱が大循環を駆動する。

＜Earth-type＞
太陽放射の大部分が地表面で吸収され、その地表面加熱が大循環を駆動する。

Slow planet. rot
Fast planet. rot.

＜Venus＞
Rotation: 243d
Radius: 6,052 km
Sur Press: 90 atm
Sur Temp: 735 K

＜Titan/moon＞
Rotation: 16d
Radius: 2,575 km
Sur Press: 1.45 atm
Sur Temp: 94 K

＜Mars＞
Rotation: 1d
Radius: 3,397 km
Sur Press: 0.006 atm
Sur Temp: 210 K

＜Earth＞
Rotation: 1d
Radius: 6,378 km
Sur Press: 1 atm
Sur Temp: 288K

Photo: NASA/JPL
Rossby number (Ro)

\[ Ro \equiv \frac{U}{2\Omega L} \]

- Inertial force
- Coriolis force

Rotation: Slow
Size: Small

Rotation: Fast
Size: Large

Venus-type

Earth-type

Venus
Titan
Mars
Earth

\( \text{Rossby number (Ro)} \)

\( \text{Inertial force} \)

\( \text{Coriolis force} \)

\( U : \text{Wind Speed Scale} \)
\( \Omega : \text{Planet. Rot. Rate} \)
\( L : \text{Horizontal Scale} \)

(Dias Pinto & Mitchell, 2014)  Photo: NASA/JPL

Gray shade: SR zonal flow (the darker shade presents the faster zonal flow)
雲で覆われた惑星の大気大循環構造

＜Venus-type＞
Rotation : Slow
Size : Small

＜Earth-type＞
Rotation : Fast
Size : Large

＜研究動機＞
流体力学として惑星大気大循環構造（特に超回転）を理解したい

〇対流圏内の放射強制で駆動するEarth-type大気大循環（Williams 1980 以降多数）

(Dias Pinto & Mitchell, 2014)  Photo : NASA/JPL
Gray shade : SR zonal flow (the darker shade presents the faster zonal flow)
Held & Suarez (1994)の計算設定で、Roを変える実験

同じ比率で、惑星自転速度と惑星半径を変えてRoを変えると、無次元摩擦抵抗Ekおよび無次元熱緩和時定数τaが違うので相似にならない。
Dias Pinto & Mitchell (2014 Icarus)

Held & Suarez (1994)の計算設定で、Roを変える実験

地球条件

Roだけを変える実験をするためには、無次元摩擦抵抗Ekおよび無次元熱緩和時定数τaを変えずに、同じ比率で、惑星自転や惑星半径を変えればよい。
Lu & Yamamoto (2020 PSS)

○ $Ro$ が大きくなると赤道風が強まる

○ $Ro<1$ では、$Ro$ が大きくなると、西風ジェットは強まり、より高緯度に位置する

○ $Ro>1$ で、西風ジェットは弱くなる

$r^*=1$

$r^*=1/8$

$r^*=1/20$

灰色 : Smagorinsky 無
黒色 : Smagorinsky 有
雲で覆われた惑星の大気大循環構造

＜Venus-type＞
Rotation : Slow  
Size : Small  

＜Earth-type＞
Rotation : Fast  
Size : Large  

＜研究動機＞
流体力学として惑星大気大循環（特に超回転）を理解したい

○対流圏内の放射強制で駆動するEarth-type大気大循環（Williams 1980以降多数）
○高ロスビー数で中層大気の放射強制で駆動する、Venus-type大気大循環（Yamamoto & Takahahsi 2016, 本研究）

(Dias Pinto & Mitchell, 2014)  Photo : NASA/JPL
Gray shade : SR zonal flow（the darker shade presents the faster zonal flow）
自転のみを変えた実験で、Roだけでなく、EkやNTも変わる。

Yamamoto & Takahashi (2016 JGR)
研究目的
金星型大気の超回転のRo依存性を明らかにする

$$R_O \equiv \frac{U}{2\Omega L}$$ (ロスピーー数)

$$E_K \equiv \frac{1}{2\Omega \tau_f}$$ (エクマン数)

$$N_T \equiv 2\Omega \tau_r$$ (熱緩和無次元数)

$L$: 水平スケール（惑星半径 $r$）
$	au_f$: 摩擦の時定数
$	au_r$: 放射緩和の時定数

ISSI Venus GCM inter-comparison (2013)と同じ条件で、自転および惑星サイズを変えて、$E_K$と$N_T$を不変になるように実験⇒超回転の$R_O$依存性のみを調査

