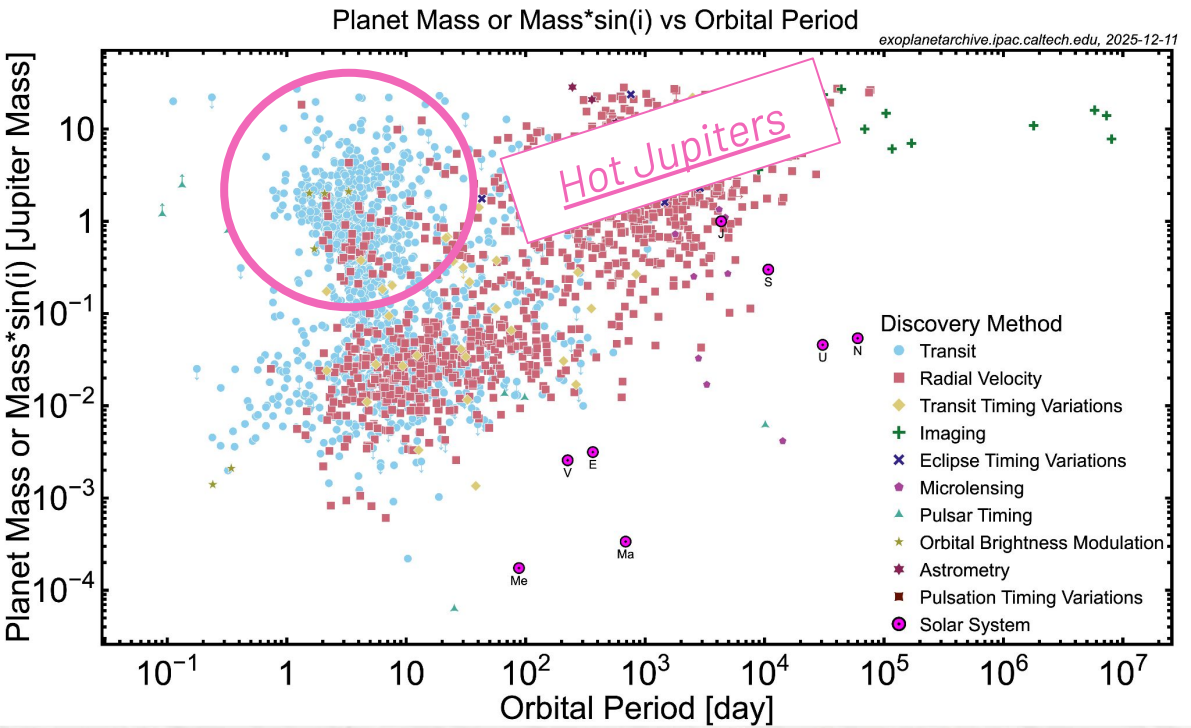
Unraveling the Mystery of the Western Hotspot Offset on the Young Hot Jupiter CoRoT-2b

Aurora Kesseli
aurorak@ipac.caltech.edu
Collaborators: Lisa Dang, Sid Gandhi, Alexis Lavail, Alex Sanchez-Lopez, Emily Rauscher, Hayley Beltz, Romain Allart, Stefan Pelletier

What is a Hot Jupiter?



- First type of exoplanet discovered!
- Orbital periods of a few days
- T_{eq} ~ 1000 - 4000K
- Thought to be tidally locked

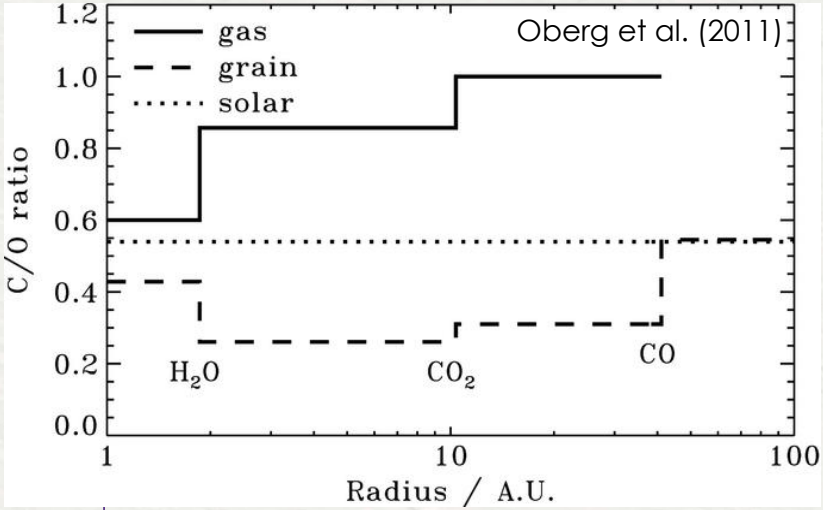
Why do we study them?

- How they form is an open question which has large consequences
- Most favorable targets: Great for testing GCMs, understanding cloud formation, etc.

