Self-Consistent Phase Curve Retrieval in the ARIEL Era

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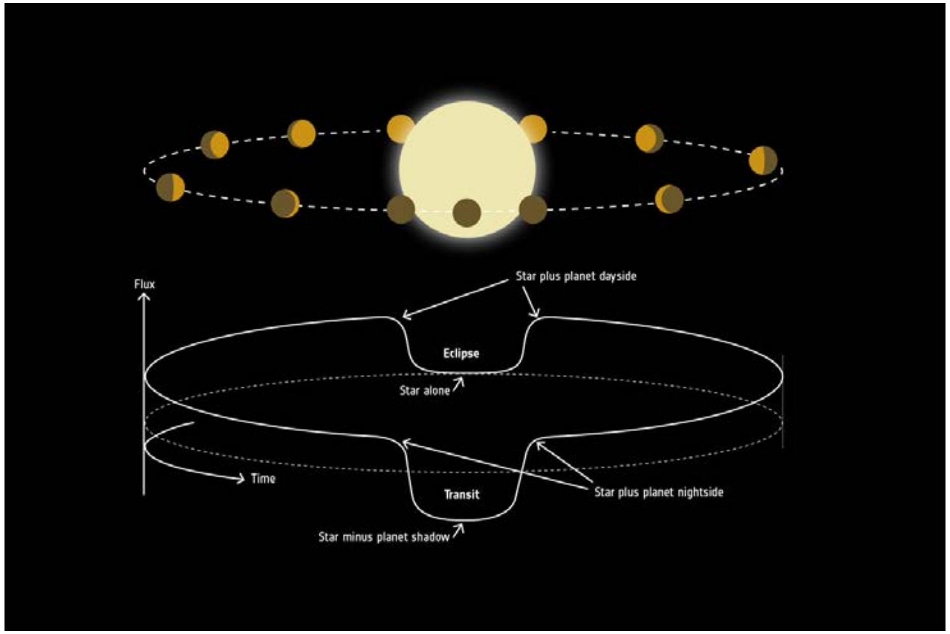
Phase Dependent Retrieval

NOVEL PARAMETRIZED 2D T-P MODEL FOR PHASECURVE RETRIEVAL

- Links temperature profiles between different phases
- Retrieves all planetary phases simultaneously
- Utilizes fundamental property of giant planet atmospheres
- Uses GCM simulations and Guilot (*2010*), Hansen (*2008*) to formulate the parametrization
- Provides valuable feedback for GCM models



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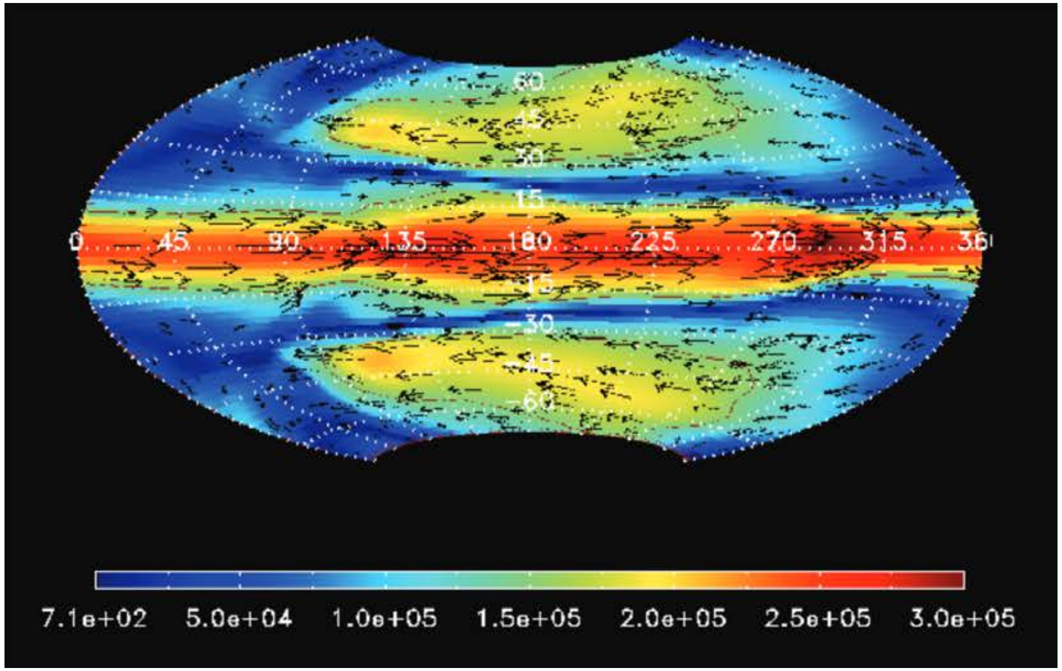
Gas Giants Fundamental Property

- **SHORT-PERIOD GAS GIANTS**
  - Tidally locked
  - Temperature gradients
  - Jets advect energy
  - Complex atmospheric dynamics
  - Compositional and temperature differences
- **PHASECURVES**
  - Most comprehensive information about planetary envelopes
    - Atmospheric dynamics
    - Chemical processes
    - Radiative energy balance
    - Temperature structure
    - Day-night redistribution

