Atmospheric circulation of hot giant planets

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NASA/JIRAM/Matt Brealey
NASA/JUNOcam/Eichstädt & Doran
ATMOSPHERIC DYNAMICS OF HOT GIANT PLANETS AND BROWN DWARFS

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Detected exo-atmospheres: Now

- Hot Jupiters
- Warm Neptunes
- Hot super-Earths

19 chemical species in 35 different atmospheres
Detected exo-atmospheres: in 10 years

63 planets in JWST cycle 1
As many planets with planned high resolution obs.
More planets this year than has ever been observed by Hubble and Spitzer!
Detected exo-atmospheres: in 10 years

63 planets in JWST cycle 1
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What a hot Jupiter really look like.

Rayleigh scattering and alkali absorption makes clear sky deep blue.

Thermal emission leaking into the optical.

Reflecting clouds on the west part of the atmosphere.
What a hot Jupiter really look like.

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Thermal emission leaking into the optical.

During eclipse and transit we see a mix of varied:
- cloudiness
- temperature
- chemistry

Reflecting clouds on the west part of the atmosphere.

RGB (105,77,94)
best match: eggplant purple
Thermal structure

Chemical equilibrium
Opacities

Heat advection, convection
Temperature contrast

Chemical composition
Quenching, cold traps
Latent heat

Atmospheric dynamics
Dynamics equations

- Newton's second law or conservation of momentum (one equation for each of the three velocity components);

\[
\frac{D\vec{v}}{Dt} = -\frac{1}{\rho} \nabla p - \vec{g} - 2\vec{\Omega} \times \vec{v} + \vec{D}.
\]

- the continuity equation or conservation of mass;

\[
\frac{D\rho}{Dt} = -\rho \nabla \cdot \vec{v}
\]

- the equation of state of the gas, usually taken as the ideal gas law;

\[
P = \frac{k_B}{\mu} \rho T,
\]

- the conservation of energy;

\[
\frac{DT}{Dt} = \frac{q}{c_p} + \frac{1}{\rho c_p} \frac{DP}{Dt}
\]
Rossby Number

\[ Ro \equiv \frac{U}{fL} \]

Compares advection and Coriolis term

\[ f = 2\Omega \sin \phi \]

Large Rossby
\[ \rightarrow \text{Geostrophic balance} \]

Small Rossby
\[ \rightarrow \text{Coriolis small} \]
### Rossby Number

$$Ro \equiv \frac{U}{fL}$$

- **Large Rossby**: $\Rightarrow$ Geostrophic balance
- **Small Rossby**: $\Rightarrow$ Coriolis small

$$f = 2\Omega \sin \phi$$

### Deformation radius

$$L_D = \frac{ND}{f}$$

- **How far gravity waves propagate before being deflected by Coriolis?**
- **Size of storms!**

$$N = \sqrt{c_p k_B \sqrt{g/H}}$$
## Rossby Number

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## Deformation radius

\[ L_D = \frac{ND}{f} \]

- How far gravity waves propagate before being deflected by Coriolis?
- Size of storms!

\[ N = \sqrt{c_p k_B g/H} \]

## Rhines scale

\[ L_{Rh} = \pi \sqrt{\frac{U}{\beta}} \]

- How big turbulent eddies become before being affected by Coriolis
- Size of jets!

\[ \beta = \frac{2\Omega \cos \phi}{R_p} \]

### Non dimensional numbers
Jupiter — scaled
(Young & Read 2017)

Hot Jupiter
(Hammond & Abbot 2022)
Jupiter — scaled (Young & Read 2017)

Hot Jupiter (Hammond & Abbot 2022)
3.2.3 Primitive equations

The most commonly used set of equations to study the dynamics of an entire planet are the Primitive equations. They can be derived from the full set of equations with four assumptions (see also Table 3.1):

1. *Constant gravity.* The gravity is supposed constant through the whole atmosphere. This is valid if the vertical extent of the atmosphere is small compared to the radius of the planet.

2. *The shallow-fluid approximation.* We write the position of the gas parcel \( r = R_p + z \) where \( R_p \) is the fixed radius of the planet and \( z \) is the altitude above this radius. We then re-write the *vector invariant* form of the momentum equation (3.4) assuming that \( R_p >> z \).

