Secondary eclipses and phase curves

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• New department at the Max Planck Institute of Astronomy in Heidelberg, Germany

• Focus is observations, theory, and instrumentation for exoplanet atmospheres!

• Advertisement: we are hiring at all levels! Jobs are advertised in the fall on the AAS job register
What is a secondary eclipse?

Thermal emission and reflected light from the planet are blocked during the secondary eclipse.

Reveals average spectrum of the dayside hemisphere.
The first detections of thermal emission
Deming et al. 2005, Charbonneau et al. 2005
Intro to thermal emission — blackbody approximation

- Luminosity \( L \sim T^4 \)
- Wavelength of peak emission is
  \[ \lambda_{\text{peak}} = \frac{b}{T} \]
  where \( b = 3000 \text{ micron*Kelvin} \)

\[
\frac{F_{\text{planet}}}{F_{\text{star}}} = \frac{\text{blackbody}(\lambda, T_{\text{planet}})}{\text{blackbody}(\lambda, T_{\text{star}})} \times \left(\frac{R_p}{R_s}\right)^2
\]
Key facilities

Atmosphere characterisation is easier when Earth’s atmosphere is not in the way!

** note: ground-based observations are also important and complementary

Spitzer Space Telescope
Launch date: 2003
85 cm mirror
Infrared; 3.6 - 160 micron

Hubble Space Telescope
Launch date: 1990
2.4 m mirror
UV-near-IR: 0.1 - 1.7 micron

JWST
Launch date: 2021
6.5 m mirror
Optical - IR: 0.6 - 30 micron
Hot Jupiter orbiting a Sun-like star:
\[ T_p = 1500, \ T_s = 5000, \ \frac{R_p}{R_s} = 0.01 \]

Warm rocky planet orbiting an M-dwarf:
\[ T_p = 400, \ T_s = 3000, \ \frac{R_p}{R_s} = 0.01 \]
Thermal emission *spectra* reveal chemical composition.
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- **Opacity** vs. **Wavelength**
- **Altitude** vs. **Temperature**
- **Brightness** vs. **Wavelength**

Credit: Tom Mikal-Evans
Intro to phase curves

- Observe a complete orbital revolution
- Changing viewing angle reveals different regions of the atmosphere over time
- Can map the global climate and chemical composition!

Animation available at github.com/lkreidberg
A new frontier: eclipse mapping!

During ingress and egress, the visible disk of the planet changes incrementally.

— De Wit et al. 2012
Science from eclipses and phase curves

- How is heat recirculated in the atmosphere?
- What is the temperature structure? Are there thermal inversions?
- How do chemical composition and clouds vary as a function of longitude?
- What is the atmospheric metallicity?
- Is an atmosphere present?
How is heat circulated in the atmosphere?
The first thermal phase curve, HD 189733b — Knutson et al. 2007

Peak brightness 16 +/- 6 degrees of the substellar point, day-night temp contrast ~ 240 K
How is heat circulated in the atmosphere?

Hotter planets have larger day-night temperature contrast

This trend is due to the decreasing ability with increasing incident stellar flux of waves to propagate from day to night and erase temperature differences.

Komacek et al. 2016
How is heat circulated in the atmosphere?
A sharp rise in brightness at 1730 K

Onset of magnetic drag? and/or the rapid dissipation of day side clouds?

Deming et al. 2023
How does the temperature change with altitude?

Thermal inversion on the dayside but not the nightside for an ultra-hot Jupiter

Mikal-Evans et al. 2022
How does the temperature change with altitude?

Inversions increase in strength with increasing irradiation

Mansfield et al. 2021
How does chemistry and cloud coverage change with longitude?

Evidence for nightside clouds

Uniform nightside temperature, possibly due to clouds (or the relatively long radiative timescale on the nightside)

How does chemistry and cloud coverage change with longitude? Sometimes we see clouds on the dayside!

Evidence for reflective clouds west of the substellar point for Kepler-7b

Hu et al. 2015

(see also Demory et al. 2013, Parmentier et al. 2016)
What is the atmospheric metallicity?

Gas giants show a diversity of compositions

Hot Saturn HD 149026b has approximately ~100x solar metallicity

— Bean et al. 2023

Hot Jupiter WASP-77A b has a subsolar metallicity

— August et al. 2023
Sub-Neptune GJ 1214b has a $\sim$100 - 1000x solar metallicity atmosphere

Kempton et al. 2023
Do rocky planets have atmospheres?

Thick atmospheres transport heat to the nightside

TRAPPIST-1c

- Thick atmosphere $\rightarrow$ full heat redistribution $\rightarrow$ 340 K
- Bare rock $\rightarrow$ no heat redistribution $\rightarrow$ 430 K
First results indicate that rocky planets do not have thick atmospheres

LHS 3844b — Kreidberg et al. 2019
TRAPPIST-1c — Greene et al. 2023
TRAPPIST-1b — Zieba et al. 2023

More on this from Natasha Batalha on Thursday!
Lots more to come!

23 phase curve, 90 eclipses in JWST Cycles 1 - 2

| WASP-69 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 | Eclipse | MIRI.LRS | L-WASP-17 |

WASP-121  PhaseC  NIRISS.SOSS
LTT-9779  PhaseC  NIRISS.SOSS
WASP-43  PhaseC  NIRSPEC.BOTS+G395H
WASP-43  PhaseC  MIRI.LRS
WASP-121  PhaseC  NIRSPEC.BOTS+G395H
GJ1214  PhaseC  MIRI.LRS
HD-80060  PhaseC  MIRI.LRS
NGTS-10  PhaseC  NIRSPEC.BOTS+PRISM
K2-141  PhaseC  MIRI.LRS
HD-80060  PhaseC  NIRSPEC.BOTS+G395H
KEPLER-51  PhaseC  NIRSPEC.BOTS+PRISM
TOI-849  PhaseC  NIRSPEC.BOTS+PRISM
TOI-849  PhaseC  NIRSPEC.BOTS+PRISM
TOI-2109  PhaseC  NIRSPEC.BOTS+G395H
TOI-2109  PhaseC  NIRSPEC.BOTS+G395H
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TOI-2109  PhaseC  NIRSPEC.BOTS+G395H
TRAPPIST-1  PhaseC  MIRI.F1500W
TRAPPIST-1  PhaseC  MIRI.F1500W
LTT9779  PhaseC  NIRSPEC.BOTS+G395H
KEPLER-86  PhaseC  NIRSPEC.BOTS+PRISM
TOI-1685  PhaseC  NIRSPEC.BOTS+G395H
TOI-561  PhaseC  NIRSPEC.BOTS+G395H
LHS3844  PhaseC  NIRSPEC.BOTS+G395H