Exoplanet phase curves with ARIEL

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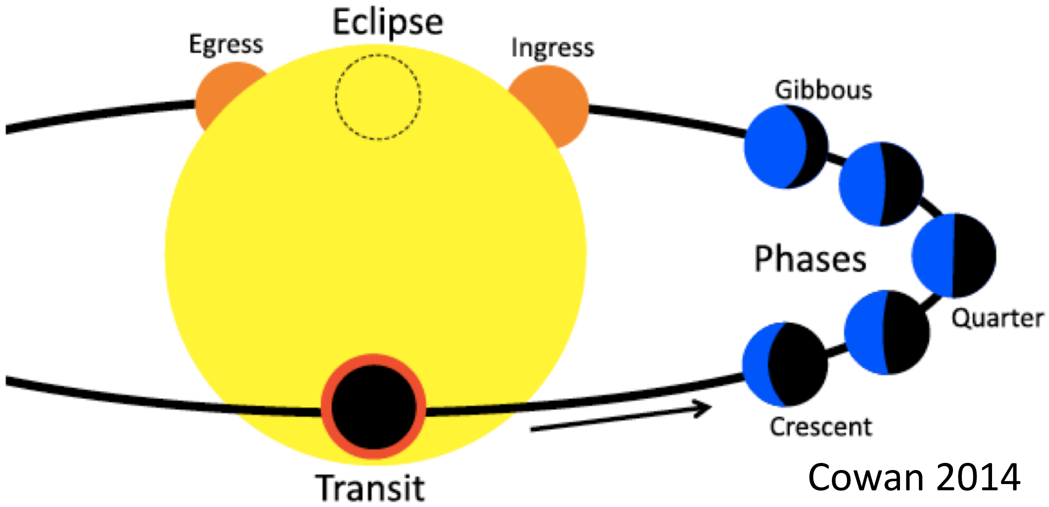
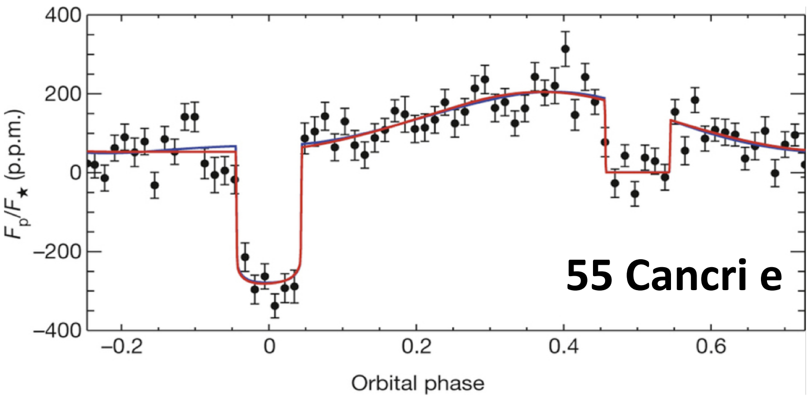
Phase curve of thermal emission or reflected light



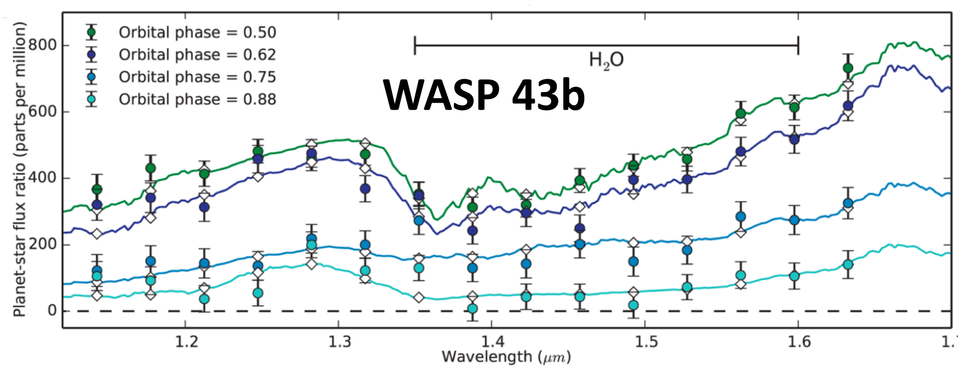
Cowan 2014

Photometric phase curve (ex: Spitzer)



Demory et al. 2016

Spectroscopic phase curve (ex: HST)



Stevenson et al. 2014

Science questions for ARIEL phase curves

Atmospheric dynamics / Thermal structure / Composition / Clouds

1) How efficient is the atmospheric heat redistribution and which parameters control it ?

2) How the atmospheric composition and thermal structure change from dayside to nightside ?

3) What is the atmospheric composition of low-mass planets ?

4) What is the albedo of exoplanets ?

