From Atmospheric Tides to Super-rotating Circulation

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Biosignatures? 

\[ 1 R_\oplus, \rho = \rho_\oplus / 2 \]

**Transit Depth** = 2102 ppm

JWST/NIRISS, Earth 2.0 + M3V @ 13 pc

J=8, 90 hrs (50 transits; 3.2 yrs )

Efficiency: 33%

Courtesy Rene Doyon, NIRISS PI

Noise level: 5 – 10 ppm

Model courtesy of L. Kaltenegger
Concept of Atmospheric Tides

- differential gravity → gravitational tides
- differential solar/stellar heating → thermal tides in atmosphere (atmospheric tides)
- like gravitational tidal forcing, periodic atmospheric tides can excite non-axisymmetric waves → angular momentum transport between different parts of atmosphere
Concept of Thermal Tides

- differential gravity $\rightarrow$ gravitational tides
- differential solar/stellar heating $\rightarrow$ thermal tides in atmosphere (atmospheric tides)
- like gravitational tidal forcing, periodic thermal tides can excite non-axisymmetric waves $\rightarrow$ angular momentum transport between different parts of atmosphere

![Graph showing solar heating, diurnal (m=1), and semidiurnal (m=2) patterns over the hour of day.](image)
Atmospheric tides on Earth

Atmospheric tides are primarily thermally driven and are associated with inertia gravity waves (impressible waves).

- Oscillations follow the Sun, not Moon.
- Oscillation amplitudes are an order of magnitude larger than theoretical gravitational tides.

Cartwright 2001

Semi-diurnal max: ~10am, 10pm
Diurnal max: ~2am

Chapman & Lindzen 1970

At sea level
Atmospheric tides on Mars

measured by Curiosity rover

Hint of equatorial super-rotation on hot Jupiters

Knutson et al. 2012 (3.6, 4.5 μ)

Phase curve of HD 189733b:
max & min fluxes occur several hours before 2nd eclipse & transit, respectively

Temperature maximum does not lie at the substellar point but shifts eastward

Knutson et al. (2007) longitudinal temperature map
hot Jupiter circulation simulations predict equatorial superrotation $\rightarrow$ advects heat downstream

Figure 9: Examples of calculations from general circulation models of hot Jupiters. Despite the use of different input parameters, techniques to treat radiation and numerical schemes for atmospheric dynamics, the chevron-shaped feature appears to be a generic outcome of the hot exoplanet regime. Courtesy of Kevin Heng (top left panel, using the FM5 GCM), Emily Rauscher (top right panel, using the T3G model), Ian Dobbs-Dixon (middle left panel, using a customized code), Nathan Mayne (middle right panel, using the U.K. Met Office GCM) and Adam Showman (bottom left panel, using the NITgcm). The bottom left panel shows an analytical model from [65], generalized from the work of [96, 149] and [138, 139].
In these simulations, how to transfer angular momentum to the equator where the specific angular momentum of the atmospheric gas is maximum? It is not trivial.....
Equatorial Dynamics

Coriolis force vanishes along the equator. There exists special dynamics: equatorial Kelvin and Rossby waves, which are predominant horizontal modes in response to slow forcing. The restoring force arises from variation in Coriolis force along latitude and hence almost impressible. See Gu & Ogilvie (2009), Showman & Povani (2011).

examples (m=1, note that they are NOT spherical harmonics):

rossby wave (n=1)  retrograde mode

(1)  \( k = 0.5, \ \omega = -0.155 \)

kelvin wave  prograde mode

(1)  \( k = 0.5, \ \omega = 0.500 \)

http://www2.nagare.or.jp/mm/2012/nakajima/en/a_wcisk_1.htm
Hot Jupiter atmosphere is like a musical instrument
Equatorial waves in hot Jupiter atmosphere

Showman & Polvani 2011

Equatorial radius of deformation for a tidally locked hot Jupiter:

\[ R_{eq} = \sqrt{\frac{(gH)^{1/2}}{\beta}} = \sqrt{\frac{(gH)^{1/2}}{2\Omega / R_{HJ}}} \approx R_{HJ} \]

2D linear wave analysis

Input:
- Stationary day-night thermal forcing

Response of a 2D atmosphere at rest:
- Superposition of stationary equatorial Kelvin and Rossby waves
- Momentum transport to equator
- Equatorial superrotating flow

Matsuno-Gill pattern

\[ u'v' \] toward equator
Questions to be answered

• Showman & Povani conducted 2D linear wave analysis. But the “instrument” is 3D: what do vertical wave structures look like, especially in the presence of a super-rotating flow?