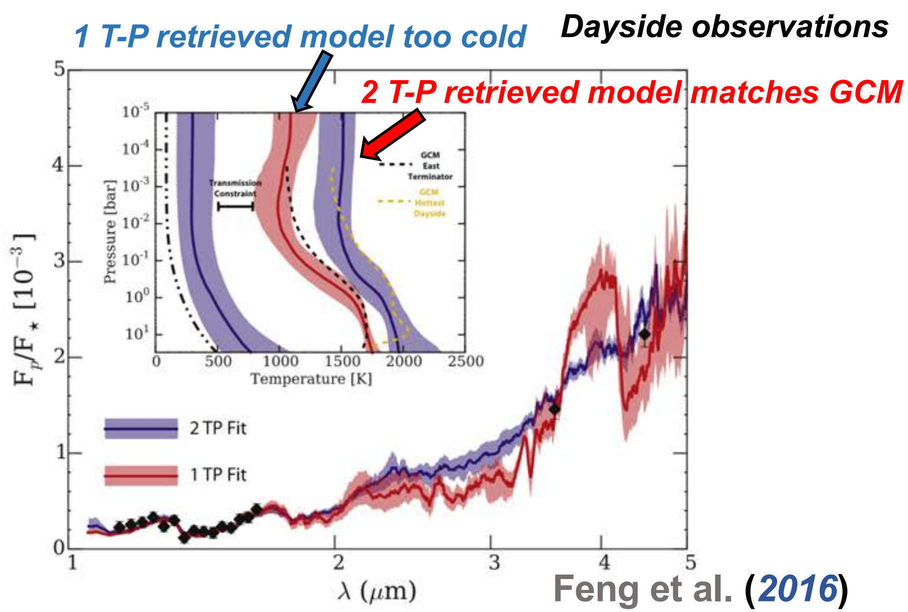
EQUATORIAL AND MID-LATITUDE JETS IN GAS GIANTS



Dobbs-Dixon & Lin (*2008*)

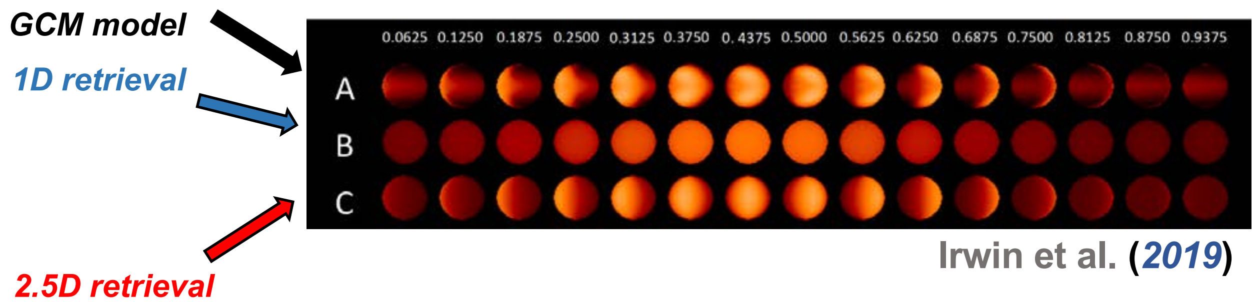
Atmospheric Retrieval - Current State

- Day- and night-side retrieval uses 1D models
- Independent phasecurve retrieval
  (e.g., Stevenson et al. *2017*, Kreidberg et al. *2018*)
- Simultaneous retrieval studies
  Feng et al. (*2016*, *2020*), Irwin et al. (*2019*)



Feng et al. (*2016*)

SIGNIFICANCE OF INDEPENDENT PHASECURVE RETRIEVAL
(Venot et al. *2020*, ApJ, accepted)