Hot Jupiter Atmospheres

Studying atmospheres take us beyond bulk properties → what the planets are made of, clues about how they formed, and how their atmospheres circulate heat

Abundances



Bulk ratios (C/O, M/H, etc.) constrain planet formation theory and evolution history

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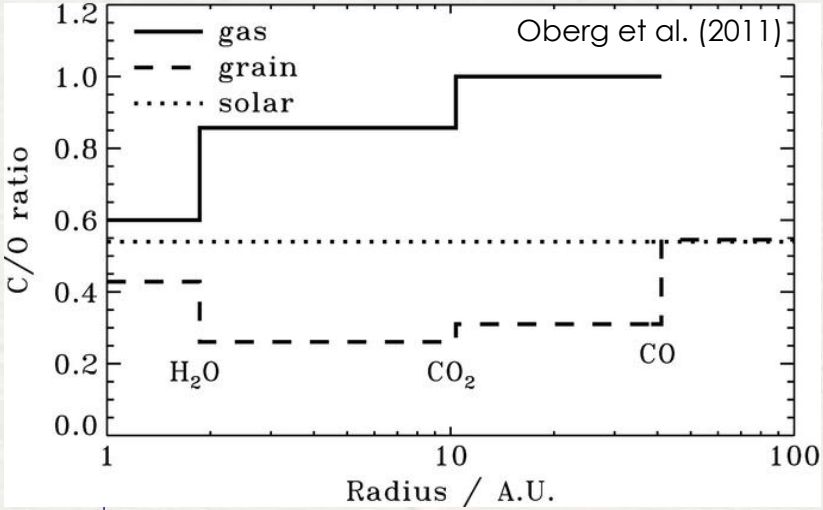

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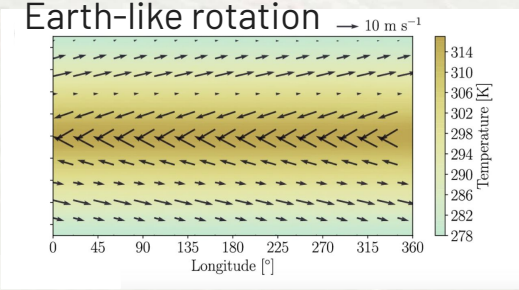
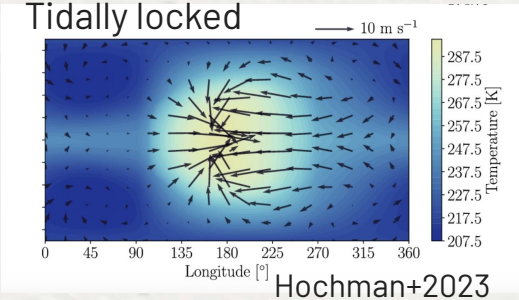
Dynamics & Circulation





Hochman+2023

The way in which planets circulate their heat can have large effects on what their atmospheres look like

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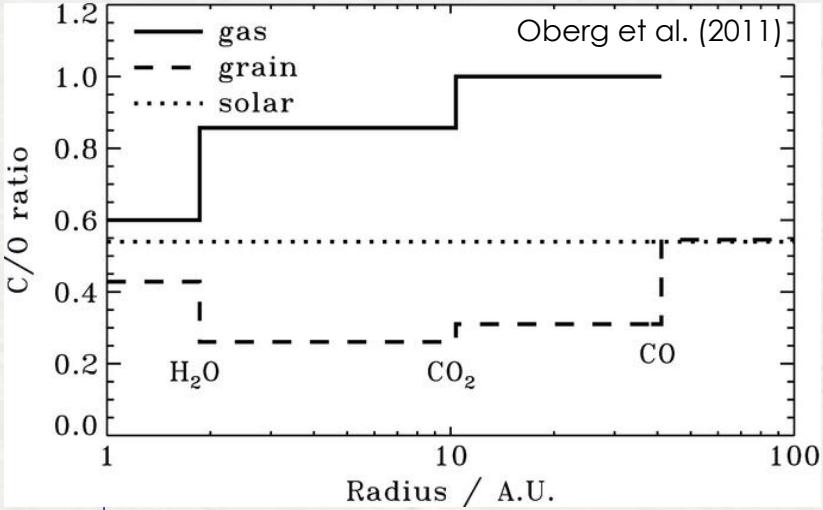

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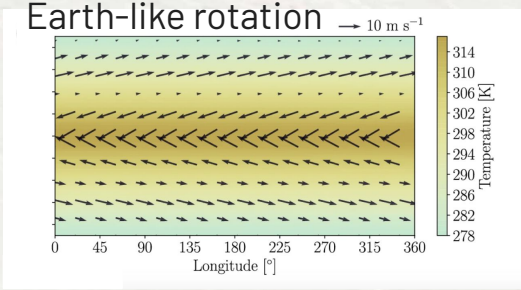
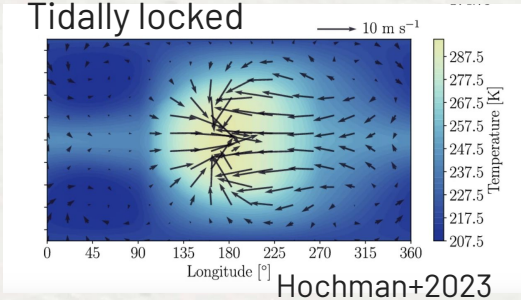
Dynamics & Circulation