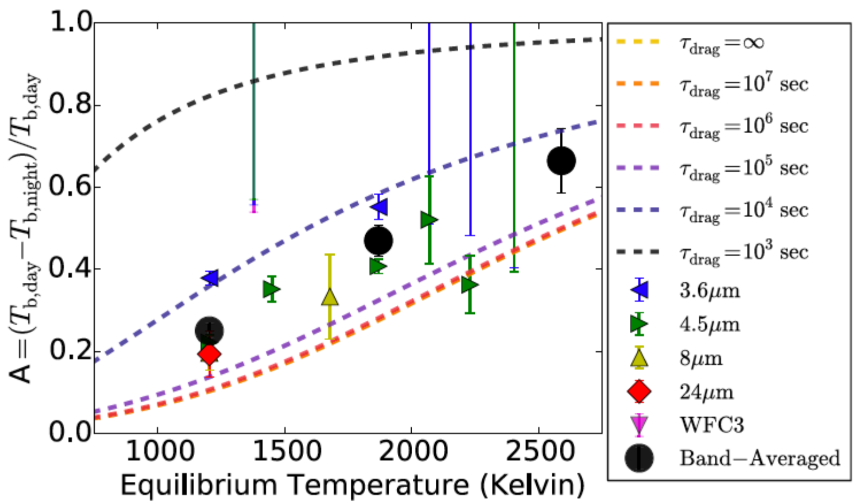
5) What is the time variability of the thermal structure and cloud distribution ?

Science questions for ARIEL phase curves

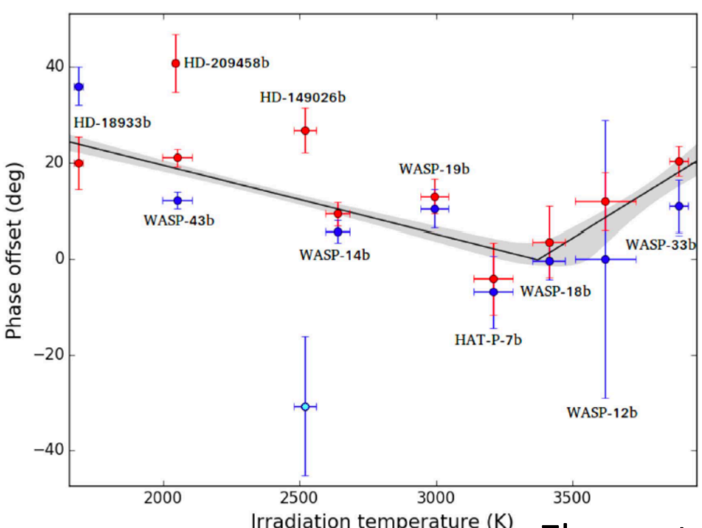
1) How efficient is the atmospheric heat redistribution and which parameters control it ?

- Estimating the heat redistribution by measuring dayside/nightside emission and hoffset for a range of irradiation, planetary radius, metallicity and eccentricity.
- Temperature mapping and eclipse mapping for measuring the latitudinal thermal gradient

→ Strong constraints on the circulation regime of irradiated exoplanets for 3D climate models.



Komacek & Showman 2017



Zhang et al. 2018

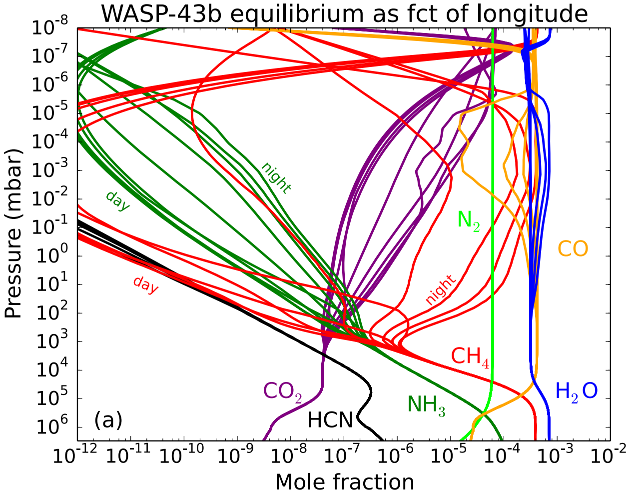
Science questions for ARIEL phase curves

2) How the atmospheric composition and thermal structure change from dayside to nightside ?

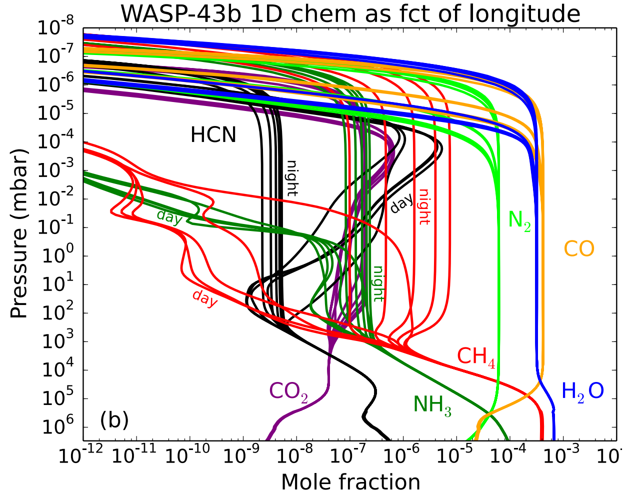
- Measuring composition and TP profiles at different phase angles from spectroscopic phase-curves.
- Studying feedbacks between atmospheric dynamics, thermal structure and composition
- Relating composition to chemical equilibrium/disequilibrium