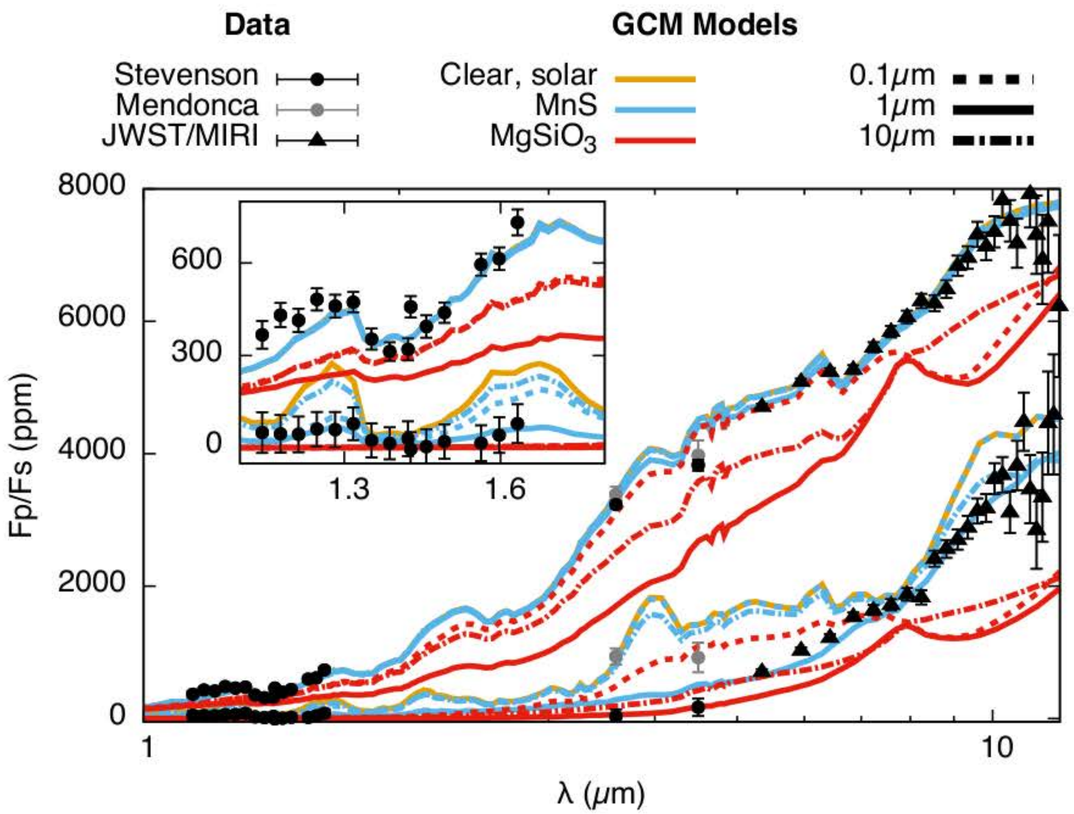


Irwin et al. (*2019*)

WASP-43b Independent Phasecurve Retrieval

Venot, Parmentier, Blecic et al., accepted (*2020*)

- **THOROUGH MODELING WORK**
  - Radiative-convective - ATMO models
  - Chemical kinetics - Venot
  - Cloud microphysics - Gao
  - Global circulation models - Parmentier
- **ATMOSPHERIC RETRIEVAL**
  - Pandexo – data and uncertainties
  - Cloud-free and cloudy models
- **QUESTIONS IMPOSED**
  - Distinguish between equilibrium and quenched cloud-free atmosphere?
  - Distinguish between MnS or MgSiO3 clouds on the night side?
- **RESULTS**
  - First conclusive quenched atmosphere
  - Distinguish cloud composition



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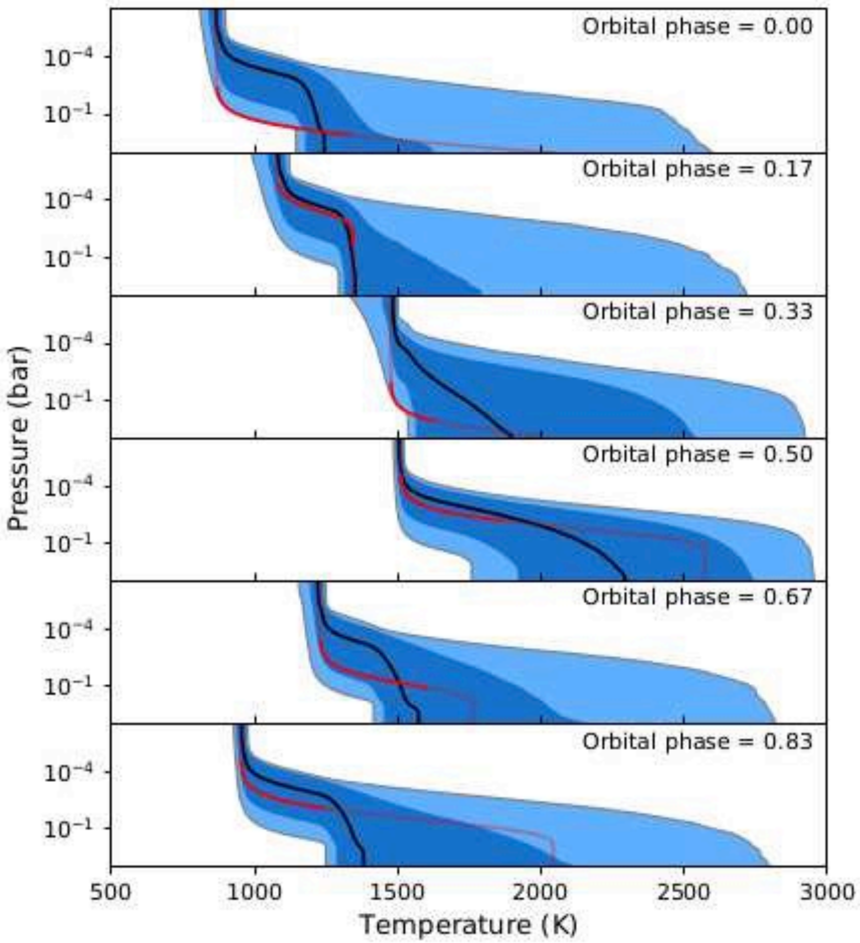
WASP-43b Independent Phasecurve Retrieval



- Cloud-free phasecurve retrieval
- Retrieve T-P profiles from each orbital phase independently
- Transport of heat noticeable
- One phase has no information about the other phase

WHAT LINKS THE PHASES TOGETHER?