Earth-like rotation



Tidally locked



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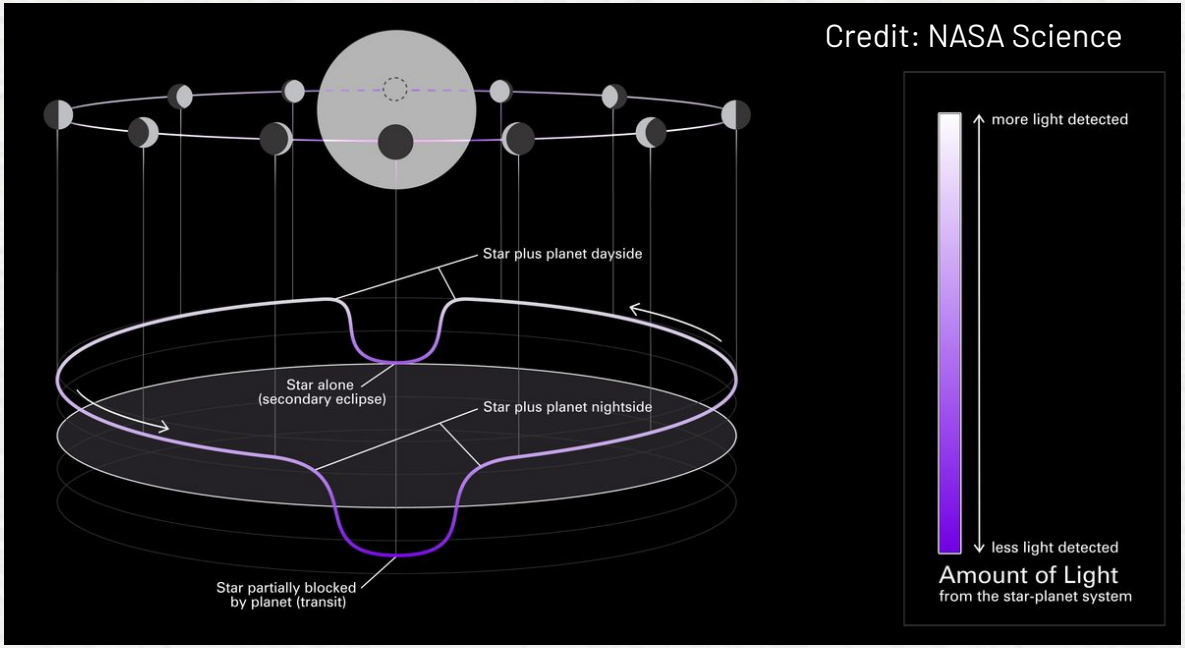
Atmospheric Circulation from Phase Curves



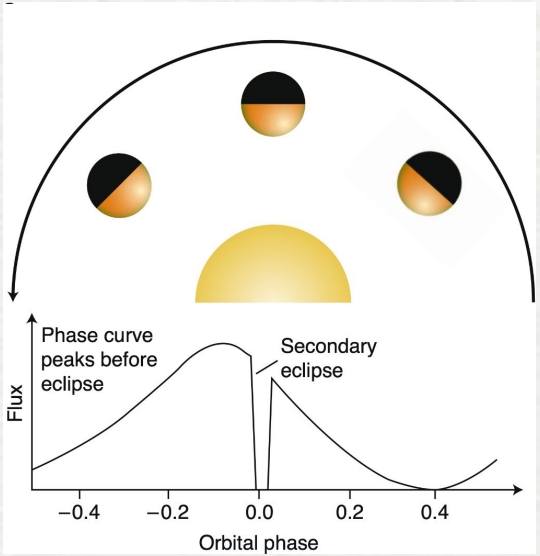
- Irradiated "dayside" of planet in view near eclipse (phase~0.5) = phase curve MAX
- Un-irradiated "nightside" of planet in view near transit (phase~0) = phase curve MIN

Returns temperature map across the full surface of planet → understand how hot Jupiters absorb and redistribute incident flux

Hotspot Offsets from Phase Curves

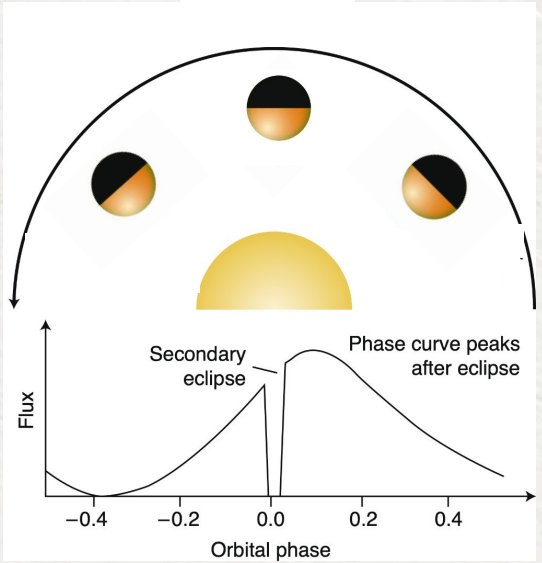
Brightest point **BEFORE** eclipse = **EASTERN** hotspot offset