云で覆われた惑星の大気大循環構造
(Tsunoda et al. 2021 JGR)

＜Venus-type＞
Rotation: Slow
Size: Small

＜Earth-type＞
Rotation: Fast
Size: Large

ROSSBY NUMBER ($R_O$)

Venus
Titan

243d
16d

27.6
4.3

0.02 0.01

Mars
Earth

1d 1d

ISSI Venus GCM inter-comparison (2013)と同じ条件で、自転および惑星サイズを変えて、$E_K$と$N_T$を不変になるように実験⇒超回転の$R_O$依存性のみを調査

(Dias Pinto & Mitchell, 2014)
Photo: NASA/JPL
Model

Idealized model setup of ISSI Venus GCM inter-comparison project (2013)

- **Venus-type radiative forcing:**
  Equator-pole temperature contrast (color shade) is relaxed by Newtonian cooling.

- **Primitive equation system using T42 GCM**

- **Experimental condition**

| Exp. | $r^*$ (-) | $\Omega^*$ (-) | $\tau_R$ (Eday) | $\tau_N$ (Eday) | $E_K$ (-) | $N_T$ (-) |
|------|-----------|----------------|-----------------|-----------------|----------|----------|
| V    | 1         | 1              | 2.96            | 24.6            | 6.45     | 1.29     |
| 3r   | 3         | 1              | 2.96            | 24.6            | 6.45     | 1.29     |
| 3$\Omega$ | 1       | 3              | 0.987           | 8.21            | 6.45     | 1.29     |
| 8r   | 8         | 1              | 2.96            | 24.6            | 6.45     | 1.29     |
| 8$\Omega$ | 1       | 8              | 0.37            | 3.08            | 6.45     | 1.29     |
| 15r  | 15        | 1              | 2.96            | 24.6            | 6.45     | 1.29     |
| 15$\Omega$ | 1      | 15             | 0.197           | 1.64            | 6.45     | 1.29     |

$\Omega^*$: Non-dim. planetary angular velocity normalized by Venus one ($2\pi/240$days)
$r^*$: Non-dim. planetary radius normalized by Venus one (6050 km)
Model

> Venus-type radiative forcing

> Primitive equation system

> Global three-dimensional flow under hydrostatic approximation

> Rossby number is altered with thermal and frictional non-dimensional numbers fixed (i.e., $E_K$ and $N_T$ are unchanged)

Rossby number is a only parameter which determines the dynamical similarity of SR and its related waves

<Dimensional primitive equations>

$$\frac{\partial u}{\partial t} + (V \cdot \nabla)u + f \times u = -\nabla \Phi - u/\tau_R,$$

$$\frac{\partial \theta}{\partial t} + (V \cdot \nabla)\theta = -\left(\theta - \theta_{eq}\right)/\tau_N,$$

where $u = ui + vj$ and $V = ui + vj + \omega k$

$u$: zonal wind velocity, $v$: meridional wind velocity,
$\omega$: vertical pressure velocity in the pressure coordinate,
$\Phi$: the geopotential, $f = 2\Omega \sin \phi$, $\theta$: potential temperature,
$\theta_{eq}$: equilibrium potential temperature

<Non-dimensional primitive equations>

$$\frac{\partial \hat{u}}{\partial t} + Ro(\hat{V} \cdot \nabla)\hat{u} + \hat{f} \times \hat{u} = -\nabla \hat{\Phi} - E_K \hat{u},$$

$$\frac{\partial \hat{\theta}}{\partial t} + Ro(\hat{V} \cdot \nabla)\hat{\theta} = -\left(\hat{\theta} - \hat{\theta}_{eq}\right)/N_T,$$

$Ro = U/(2\Omega L),$

$E_K = 1/(2\Omega \tau_R),$

$N_T = 2\Omega \tau_N.$

(Dias Pinto & Mitchell, 2014)
Model

- Venus-type radiative forcing
- Primitive equation system

Experiments for high Ro
> Venus condition (Ω*=1, r*=1)
> Size dependence with Ω*=1 (r*=1, r*=3, r*=8, r*=15)
> Rotation dependence with r*=1 (Ω*=1, Ω*=3, Ω*=8, Ω*=15)

Ω*: Non-dim. planetary angular velocity normalized by Venus one (2π/240d)
r* : Non-dim. planetary radius normalized by Venus one (6050 km)