EQUATORIAL JET

- T-P includes both advection and radiative time scales
- Sources and sinks
- Returns energy redistribution information
- Amplitude and phase offset
- Inform back GCM models

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2D Parametrization Scheme

- Utilizes GCM simulations from Ian Dobbs-Dixon
- Expands on Guilot (*2010*), Hansen (*2008*) formulation

Purely Radiative Solution

$$\int_0^\infty \kappa_\nu (J_\nu - B_\nu) \mathrm{d}\nu = 0$$

Emission balances absorption at any location

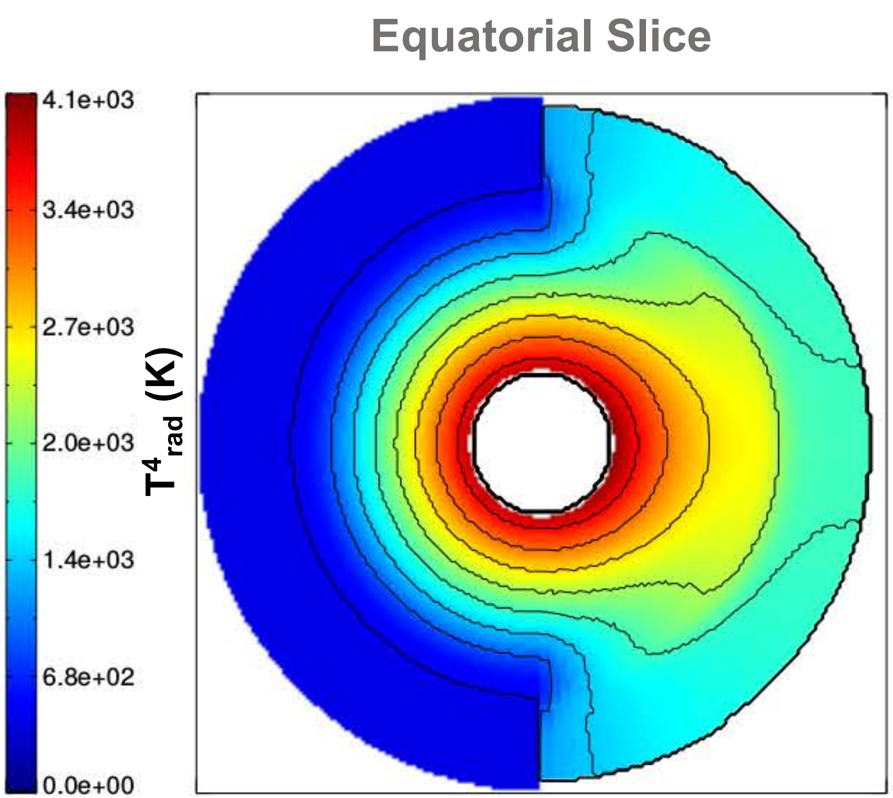
RESULTANT TEMPERATURE DISTRIBUTION: function of longitude and optical depth

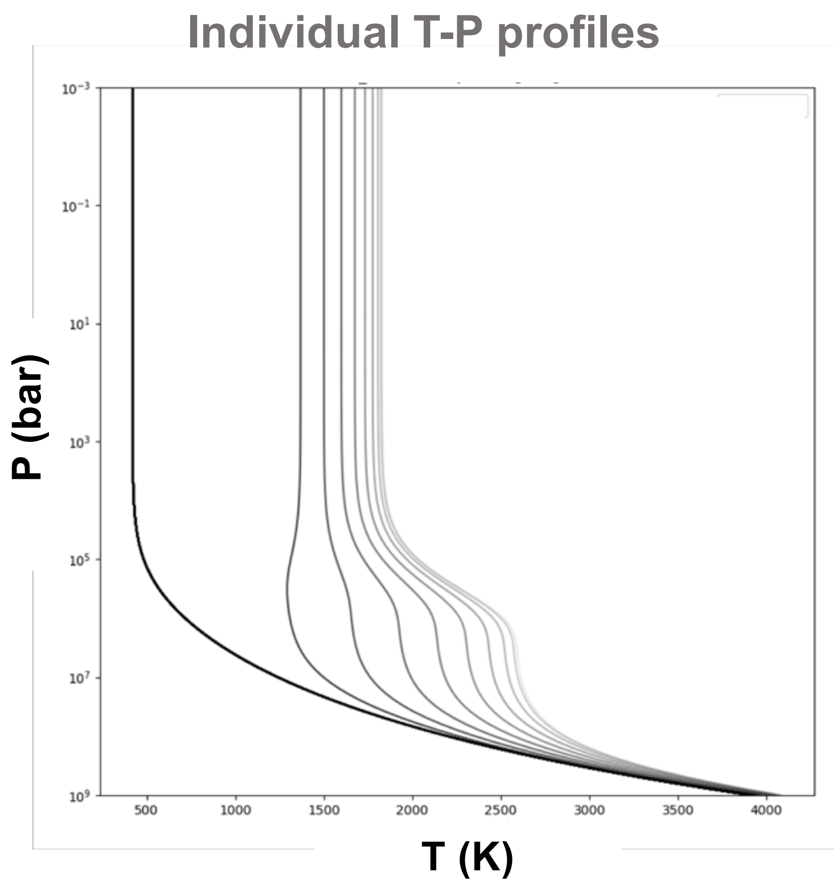
$$T^4 = \frac{3T_{\mathrm{int}}^4}{4}\left[\frac{2}{3} + \tau\right] + \frac{3T_{\mathrm{irr}}^4}{4}\mu_* \left[\frac{2}{3} + \frac{\mu_*}{\gamma} + \left(\frac{\gamma}{3\mu_*} - \frac{\mu_*}{\gamma}\right) \mathrm{e}^{-\gamma\tau/\mu_*}\right]$$

$$\mu_* = \cos\theta_*$$

Guillot (*2010*)
Hansen (*2008*)