Orbital motion



Brightest point **AFTER** eclipse = **WESTERN** hotspot offset

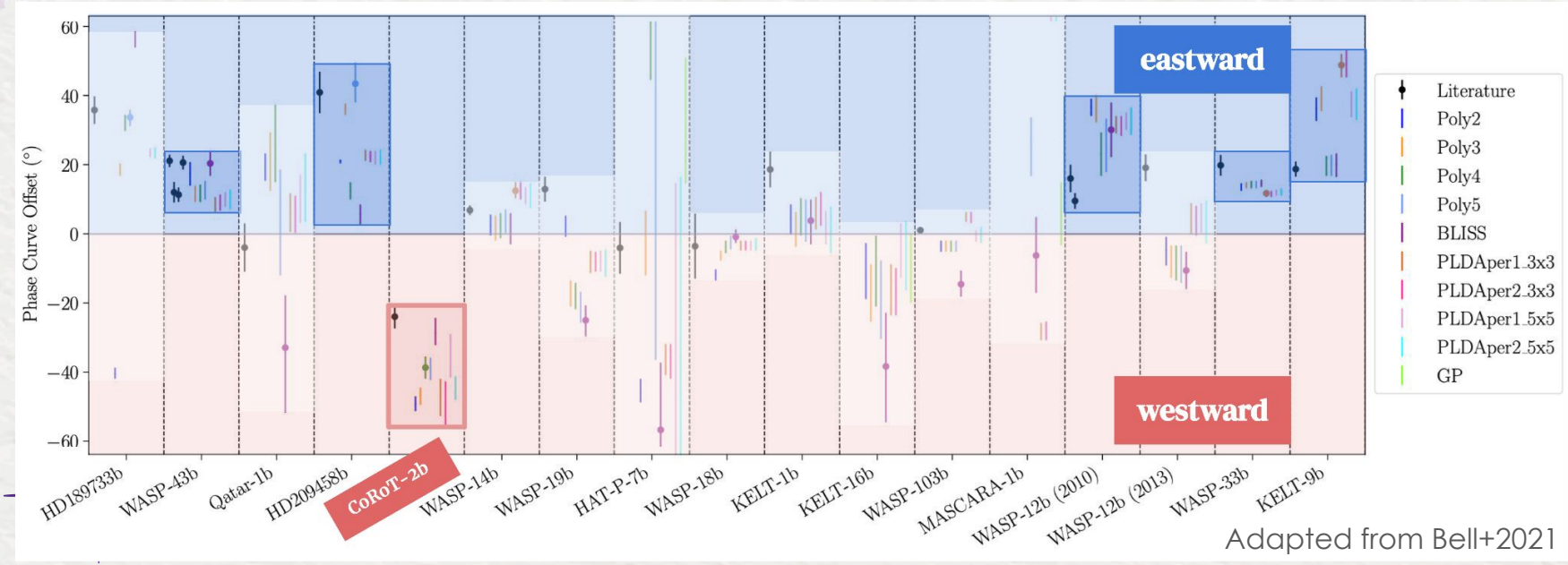
Orbital motion



Adapted from Barstow 2018

Patterns in Hot Jupiter Phase Curves

- Most planets that have *Spitzer*/IRAC 4.5 μm band phase curves show no hotspot offset or an eastern hotspot offset (Bell+2021)
- CoRoT-2b is only robust westward hotspot offset (Dang+2018)



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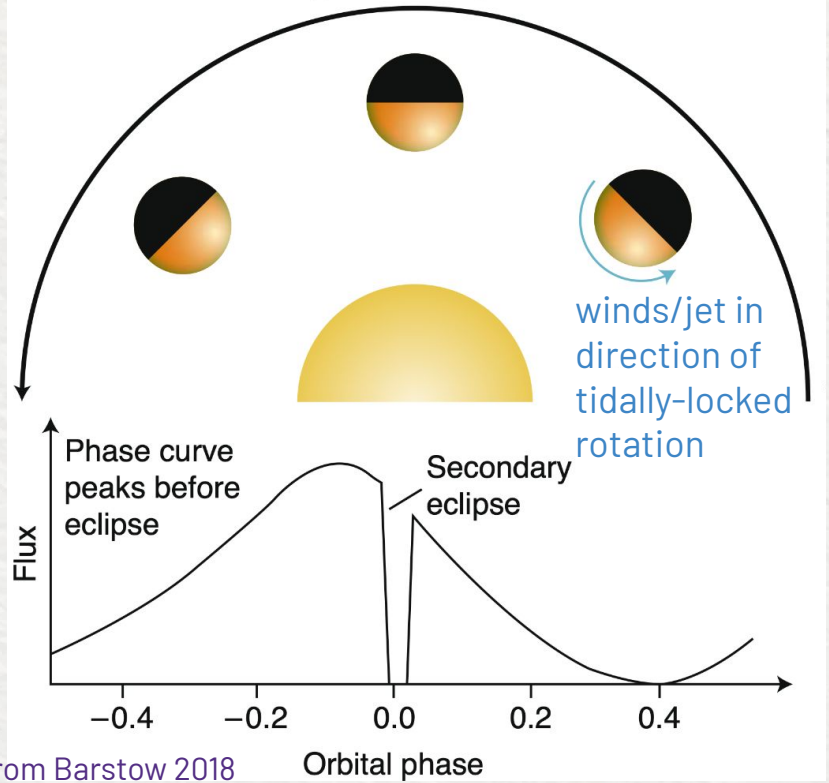
Typical Hot Jupiter shows eastern hotspot offset

Typical Hot Jupiter: no hotspot offset or offset in direction of tidally locked rotation