<Non-dimensional equations>
\[
\begin{align*}
\partial \hat{u} / \partial t + Ro(\hat{V} \cdot \nabla)\hat{u} + \hat{f} \times \hat{u} &= -\nabla \hat{\Phi} - E_K \hat{u}, \\
\partial \hat{\theta} / \partial t + Ro(\hat{V} \cdot \nabla)\hat{\theta} &= -(\hat{\theta} - \hat{\theta}_{eq})/N_T,
\end{align*}
\]
\[Ro = U/(2ΩL),\]
\[E_K = 1/(2Ωτ_R),\]
\[N_T = 2Ωτ_N.\]

| Exp. | r* (−) | Ω* (−) | τ_R (Eday) | τ_N (Eday) | E_K (−) | N_T (−) | Ro^{JET} (−) |
|------|--------|--------|------------|------------|--------|--------|-------------|
| V    | 1      | 1      | 2.96       | 24.6       | 6.45   | 1.29   | 23.2        |
| 3r   | 3      | 1      | 2.96       | 24.6       | 6.45   | 1.29   | 19.8        |
| 3Ω   | 1      | 3      | 0.987      | 8.21       | 6.45   | 1.29   | 19.0        |
| 8r   | 8      | 1      | 2.96       | 24.6       | 6.45   | 1.29   | 12.2        |
| 8Ω   | 1      | 8      | 0.37       | 3.08       | 6.45   | 1.29   | 12.8        |
| 15r  | 15     | 1      | 2.96       | 24.6       | 6.45   | 1.29   | 7.8         |
| 15Ω  | 1      | 15     | 0.197      | 1.64       | 6.45   | 1.29   | 7.4         |

E_K & N_T unchanged
High Ro (>1) is realized
Zonal-mean general circulations for Ro

**Zonal flow** (black contour, warm color shade for fast)  
**Clock & anticlock stream func.** (color contour)

*Ω* = *r* = 1

Zonal - mean general circulations for Ro ~ 23

**Ro**~ JET ~ 15

36.8 m/s

74.6

95.1

114

**Ω** ~ 3 (r*=1)

**Ω** ~ 8 (r*=1)

**Ω** ~ 15 (r*=1)

71.4

99.5

108

Dynamical similarity for same Ro between different experiments

(Tsunoda et al. 2021 JGR)
As $r^*$ or $\Omega^*$ is increased, max. zonal-flow speed becomes greater.

(Tsunoda et al. 2021 JGR)
Sensitivity of SR to Ro

惑星半径や自転速度に比例し、中高緯度ジェットが増加する。

惑星半径や自転速度の増加に伴う赤道流増加が鈍る。
（$r^* = \Omega^* \sim 10$で傾きが小さくなる）

超回転を$Ro$で整理

(Tsunoda et al. 2021 JGR)
**Sensitivity of SR to Ro**

- **Equatorial Flow**:\( u_{EQ} \)
- **Jet Velocity**:\( u_{JET} \)
- **Equatorial Rossby Number**:\( Ro_{EQ} \)
- **Jet Rossby Number**:\( Ro_{JET} \)
- **Equatorial Rossby Number**:\( S_{EQ} = \frac{u_{EQ}}{r \Omega} \)
- **Jet Rossby Number**:\( S_{JET} = \frac{u_{JET}}{r \cos \phi \Omega} \)
- **Equatorial Rossby Number**:\( Ro_{EQ} = \frac{u_{EQ}}{2r \Omega} \)
- **Jet Rossby Number**:\( Ro_{JET} = \frac{u_{JET}}{r \cos \phi \Omega} \)

\( ESE = \frac{S_{EQ}}{S_{JET}} \)

- **ESE \( \rightarrow 1\)**: Rigid-body rotation type
- **ESE \( \rightarrow 0\)**: Mid-latitude jet type

\( Ro \)が大きくなるにつれて、線形的に超回転が強く、赤道流も中高緯度ジェットも一つの線にのる。

(Tsunoda et al. 2021 JGR)
Hadley circulation globally transport both heat and momentum poleward.

Hadley circulation heat flux dominates over eddies, except for the polar region.

The poleward mom flux of Hadley circulation balances equatorward eddy momentum flux.
SR dynamical process (Exp. V)

**Gierasch–Rossow–Williams mechanism**

Hadley circulation globally transport both heat and momentum poleward.

Hadley circulation heat flux dominates over eddies, except for the polar region.