Purely Radiative Solution





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Radiative Solution With Advection

$$\int_0^\infty \kappa(J_\nu - B_\nu)\mathrm{d}\nu = q\nabla T$$

Horizontal energy sink and gain

RESULTANT TEMPERATURE DISTRIBUTION: function of longitude and optical depth

$$\mu_* = \cos\theta_*$$

Radiation part

$$T^4 = \frac{3T_{\mathrm{int}}^4}{4}\left[\frac{1}{3f_{H\mathrm{th}}} + \frac{\tau}{3f_{K\mathrm{th}}}\right] + \frac{3T_{\mathrm{irr}}^4}{4}\mu_*\left[\frac{1}{3f_{H\mathrm{th}}} + \frac{\mu_*}{3\gamma f_{H\mathrm{th}}} + \left(\frac{\gamma}{3\mu_*} - \frac{\mu_*}{3\gamma f_{H\mathrm{th}}}\right)\mathrm{e}^{-\gamma\tau/\mu_*}\right]$$

Advection part

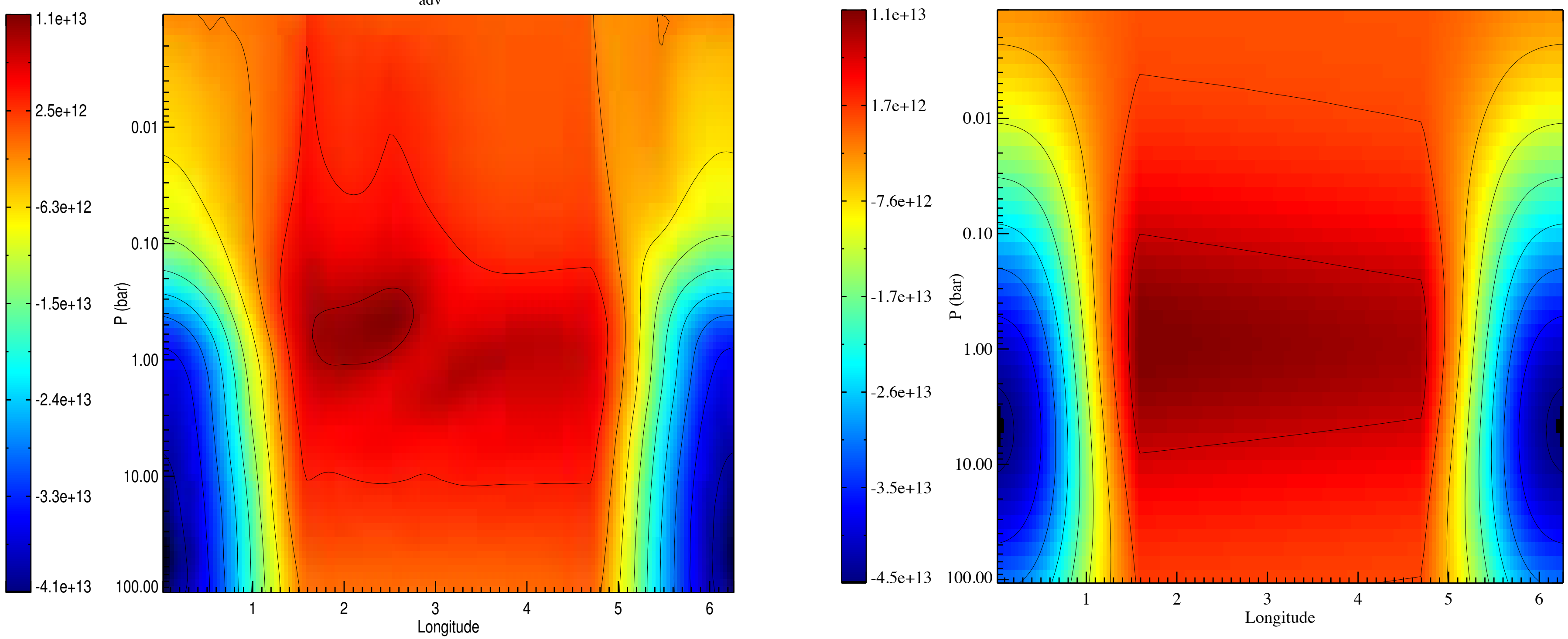
$$-\frac{\pi}{\sigma}\left\{\left(\frac{1}{f_{H\mathrm{th}}} + \frac{\tau}{f_{K\mathrm{th}}}\right)\int_0^\infty q\nabla T\,\mathrm{d}m + \frac{\tau}{f_{K\mathrm{th}}}\int_0^m\left(\frac{m'}{m} - 1\right)q\nabla T\,\mathrm{d}m' - q\nabla T\right\}.$$

Guillot (*2010*)
Hansen (*2008*)

$$T^4(\phi, \tau) = (T_{\mathrm{rad}}(\phi, \tau))^4 + (T_{\mathrm{adv}}(\phi, \tau))^4$$