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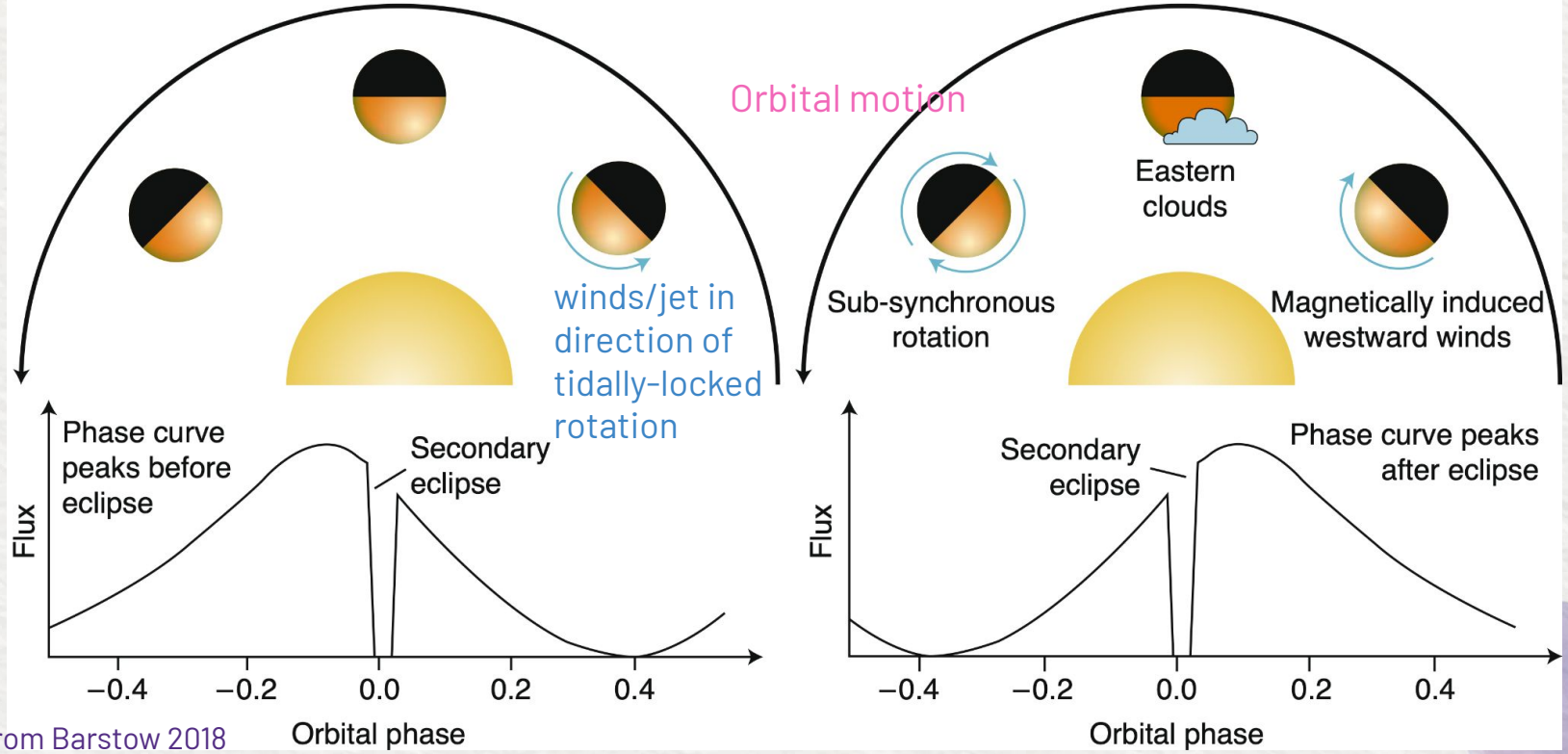
CoRoT-2b's western hotspot offset

Typical Hot Jupiter: no hotspot offset or offset in direction of tidally locked rotation

CoRoT-2b: 23° hotspot offset *opposite* to tidally locked rotation (Dang+2018)



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CoRoT-2b at a glance:

$M_p = 3.3 \pm 0.2\ M_J$

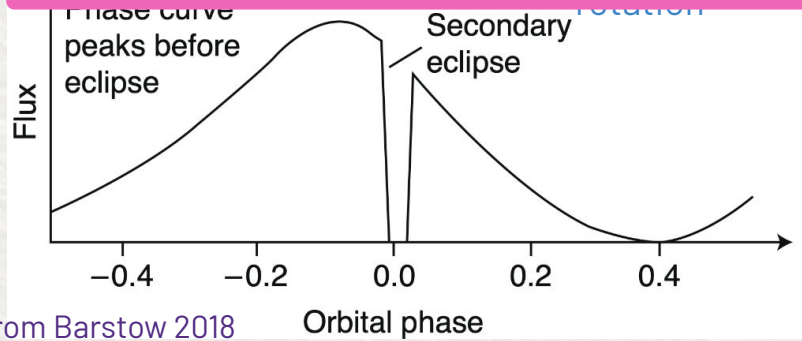
$R_p = 1.47 \pm 0.04\ R_J$

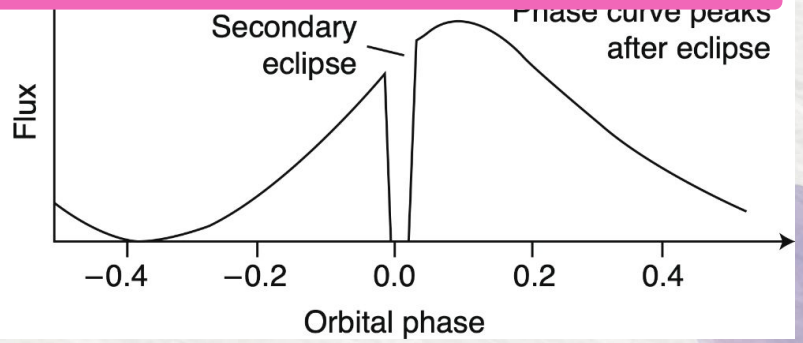
$P_{orb} = 1.74$ days

$T_{eq} = 1521 \pm 21$ K

Host Star = $0.97\ M_{sun}$, 100 – 300 Myr

Orbital motion





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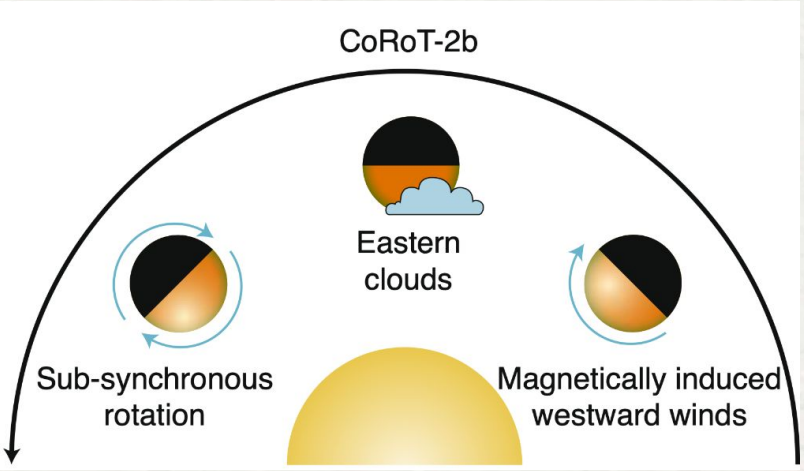
High resolution spectroscopy can help!

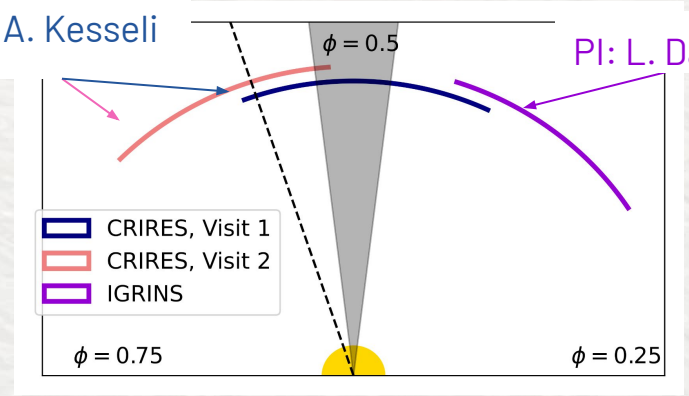
- High resolution spectroscopy can resolve winds as a function of phase to determine whether winds are flowing eastward to westward
- Rotational broadening can place constraints on whether the planet is synchronously rotating
- Retrievals can help to constrain temperatures, abundances, and clouds

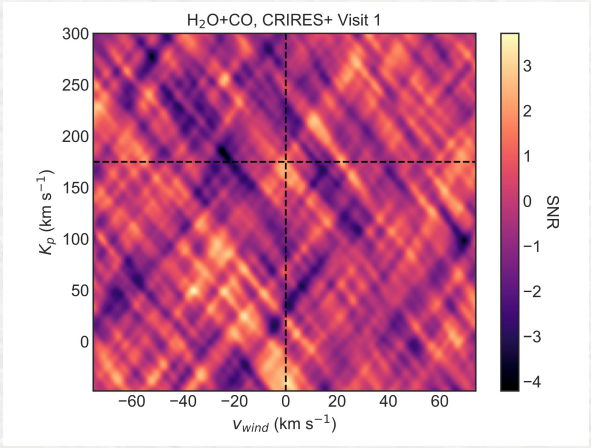


Phase-resolved high resolution spectroscopy

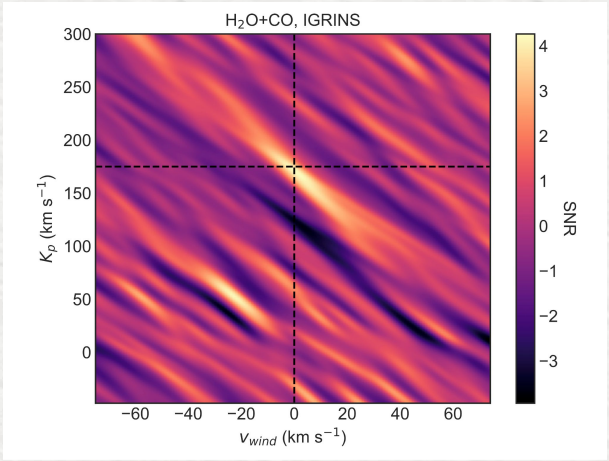
PI: A. Kesseli

PI: L. Dang

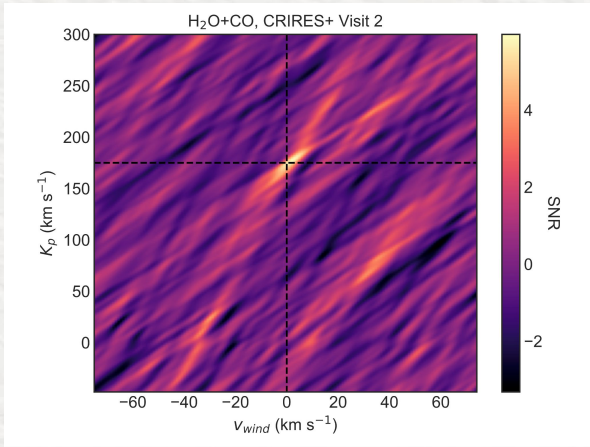




CRIRES+ 1: no significant detection



IGRINS: Detection at planet's expected velocity w/ **SNR~4.5**



CRIRES+ 2: Detection w/ SNR~6

Phase-resolved high resolution spectroscopy

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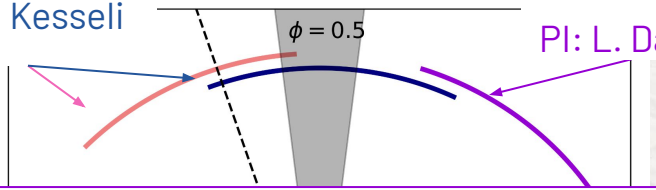