3. *The traditional approximation.* Whenever the *shallow-fluid approximation* is applied at the spherical coordinates equation and not to the vector invariant equations, the resulting equations lack of self-consistency and, in particular, they do not conserve the angular momentum anymore (Phillips 1966). In that case, the terms proportional to \( 1/r \) (metric terms) and the Coriolis terms proportional to \( f' \) are neglected in the momentum equations. To be valid, this approximation needs \( N^2 >> \Omega^2 \) (Phillips 1968), however White & Bromley (1995) show that it might break whenever large diabatic processes are at stake, a limitation further confirmed by (Mayne et al. 2014).

4. *The hydrostatic approximation.* In the vertical momentum equation, the gravitational term is assumed to be balanced by the pressure gradient term. This is valid as long as the vertical extent of the atmosphere is small compared to its vertical extent (i.e. \((H/L)^2 << 1\)).
Usually valid but ….. because exoplanets can be crazy, they are sometimes borderline! Mainly planets for which the atmosphere is a significant part of their radius.

See Mayne et al papers

The Limits of the Primitive Equations of Dynamics for Warm, Slowly Rotating Small Neptunes and Super Earths.

N. J. Mayne,1 B. Drummond,1 F. Debras,2 E. Jaupart,2 J. Manners,3 I. A. Boutle,3 I. Baraffe,2,1 and K. Kohary1
General agreement of the *broad* features
Equatorial superrotation in Hot Jupiters

- Kelvin wave trapped at +/-Ld latitude
- Rossby wave at high latitude

![Graph showing the distribution of atmospheric properties in Hot Jupiters, with vectors indicating wind direction and contours showing pressure or temperature.]

- [Axes: Northward distance vs. Eastward distance]
- [Graph b: Temperature or pressure distribution with vectors indicating wind direction.]
- [Graph c: Acceleration vs. Northward distance, showing the curvature of the isopleths indicating the direction and strength of the Rossby wave.]
Equatorial superrotation in Hot Jupiters

Rossby wave at high latitude
Kelvin wave trapped at +/-Ld latitude
Rossby wave at high latitude

Flux of longitudinal momentum:

\[ F = mu \times v \]

\[ < F > = m < uv > \]

\[ < F > = m < u'v' > \]

\[ < F > = m < u > < v' > + m < u'v' > + m < u > < v > + m < u' > < v > \]
General agreement of the *broad* features

Knutson et al. (2007) *(Observation)*

Showman & Guillot (2002)

Mendonca et al. (2018)

Heng et al. (2011)

Showman et al. (2009)

Cho et al. (2015)

Rauscher & Menou (2012)

Amundsen et al. (2016)

Fig. 4: Example GCM simulations of hot Jupiters from a variety of groups in the field. Despite differences in forcing setup numerics, and other factors, all the models exhibit similar circulation regimes, comprising significant day-night temperature differences, a fast eastward equatorial jet, and an eastward-shifted dayside hot spot. All models assume synchronously rotation and conditions appropriate for typical hot Jupiters. Top left shows observations of HD 89753b from Knutson et al. (2007). Simulations of HD 209458b are shown from Showman and Guillot (2002), Feng et al. (2010), Rauscher and Menou (2012b), Amundsen et al. (2016), Cho et al. (2015). Simulations of HD 189733b from Showman et al. (2009). Simulations of WASP-43b from Mendonca et al. (2016). These seven simulations were performed with totally distinct numerical codes, involving varying approximation of radiative forcing and using seven independent dynamical cores. For each image, the sunspot at point is in the center of the panel, except for Mendonca et al. (2016), where the antistellar point is in the center.
Hot Spot shift

(a) **Height field of the** exact forced solution (*Matsuno* 1966).

(b) Solution Doppler-shifted eastwards by jet.

(c) Height perturbation from jet.

(d) Sum of (b) and (c), giving the same form as the full

Matsuno-Gill pattern

Eastward jet formation

Shifted Matsuno-Gill pattern

Hot spot shift
Thermal emission

Courtesy Tom Louden
Dayside is ~ 900°C (1620°F) hotter than nightside.