• how to reach a final equilibrium state?
3D thermal forcing

Tsai, Dobbs-Dixon, Gu 2014
Use HD189733b as a fiducial model:

vertical heating profile

meridional heating profile

longitudinal heating profile

linear theory

rad. hydro simulation
Atmospheric response

(effect of $\alpha$ and $u_0$)

Increasing damping

- Weak damping
  - $\alpha = 0.01$

- Moderate damping
  - $\alpha = 0.1$

- Strong damping
  - $\alpha = 0.5$

Rossby-wave resonances

- Resonance: when $u_0 + c_{\text{wave}} \to 0$

- Resonance peaks are suppressed

- Resonances more suppressed
  → Kelvin waves more dominant (they couple better with thermal forcing)

Kelvin-wave resonances

Tsai, Dobbs-Dixon, Gu 2014: 3D linear wave analysis with a mean zonal flow ($u_0$) included

$u_0$ (mean zonal flow)

Westward

Eastward
wave structure varies with depth: moderate damping

Tsai, Dobbs-Dixon, Gu 2014

at $p = 0.03$ bar

when $u_0 = 1000$ (m/s) $\alpha = 0.1$

$\nu = 10^8$ cm$^2$/s  rad. hydro simulation

linear theory
wave structures vary with depth: moderate damping

Tsai, Dobbs-Dixon, Gu 2014

rad. hydro simulation

linear theory

at p = 0.2 bar
when \( u_0 = 1000 \text{ (m/s)} \) \( \alpha = 0.1 \)
wave structures vary with depth: moderate damping

Tsai, Dobbs-Dixon, Gu 2014

at $p = 0.3$ bar

when $u_0 = 1000$ (m/s) $\alpha = 0.1$
Wave structures vary with depth: moderate damping

Tsai, Dobbs-Dixon, Gu 2014

dispersive Rossby waves due solely to vertical stratification

rad. hydro simulation

linear theory

\( \Phi = P_{m=1} \) (Zonal Psurf) @P=4.6415888

\( \Phi = P_{m=1} \) (Zonal Psurf) @P=4.6415888

at \( P = 1 \) bar

when \( u_0 = 1000 \) (m/s) \( \alpha = 0.1 \)
wave structures vary with depth: strong damping

Tsai, Dobbs-Dixon, Gu 2014

\[ \nu = 10^9 \text{ cm}^2 / \text{s} \] rad. hydro simulation

\[ \alpha = 0.5 \] linear theory

at \( p = 0.03 \text{ bar} \)

when \( u_0 = 1000 \text{ (m/s)} \) \( \alpha = 0.5 \)
wave structures vary with depth: strong damping

Tsai, Dobbs-Dixon, Gu 2014

at $p = 0.18$ bar

when $u_0 = 1000$ (m/s) $\alpha = 0.5$
wave structures vary with depth:
strong damping

Tsai, Dobbs-Dixon, Gu 2014

at $p = 0.21$ bar
when $u_0 = 1000$ (m/s) $\alpha = 0.5$
wave structures vary with depth: strong damping

Tsai, Dobbs-Dixon, Gu 2014

dispersive Kelvin waves
due solely to vertical stratification

at $p = 0.5$ bar
when $u_0 = 1000$ (m/s) $\alpha = 0.5$
Why reach a final equilibrium state?

interaction between waves and superrotating flow

\[
\text{acceleration} = \frac{du_0}{dt} = -\text{div}(\text{momentum flux})
\]

Tsai, Dobbs-Dixon, Gu 2014
3D linear theory

Showman & Polvani 2011
3D rad. hydro.

Do initial conditions give different final equilibrium states of the atmosphere? (Thrastarson & Cho 2010; Liu & Showman 2013)
Summary & Outlook

- Atmospheric tidal waves are mostly thermally driven by stellar irradiation. They are almost impossible waves.
- Atmospheric tides on tidally locked hot Jupiters are equatorial waves and can transport angular momentum toward the equator, forming planetary-scale equatorial superrotating circulation, which can explain phase-curve observations for hot Jupiters.
- The atmospheric evolution depends on the interaction between the superrotating flow and waves (e.g. Rossby-wave resonance).

Future is bright

- Simulation: improve radiative HD/MHD simulations (GCMs) to model exoplanetary atmospheres
- Observation: transit space missions (TESS, CHEOPS, PLATO), next-generation ground-based telescopes (E-ELT, GMT, TMT)
- Science: what are the climates on “habitable planets”? 