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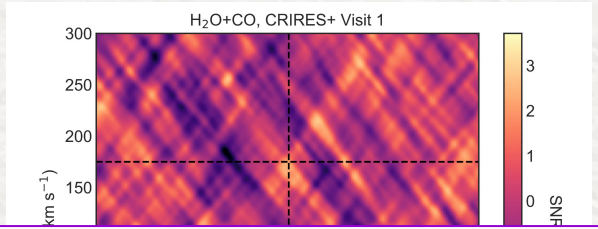

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Paper on abundances and abundance ratios from IGRINS epoch alone under review (Shu, Dang, et al. incl. Kesseli)

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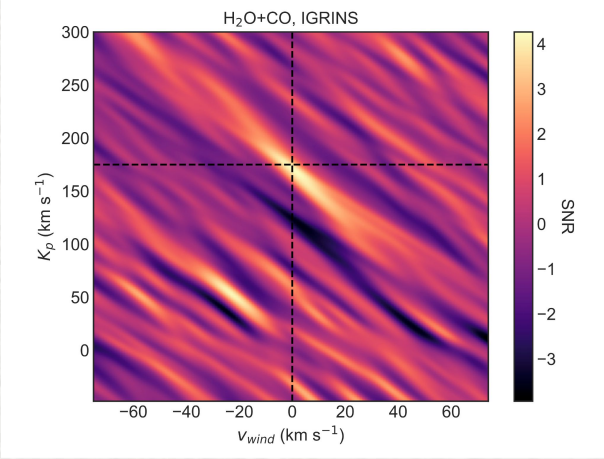

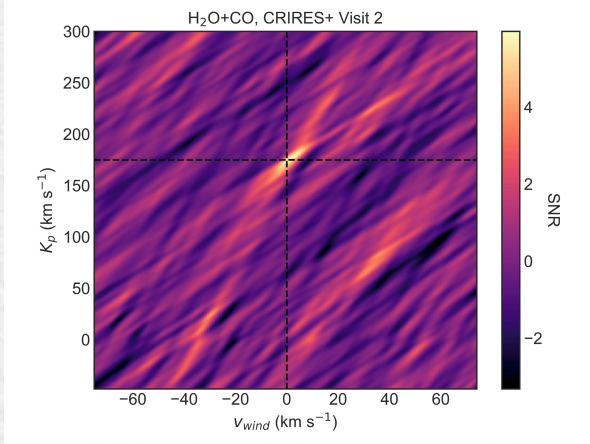

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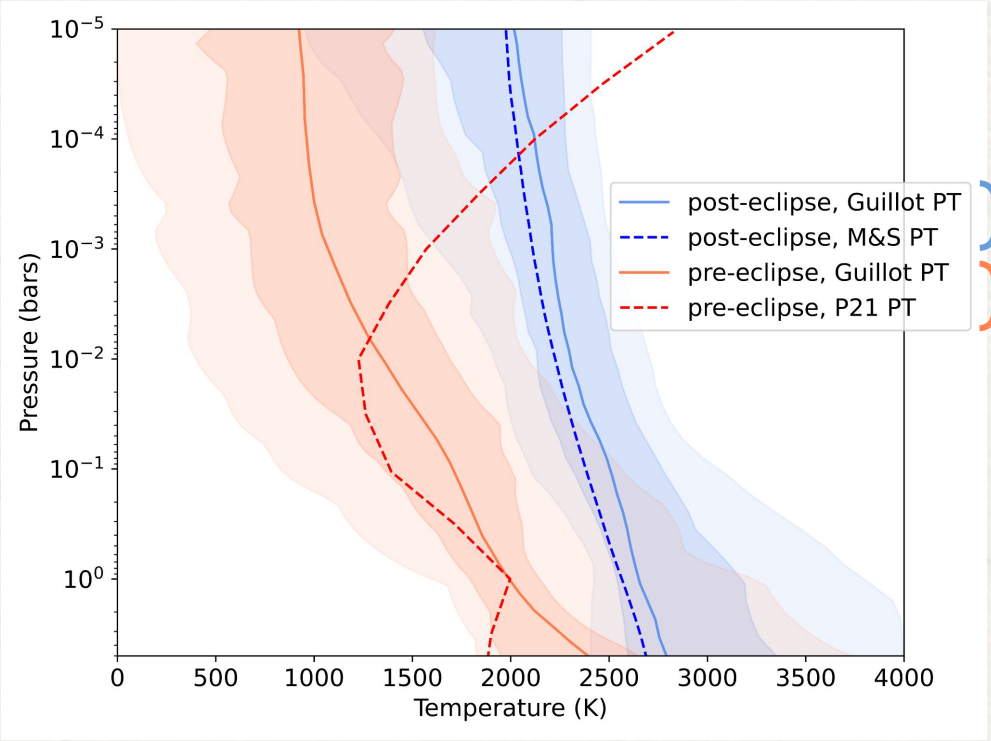
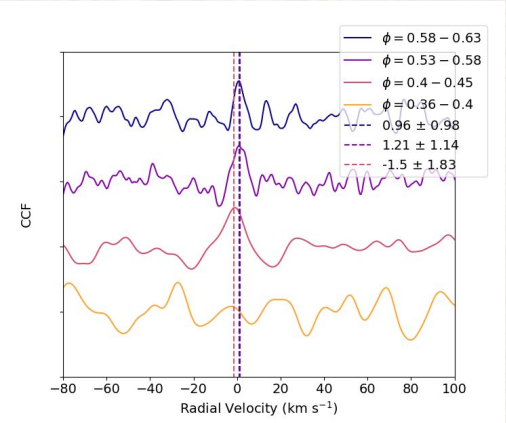
Pre-eclipse vs. Post-eclipse Retrievals