Amplitude

Thermal emission

Courtesy Tom Louden
Offset of the maximum

East hotter than west

Thermal emission

Courtesy Tom Louden
Qualitatively correct
Quantitatively wrong
Qualitatively correct
Quantitatively wrong
Qualitative behaviour?
Radiative timescale

\[ F = 4\sigma T^3 dT \]
\[ E = mc_p dT = \frac{P}{g} c_p dT \]

\[ \frac{E}{F} = \tau_{\text{rad}} \sim \frac{P}{g} \frac{c_p}{4\sigma T^3} \]
Radiative timescale

\[ F = 4\sigma T^3 dT \]

\[ E = mc_p dT = \frac{P}{g} c_p dT \]

\[ \frac{E}{F} = \tau_{\text{rad}} \sim \frac{P}{g} \frac{c_p}{4\sigma T^3} \]

This is valid at the photosphere only!
$\Delta T_{eq} = 1000K$

$\tau_{rad,top}(sec)$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$
Figure 3. Heat redistribution parameter $f = (T_{\text{day}}/T_{\text{eq}})^4$ for models with (purple) and without (orange) nightside clouds. We additionally show the fits provided in section 3.2. When nightside clouds are present the heat transport is much less efficient.
\[ \tau_{\text{rad}} \approx \frac{P_{\text{photo}}}{g \frac{c_p}{4 \sigma T_{\text{photo}}^3}} \propto \frac{P_{\text{photo}}}{T_{\text{photo}}^3}, \]

\[ \tau_{\text{wave}} \approx \frac{\pi R_p}{\sqrt{k_B T_{\text{photo}}/\mu}} \propto \frac{1}{\sqrt{T_{\text{photo}}}}. \]

\[ \tau_{\text{adv}} \approx \frac{\pi R_p}{U_{\text{jet}}} \propto \frac{1}{T_{\text{eq}}}. \]
\[ \tau_{\text{rad}} \left( T_{\text{night}} \right) \approx \tau_{\text{adv}} \]

\[ T_{\text{night}} \approx \left( \frac{P_{\text{photo}} \ c_p \ U_{\text{jet}}}{g \ 4\sigma \ \pi R_p} \right)^{1/3} \]

\[ T_{\text{night}} \propto \left( T_{\text{eq}} \right)^{1/3} \]
$\tau_{\text{rad}} (T_{\text{night}}) \approx \tau_{\text{adv}}$

$T_{\text{night}} \approx \left( \frac{P_{\text{photo}}}{g} \frac{c_p}{4\sigma} \frac{U_{\text{jet}}}{\pi R_p} \right)^{1/3}$

$T_{\text{night}} \propto (T_{\text{eq}})^{1/3}$

Helling et al. 2020
All hot Jupiters have roughly the same nightside temperature because of the strong temperature dependence of the radiative timescale to temperature!

\[ \tau_{\text{rad}} \left( T_{\text{night}} \right) \approx \tau_{\text{adv}} \]

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\[ T_{\text{night}} \propto \left( T_{\text{eq}} \right)^{1/3} \]

All hot Jupiters have roughly the same nightside temperature because of the strong temperature dependence of the radiative timescale to temperature!

And clouds help….
Global Circulation Model: solves the primitive equation, Euler equation adapted to atmospheres

SPARC: solves the radiative energy balance with non-grey, molecular opacities

$T_{eq} = 1400$K, $p=115$ mbar

Parmentier+ in prep.
Qualitatively correct
Quantitatively wrong
Qualitatively correct
Quantitatively wrong
Dissipation ?
Numerical drag, essential for models?

Current GCMs equilibrate the winds with the numerical drag...

And so our wind speed is very uncertain!
When drag really goes away…

Very high spatial resolution → Less numerical drag !
When drag really goes away...

Skinner et al. 2020

Very high spatial resolution models produces variability not seen in HJ!