The poleward mom flux of Hadley circulation balances equatorward eddy momentum flux.

Global-mean Vertical AM fluxes

The upward AM flux of Hadley circulation balances the downward eddy flux.
Eddy mom flux process (Exp. V)

**Figure 6.** (a–e) Latitude–pressure distributions of zonal mean horizontal (shading) and vertical (contours) eddy angular momentum fluxes divided by the planetary radius (kg m\(^{-1}\) s\(^{-2}\)).

**Figure 7.** Zonal wavenumber–latitude distributions of zonal-mean eddy horizontal momentum flux (m\(^2\) s\(^{-2}\), shading) and heat flux (K m s\(^{-1}\), contours) at 3.96×10\(^5\) Pa.

**Figure B2.** Longitude–latitude distributions of eddy geopotential height (m, contours) and horizontal wind velocity (m s\(^{-1}\), vectors) at 3.96×10\(^5\) Pa.

(Tsunoda et al. 2021 JGR)
Zonal-mean eddy AM fluxes for Ro

\( r^* = 3 \) (\( \Omega^* = 1 \))

\( \Omega^* = r^* = 1 \)

\( \Omega^* = 3 \) (\( r^* = 1 \))

\( \Omega^* = 15 \) (\( r^* = 1 \))

\( \Omega^* = 15 \) (\( r^* = 1 \))

(Tsunoda et al. 2021 JGR)

Ro\(^{JET} \sim 23\)

Ro\(^{JET} \sim 15\)

Ro\(^{JET} \sim 8\)

**Figure 6.** (a–e) Latitude–pressure distributions of zonal mean horizontal (shading) and vertical (contours) eddy angular momentum fluxes divided by the planetary radius (kg m\(^{-1}\) s\(^{-2}\)).
Vertically-integrated horiz mom fluxes for $\text{Ro}^{\text{JET}}$

$r^* = 3$ ($\Omega^* = 1$)

$r^* = 15$ ($\Omega^* = 1$)

$\Omega^* = r^* = 1$

(Tsunoda et al. 2021 JGR)

$\text{Ro}^{\text{JET}} \approx 23$

$\text{Ro}^{\text{JET}} \approx 15$

$\text{Ro}^{\text{JET}} \approx 8$

**Figure 4.** (f–j) Meridional distributions of vertically integrated horizontal momentum fluxes of zonal mean circulation ($HMF_{ZMC}$, solid curve) and eddies ($HMF_{EDY}$, dashed curve)
Vertically-integrated horiz heat fluxes for Ro

Ω* = r* = 1

(Tsunoda et al. 2021 JGR)

Ro^{JET} \sim 23

Ω* = 3 (r* = 1)

Ro^{JET} \sim 15

Ω* = 15 (r* = 1)

Ro^{JET} \sim 8

Figure 4. (a–e) Meridional distributions of vertically integrated horizontal heat fluxes of zonal mean circulation ($HHF_{ZMC}$, solid curve) and eddies ($HHF_{EDY}$, dashed curve)
Global-mean vert mom fluxes for Ro

Ω* = r* = 1

(Tsunoda et al. 2021 JGR)

Ro^{JET} \sim 23

Figure 4. (k–o) vertical distributions of global-mean vertical angular momentum fluxes of zonal mean circulation (VMF_{ZMC}, solid curve) and eddies (VMF_{EDY}, dashed curve).
Sensitivity of SR dynamical process to Ro

Horiz. heat transport

Horiz. mom. transport

南北温度差と帯状平均子午面循環熱輸送はRoの増加とともに、減少する。

帯状平均渦熱輸送はRoにあまり依存しない

南北の風速差と帯状平均渦運動量輸送は、Roの増加とともに、減少する。

(Tsunoda et al. 2021 JGR)
**Sensitivity of SR dynamical process to Ro**

Horiz. heat transport

![Graph showing heat transport vs. Ro](image)

**Horiz. mom. transport**

![Graph showing momentum transport vs. Ro](image)

**SR intensity**

![Graph showing SR intensity vs. Ro](image)

南南北温度差と帯状平均子午面循環熱輸送はRoの増加とともに、減少する。帯状平均渦熱輸送はRoにあまり依存しない。

帯状平均渦熱輸送はRoの増加とともに、減少する。

渦角運動量輸送と子午面循環熱輸送は弱いが、超回転強度は強まる。

高Roでは、弱い輸送で効率よく超回転が発達する。

(Tsunoda et al. 2021 JGR)
Sensitivity of wave and its mechanism to Ro

Time-longitude cross-sections of eddy geo-potent height (m, color shade)

Time-scale is normalized by planet. rot. period.