Utilizing GCM to Define Advection

T^4_{adv} subtracted **T^4_{adv} parametrized**



$$(T_{adv}(\phi, \tau))^4 = (T(\phi, \tau))^4 - (T_{rad}(\phi, \tau))^4$$

GCM output

Analytic radiative solution

Dobbs-Dixon & Blecic, in prep

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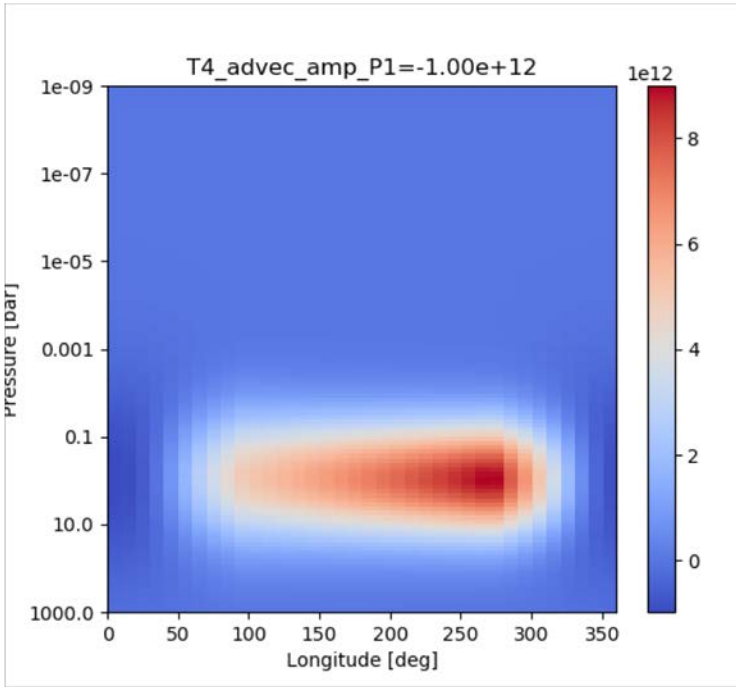
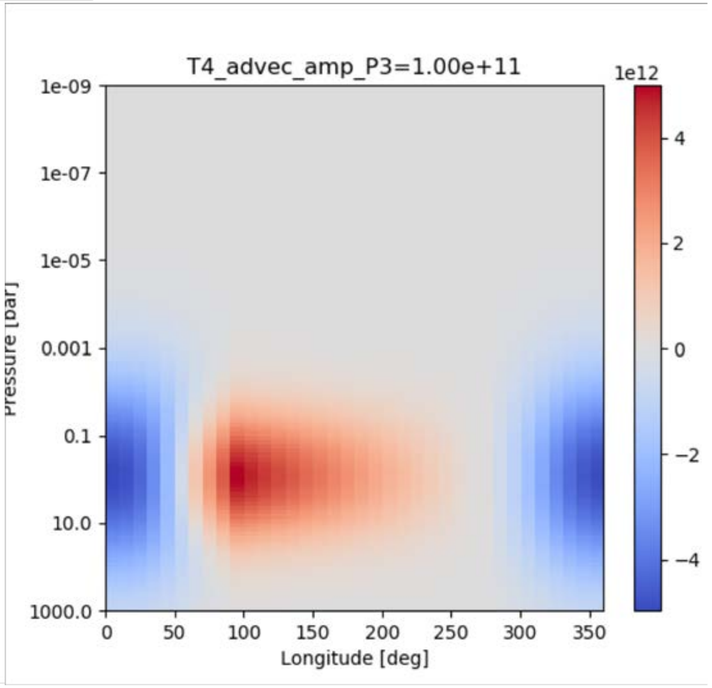
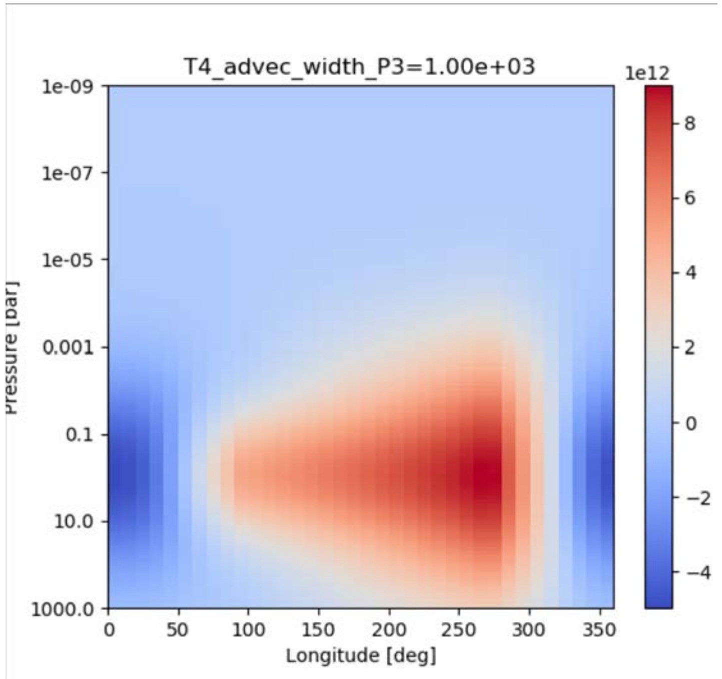
Variation in Jet Parameters