Agol et al.
Parameterizing drag

\[ \mathbf{F}_{\text{drag}} = -k_v(p) \mathbf{v}. \]

Drag equivalent to 10 GAUSS

No drag

Arcangeli et al. 2019
Drag: exemple of WASP-18b

Arcangeli et al. 2019
Parameterizing drag

\[ \mathcal{F}_{\text{drag}} = -k_v(p)v \]

\[ \Delta T_{\text{eq}} = 1000 \text{K} \]

\[ \tau_{\text{rad, top}}(\text{sec}) \]

Temperature (K)

Latitude (degrees)

Longitude (degrees)
Parameterizing drag

\[ F_{\text{drag}} = -k_v(p) v. \]

Parmentier & Crossfield 2018
Physical sources of drag

Hydrodynamical: shear instability, Kelvin-Helmoltz instabilities, shocks, wave-jet interactions

Magnetic: Ohmic drag
Shear & Kelvin Helmoltz instabilities

Kelvin Helmoltz instabilities connected to…

Shear instabilities?

Fromang 2018

Fig. 15: Spacetime (time-pressure) diagram of the zonally averaged high frequency component of the zonal wind (see text for details) in color contours (note that the color table has been saturated at $50 \text{ m s}^{-1}$). Contours of $Ri$ (solid lines) and $T$ (dashed lines) are overplotted. For $Ri$, contours are for $Ri = 0.1$ and $0.25$. For the temperature, contours are for $T = 1900$, $2000$, $2100$ and $2200$ K.
Shear & Kelvin Helmoltz instabilities

Beta plane approximation

Fromang 2018
Shear & Kelvin Helmholtz instabilities

Hot Jupiter Atmospheric Flows at High Resolution

Kristen Menou,1,2,3

Localized equatorial β-plane simulations by Fromang et al. (2016) have revealed that a barotropic (horizontal shear) instability of the equatorial jet appears at horizontal resolutions beyond those typically achieved in global models; this instability could limit wind speeds and lead to increased atmospheric variability. To address this possibility, we adapt the computationally efficient, pseudo-spectral PlaSim GCM, originally designed for Earth studies, to model Hot Jupiter atmospheric flows and validate it on the Heng et al. (2011) reference benchmark. We then present high resolution global models of HD209458b, with horizontal resolutions of T85 (128x256) and T127 (192x384). The barotropic instability phenomenology found in β-plane simulations is not reproduced in these global models, despite comparably high resolutions. Nevertheless, high resolution models do exhibit additional flow variability on long timescales (of order 100 planet days or more), which is absent from the lower resolution models. It manifests as a breakdown of north-south incompressible approximation?
Hot Jupiters are conductive!

\[ \sigma = 1 \text{ (S/m)} \]

\[ K \text{ ionization} \quad \text{Na ionization} \]

- \( P = 0.001 \text{Bar} \)
- \( P = 0.01 \text{Bar} \)
- \( P = 0.1 \text{Bar} \)
- \( P = 1 \text{Bar} \)
\[ \nabla \cdot \vec{\rho} \vec{v} = 0 \]
\[ \nabla \cdot \vec{B} = 0 \]
\[ \rho = \left( \frac{\partial \rho}{\partial T} \right)_p T + \left( \frac{\partial \rho}{\partial p} \right)_T p \]
\[ \vec{p} = -\nabla \cdot (\vec{\rho} \vec{v}) - \nabla p - \rho \vec{g} \vec{t} \]
\[ + 2 \vec{\rho} \times \vec{\Omega} + \nabla \cdot \left( 2 \vec{\rho} \vec{v} \left( c_{ij} - \frac{1}{3} (\nabla \cdot \vec{v}) \delta_{ij} \right) \right) \]
\[ + \frac{\nabla \times \vec{B} \times \vec{B}}{\mu_0} \]
\[ \frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) - \nabla \times (\vec{\eta} \nabla \times \vec{B}) \]
\[ \frac{\partial T}{\partial t} + (\vec{v} \cdot \nabla) T = \]
\[ -v_r \left( \frac{\partial T}{\partial r} - (\gamma - 1) \bar{T} h_\rho \right) + (\gamma - 1) \bar{T} h_\rho v_r \]
\[ + \gamma \bar{\kappa} \left[ \nabla^2 T + (h_\rho + h_\tau) \frac{\partial T}{\partial r} \right] \]
\[ + \frac{T_{eq} - T}{\tau_{rad}} + \frac{\bar{\eta}}{\mu_0 \rho c_\rho} |\nabla \times \vec{B}| \]
Ideal MHD: depends strongly on magnetic field strength!