Wave structures are also similar for the same Ro.

They are quite different between high and low Ro.

(Tsunoda et al. 2021 JGR)
Sensitivity of wave and its mechanism to Ro

Time-latitude cross-sections of horizon eddy mom (shade) and heat (contour) fluxes

Time-scale is normalized by planet. rot. period.

Wave structures are also similar for the same Ro.

They are quit different between high and low Ro.

(Tsunoda et al. 2021 JGR)
Sensitivity of wave and its mechanism to $Ro$.

We introduce energy conversions from zonal-mean to eddy energies.

- **Barotropic kinetic energy conversion**

  \[
  CK(s) = -\frac{1}{r} \int_V \left( \frac{\partial \bar{u}}{\partial \varphi} + \bar{u} \tan \varphi \right) u'(s)v'(s)dV
  \]

  The horizontal zonal-wind shear induces eddies when $CK > 0$ (e.g., Barotropic instability or Spherical horizontal shear instability).

- **Barotropic potential-energy conversion**

  \[
  CP(s) = -\frac{1}{r} \int_V \frac{\partial \bar{T}}{\partial \varphi} \left( \frac{R}{NH} \right)^2 T'(s)v'(s)dV
  \]

  The horizontal temperature gradient induces eddies when $CP > 0$ (e.g., Baroclinic instability).

# Here, $s$ indicates zonal wavenumber.
Sensitivity of wave and its mechanism to Ro

Time-longitude cross-sections of eddy geo-potent height (m, color shade)

Barotropic energy conversion

Ro ~ 8
\( r^* = 15 \ (\Omega^* = 1) \)

Baroclinic energy conversion

Barotropic energy conversion

Ro ~ 15
\( r^* = 3 \ (\Omega^* = 1) \)

Baroclinic energy conversion

(Tsunoda et al. 2021 JGR)
Summary

We confirmed dynamical similarity to the same Ro in the GRW mechanism. The sensitivity of SR to Ro is summarized as follows.

- **Strong** mom flux
- **Strong** zonal wind
- **Low** SR intensity
- **Slow** Rossby wave
  - continuously produces equatorward mom flux

- **Weak** mom flux
- **Weak** zonal wind
- **High** SR intensity
- **Fast** Rossby wave
  - intermittently produces equatorward mom flux
まとめ
金星型大気超回転の高ロスビー数（$Ro^{JET} > 1$）依存性を調査した。

〇低ロスビー数（$Ro^{JET} \sim 8$）
・順圧エネルギー変換に伴い、自転よりも遅いロスビュー波が、連続的な赤道向き運動量輸送を生み出す。
・帯状平均流は中高緯度ジェットが卓越する。
・帯状風速と赤道向き渦運動量輸送は大きいが、赤道超回転は十分に発達しない。
⇒超回転強度Sと赤道超回転効率ESEが小さい

〇高ロスビー数（$Ro^{JET} \sim 20$）
・順圧エネルギー変換と傾圧エネルギー変換に伴い、ロスビュー波の運動量および熱輸送が短い周期で間欠的に増幅する。
・帯状平均流は中低緯度で概ね同速分布に近い赤道超回転となる。
・間欠的で弱い運動量輸送だが、赤道超回転が効率よく発達する。
⇒超回転強度Sと赤道超回転効率ESEが大きい

Tsunoda Y. et al., “Rossby number dependence of Venus/Titan-type superrotation and its related intermittency,” J. Geophy. Res.: Planets, 126 (2021), e2020JE006637
### Future works

The present work suggests the following three-regimes based on the energy conversion. Venus-type SRing regime is newly classified into Venus-regime and Titan-regime.

**<Venus-type> SRing regime**

| Venus-regime (Ro~20) | Titan-regime (Ro~8) |
|----------------------|----------------------|
| Barotropic & Baroclinic | Barotropic |
| ?                    | Baroclinic |

**<Earth-type> Classical-regime**

| (Ro~0.01) |
|-----------|

(1) We must elucidate the regime boundaries and their dynamical characteristics on Venus-type planets.

(2) We must elucidate the spin-up process of SR.

(3) We must elucidate the sensitivity of SR to diffusion (Yamamoto & Takahashi 2022 JGR).