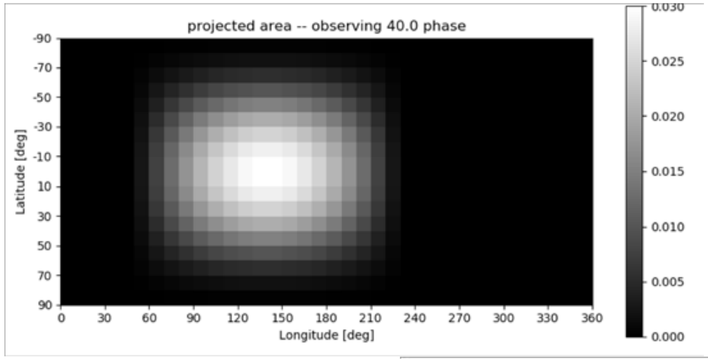


$$(T_{adv}(\phi, \tau))^4 = (T(\phi, \tau))^4 - (T_{rad}(\phi, \tau))^4$$

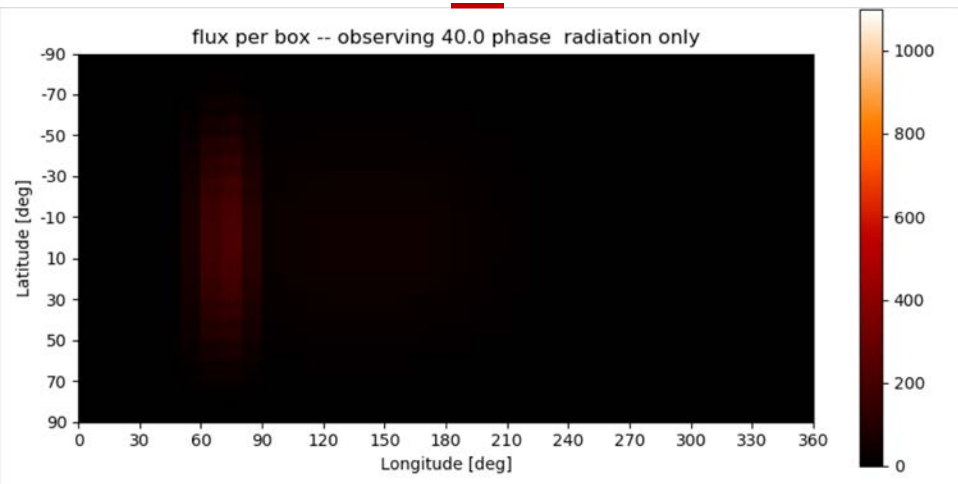
Dobbs-Dixon & Blecic, in prep

Extracting Phase Dependent Spectra

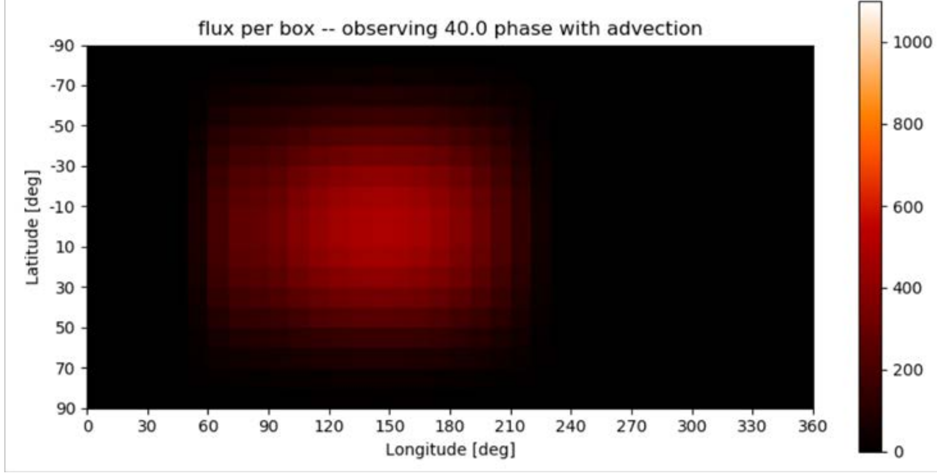
Observer's Visible Area at 40 degrees phase