Works only for the very hot planets... unless $B > 100$ Gauss

**Magnetic drag**

$U$ [m/s]

$T_{eq}$ [K]

$B$

- 1 Gauss
- 3 Gauss
- 10 Gauss
- 30 Gauss
- 100 Gauss

Koll & Komacek
Qualitatively correct
Quantitatively wrong

Magnetic drag?
Ideal MHD

Rogers 2017

Hindle et al. 2022
Ideal MHD

Rogers et al.

Armstrong et al.

But... only 2 planets....
Maybe instrument systematics
Clouds ?
Clouds in HST/WFC3?

**H$_2$O absorption feature**

Water absorption should look like this

\[
R_p(\lambda_1) - R_p(\lambda_2) = \log \left( \frac{\xi_a S_a(\lambda_1)}{\xi_b S_b(\lambda_2)} \right) H
\]

Expected

Deming et al. 2013

Lecavelier Des Etangs et al. 2008,
Benneke+2012, Griffith+2014, Line+2016,
Heng+2017

If water only is seen then the transmission spectrum is not sensitive (to order 0) to the water abundance.
Clouds in HST/WFC3?

If water only is seen then the transmission spectrum is not sensitive (to order 0) to the water abundance.

\[ R_p(\lambda_1) - R_p(\lambda_2) = \log \left( \frac{\xi_a S_a(\lambda_1)}{\xi_b S_b(\lambda_2)} \right) H \]

Abundance

Cross-section


Water absorption should look like this but it does not.
Clouds in HST/WFC3?

Water absorption should look like this but it does not.

\[ R_p(\lambda_1) - R_p(\lambda_2) = \log \left( \frac{\xi_a S_a(\lambda_1)}{\xi_b S_b(\lambda_2)} \right) H \]
Clouds in HST/WFC3?

Water absorption should look like this but it does not

→ it is obscured by $\text{H}_2$

small water abundance

Deming et al. 2013

\[ R_p(\lambda_1) - R_p(\lambda_2) = \log \left( \frac{\xi_a S_a(\lambda_1)}{\xi_b S_b(\lambda_2)} \right) H \]
Water absorption should look like this but it does not

→ it is obscured by H$_2$

small water abundance

→ it is obscured by clouds

any water abundance

\[ R_p(\lambda_1) - R_p(\lambda_2) = \log \left( \frac{\xi_a S_a(\lambda_1)}{\xi_b S_b(\lambda_2)} \right) H \]
Clouds in GCMs naturally form spatial patterns!
How to form partial clouds?

—Circulation driven partial clouds

*Probably always present, enhanced by radiative feedback?*

Parmentier+ 2013, passive tracers

(see also Charnay+2016)

Parmentier+ 2013, passive tracers

(see also Charnay+2016)

Lines+2018 radiatively active clouds
How to form partial clouds?

-Temperature driven partial clouds

More important for hot & tidally locked

West limb at nightside temperature
Cloudy

East limb at dayside temperature
Cloudless

See also: MacDonald+2016, Kempton+2018
How to form partial clouds?

Or a combination of both

Mean particle sizes in HD189

coupled microphysics GCM

Lee et al. 2016

(see also Lines+2017)

Dayside reflected light of HD189733b with MnS as passive tracers SPARC/MITgcm
Wavelength dependence of the phase curve

Reflective light phase curve: negative offset

West cloudier than east

Kepler-7b

Demory et al. 2013

Offset of the maximum

Thermal emission

Courtesy Tom Louden
Wavelength dependence of the phase curve

Parmentier et al. 2016

The graph shows the wavelength dependence of the phase curve for different planets: Kepler-12 b, Kepler-7 b, Kepler-8 b, Kepler-41 b, and HAT-P-7 b. The x-axis represents the equilibrium temperature ($T_{eq}$) for $A_B=0$, while the y-axis shows the Kepler phase curve offset in degrees. The data points indicate a trend for each planet, with HAT-P-7 b showing a notable offset.
Wavelength dependence of the phase curve