1. **Consistent abundance ratios (C/O)** between the pre-eclipse epoch and post-eclipse epoch
2. A more isothermal and **hotter PT profile post-eclipse** than pre-eclipse → **as expected for a western hotspot offset**

Assessing hypotheses for Offset

01 Magnetism



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Dang+2018 estimate a magnetic dynamo ~230 G to create hotspot offset

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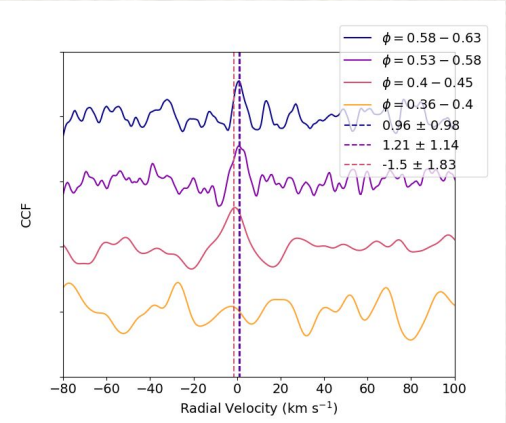

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Features strongly detected in both epochs. Neither epoch shows strong constraints on clouds but **rule out thick clouds above 10^{-2} bars**

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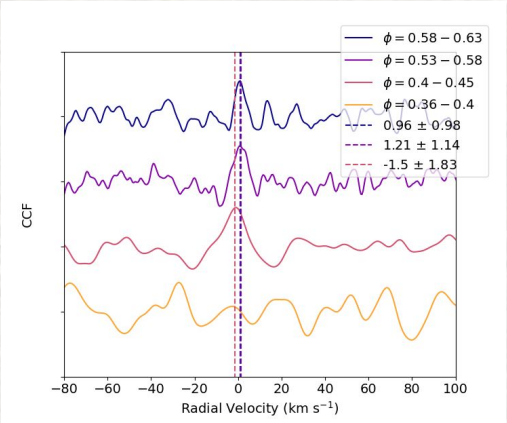

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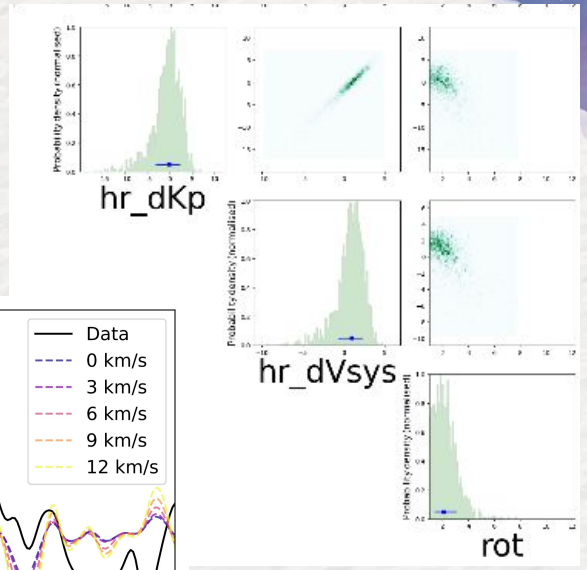
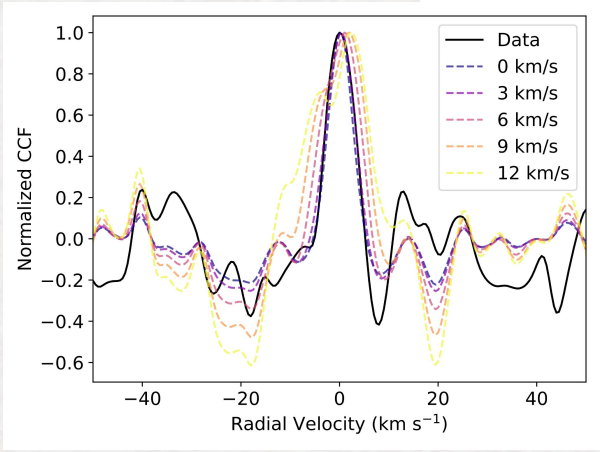
03 Sub-synchronous Rotation

Planet rotational broadening:

1. Retrieval = $2.34^{+0.7}_{-0.83}$ km/s
2. CCF method = 2.1 km/s





Synchronous rotation yields 4.37±0.13 km/s, **2.7-σ > than measured**

Sub-synchronous Rotation?

Other Hot Jupiters tend to show ***larger*** rotational broadening than expected from tidal locking

1. **WASP-43 b (hot Jupiter)**: Lesjak+2023 measure planet's rotational broadening of 11.7 ± 2.5 km/s, when the tidally locked equatorial velocity should be 6.3 km/s
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CoRoT-2b has a small, but significant eccentricity (e = 0.0143±0.007, Gillon+2010) and a young age of 100-300 Myr (Schröter+2011, Guillot & Havel 2011) → not yet fully synchronized?

Conclusions

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3. Using 3 epochs of high-res spectroscopy we find:
   a. PT profiles consistent with a western hotspot offset
   b. A low rotational broadening compared to expectations from tidal locking, which may indicate that sub-synchronous rotation is responsible for the western hotspot offset.