Flux at 4.5 um No Advection



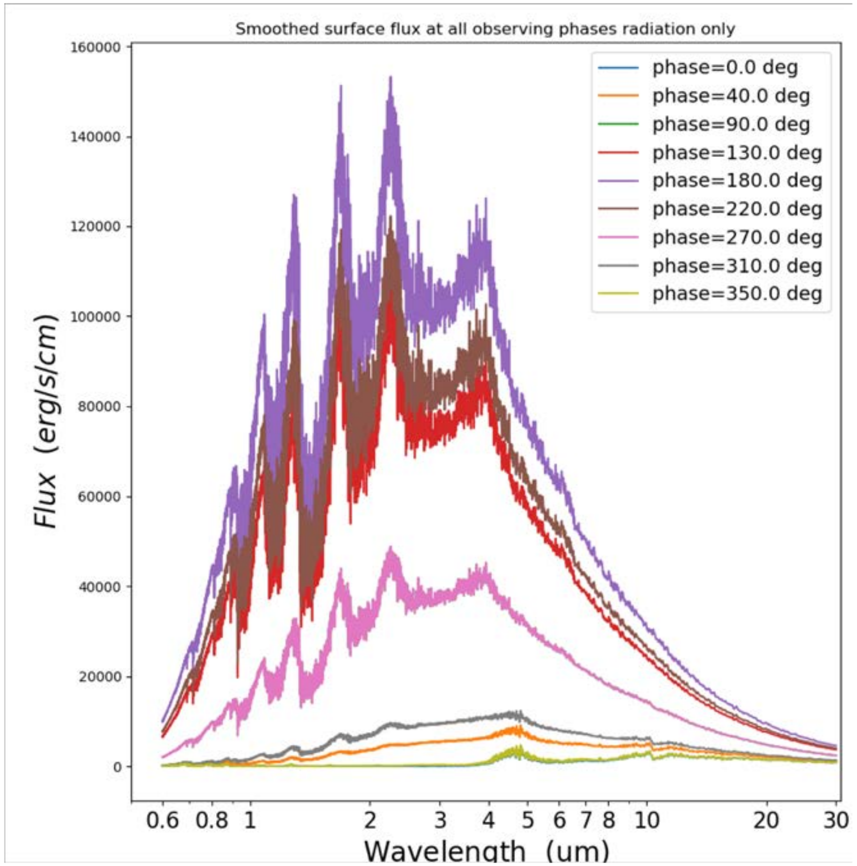
Flux at 4.5 um With Advection



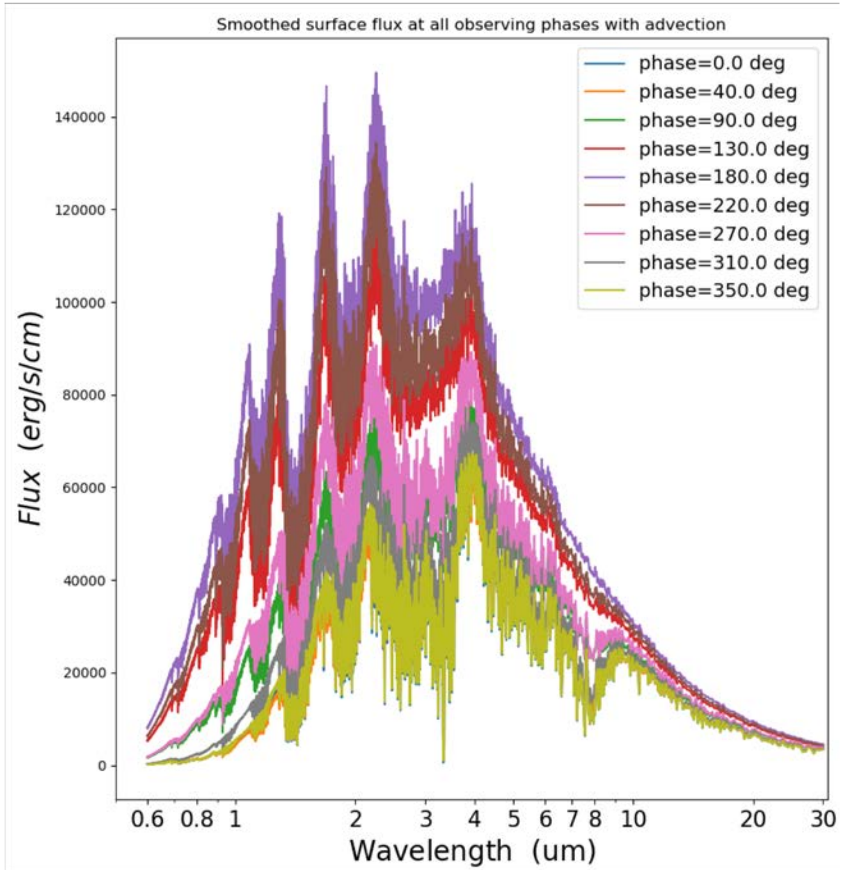
Dobbs-Dixon & Blecic, in prep

Extracting Phase Dependent Spectra

Flux No Advection



Flux With Advection



Dobbs-Dixon & Blecic, in prep

Summary

- Developed a novel parametrized 2D temperature scheme for atmospheric retrieval to generate phase dependent spectra where the individual phases are physically coupled (forward model)
- Next step is the implementation in retrieval – open-source PyratBay framework (**Cubillos & Blecic**, in prep)
- The goodness of fit of the model will be evaluated utilizing all orbital phases simultaneously
- The model will return the physical properties of the jet, the phase curve amplitude and offset
- Outputs can be used used to inform back the GCM

Dang et al. (*2018*)

Prospects

- Coupling with kinetic and thermal stability cloud models (**Blecic et al.**, in prep)
- Coupling with 2D chemical models
- The scheme is easily extended to 3D as it is evaluated in each pixel, allowing in addition a variation in latitude
- Represents comprehensive approach (physically motivated 3D T-P, chemical and cloud model) will be invaluable asset for ARIEL targets
- Photometric and spectroscopic observations between 0.5 and 7.9 um will allow us to answer all questions listed by Benjamin in a self-consistent way