Parmentier et al. 2016
Wavelength dependence of the phase curve

![Graph showing the phase curve with different wavelengths and phases.](image)

- **Fp/Fₚₜ [ppm]**
- **Phase (°)**
- **Total**, **Reflected**, **Emitted**

Parmentier et al. 2016

**Model:** Teq = 1900K
Wavelength dependence of the phase curve

Parmentier et al. 2016
Travel to your nearest Hot Jupiter

Equilibrium temperature

Cloud chemical composition

Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye
Travel to your nearest Hot Jupiter

Equilibrium temperature

Parmentier et al. 2016

Cloud chemical composition

Large $T_{eq}$: No clouds

Hot Jupiter daysides as seen by a human eye
Travel to your nearest Hot Jupiter

Equilibrium temperature

Cloud chemical composition

Small $T_{eq}$: Fully cloudy

Large $T_{eq}$: No clouds

Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye
Travel to your nearest Hot Jupiter

Equilibrium temperature

- Small $T_{eq}$: Fully cloudy
- Large $T_{eq}$: No clouds

Observations: partially cloudy

Cloud chemical composition

Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye
Travel to your nearest Hot Jupiter

Equilibrium temperature

Small $T_{eq}$: Fully cloudy

Observations: partially cloudy

Large $T_{eq}$: No clouds

Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye
Travel to your nearest Hot Jupiter

Equilibrium temperature

Small $T_{eq}$:

- **Fully cloudy**

Observations:

- **partially cloudy**

Large $T_{eq}$:

- **No clouds**

Cloud chemical composition

- $\text{Na}_2\text{S}$
- $\text{CaTiO}_3$
- $\text{Al}_2\text{O}_3$
- $\text{Fe}$
- $\text{MgSiO}_3$
- $\text{Cr}$
- $\text{MnS}$

Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye
A temperature dependent cloud composition?

Kepler phase curve offset (°)

Data
Cloudless
CaTiO3
Fe
Al₂O₃
MgSiO₃
Cr
MnS
Na₂S

Parmentier et al. 2016
How nightside clouds affect the circulation?

Clear atmosphere

\[ T_{\text{eq}} = 1400\text{K}, \ p = 115\ \text{mbar} \]
How nightside clouds affect the circulation?

Clear atmosphere

MnS optical properties & abundances

Cloud base 200mbar

Well mixed vertically

Monosize

Parmentier et al. 2020
How nightside clouds affect the circulation?

Clear atmosphere

Nightside clouds

Parmentier et al. 2020
How nightside clouds affect the circulation?

Clear atmosphere

Reduce day/night temperature contrast

Nightside clouds

Does not affect hot spot shift

Parmentier et al. 2020
How nightside clouds affect the thermal phase curve?

Amplitude increased
Phase offset reduced

$F_p/F_s$ (ppm) - Spitzer 3.5μm

Cloudless
Cloudy nights

Parmentier et al. 2020
How nightside clouds affect the thermal phase curve?

- Amplitude increased
- Phase offset reduced
- Phase curve amplitude ≠ day/night temperature contrast on isobars

Phase curve offset ≠ hot spot position

Parmentier et al. 2020
Phase curves are not probing isobars!

Parmentier et al. 2022
Clouds: when small changes have a big impact

Inhomogeneous clouds allow theory and observations in better agreement

Hypothesis:
Cloudy nights
Clear sky days

Parmentier & Crossfield. 2017
JWST will test this before the end of the year!

To be observed before the end go the month!
Composition ?
Molecular dissociation for hot planets
Molecular dissociation for hot planets

% of dissociated water at the expected 1.4μm photosphere

Gravity (m/s²)

Dayside photospheric temperature (K) with dayside only redistribution
Ultra-hot Jupiters: thermal dissociation

Thermal dissociation and condensation makes 3D chemical patterns!
**Normalized day-night temperature contrast**

- **y-axis**: Normalized day-night temperature contrast
- **x-axis**: Dayside-redistribution equilibrium temperature [K]

**Legend**:
- Green dashed line: \( \tau_{\text{drag}} = 10^7 \text{ s} \)
- Black solid line: \( \tau_{\text{drag}} = 10^4 \text{ s} \)
- Light green dashed line: No dissociation

**Data Sources**:
- CoRoT-2b
- HD 149026b
- WASP-14b
- WASP-16b
- HAT-P-7b
- WASP-17b
- WASP-26b
- WASP-18b
- WASP-123b
- WASP-124b
- WASP-126b
- WASP-33b
- WASP-38b
- WASP-2100b
- KELT-9b

**Markers**:
- **TESS**: 4.5\(\mu\)m
- **WFC3**: 3.6\(\mu\)m
- **8\(\mu\)m
Modelling the high-resolution spectra of 3D exoplanets

Start of the transit:
Hot part of leading limb

End of transit:
Hot part of trailing limb dominates

Wardenier et al. 2021
Almost local wind speed measurement is now possible!
Locally measured wind speed on WASP-76b!

Gandhi et al. 2022
Diversity of circulation?
A diversity of parameters
Modelling hot Jupiter’s population

Alexander Roth in prep.
Global Circulation Model: solves the primitive equation, Euler equation adapted to atmospheres
SPARC: solves the radiative energy balance with non-grey, molecular opacities

Modelling hot Jupiter’s population

$T_{eq} = 1400\text{K, } p = 115\text{ mbar}$

Parmentier+2020
«Redistribution factor»: how hot is the dayside in terms of $T^4$ compared to full redistribution
Modelling hot Jupiter’s population

« Redistributed factor » : how hot is the dayside in terms of $T^4$ compared to full redistribution

Hotter planets are poorer at transporting heat
But there is an enormous variability!
Modelling hot Jupiter’s population
Modelling hot Jupiter’s population

Blackbody

S_H2O

Water index

Mansfield+2020
Modelling hot Jupiter’s population

$S_{H20}$ Water index

Mansfield+2020
Modelling hot Jupiter’s population

![Graph showing the relationship between water feature strength ($S_{H_2O}$) and dayside temperature (K). The graph includes data points for 'With TiO and VO', 'Without TiO and VO', and 'Planet Data'.]
Models with TiO/VO have inversions and $S_{\text{H}_2\text{O}}>0$

In chemical equilibrium TiO/VO condenses at $\sim 1600\text{K}$
Models with TiO/VO have inversions and \( S_{\text{H}_2\text{O}}>0 \).

Models without TiO/VO have no inversions and \( S_{\text{H}_2\text{O}}<0 \).

In chemical equilibrium TiO/VO condenses at \(~1600\text{K}\).
Models with TiO/VO have inversions and $S_{\text{H}_2\text{O}}>0$

Models without TiO/VO have no inversions and $S_{\text{H}_2\text{O}}<0$

In chemical equilibrium TiO/VO condenses at \~1600K

Water dissociation and H-, makes ultra-hot Jupiters near blackbodies at 1-2microns
Models with TiO/VO have inversions and $S_{H2O} > 0$

Models without TiO/VO have no inversions and $S_{H2O} < 0$

Water dissociation and H-, makes ultra-hot Jupiters near blackbodies at 1-2 microns

In chemical equilibrium TiO/VO condenses at ~1600K

The models are *avoiding* the data!
**A diversity of condensates?**

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**Confidence level:**
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PPVII chapter
A diversity of condensates?

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Condensed corner?

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Condensation affects abundances

TiO abundance on the dayside of a hot Jupiter with nightside condensation
Condensation affects abundances

- TiO abundance set by competition between
  - Settling on the nightside
  - Vertical mixing everywhere

If TiO is trapped in particles larger than a few microns, there won’t be enough on the dayside to form a thermal inversion.

TiO abundance on the planet dayside depends on detailed microphysics on the planet nightside!
Conclusions

— Large scale day/night heating drive pressure gradient balanced by Coriolis (period)/ drag/ advection/wave transport.

— Radiative cooling important affected by composition/clouds !

— Drag mechanisms unclear. Current models equilibrate with either numerical drag or parameterised drag

— No good estimate of actual wind speed despite observations being able to measure them directly

— Spatially varying clouds and composition can change observable. Phase curve offset to hot spot offset mapping not immediate ! *Eclipse mapping solution ?*

— Data is becoming of very good quality, models needs to up their game !