→ Constraints for chemical models

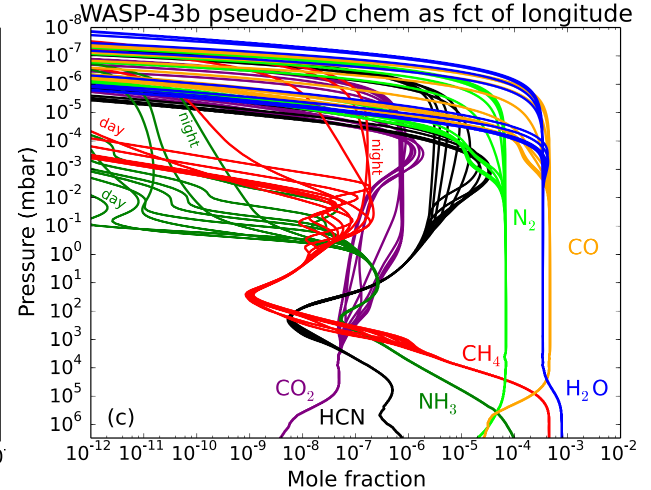
Chemical equilibrium



Disequilibrium due to vertical mixing



Disequilibrium due to vertical and horizontal mixing

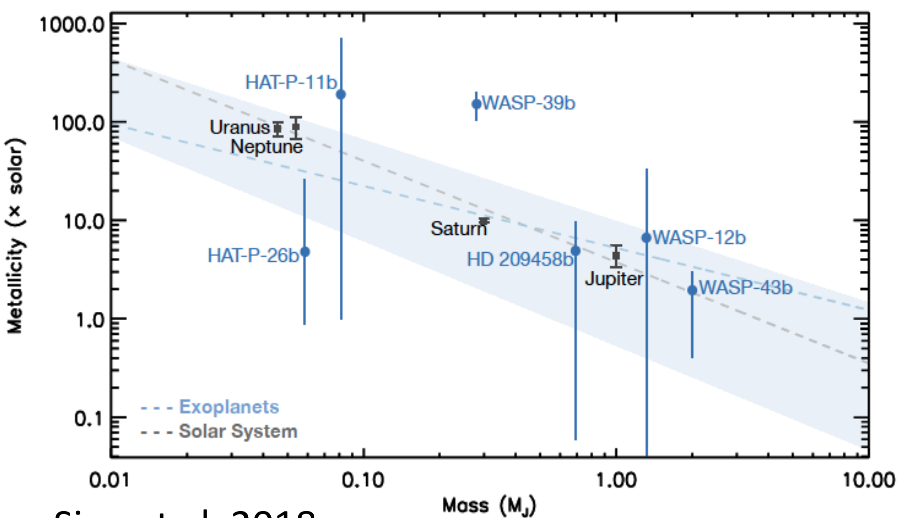


Venot et al., in prep

Science questions for ARIEL phase curves

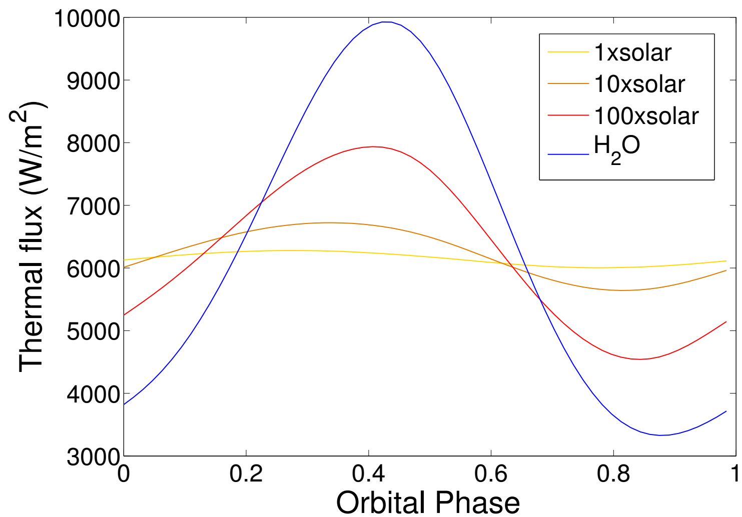
3) What is the atmospheric composition of low-mass planets ?

- Estimating the atmospheric metallicity by measuring the amplitude of phase curves as an indirect and independent technique for rocky planets and sub-Neptunes.
- Revealing the presence of an atmosphere by measuring heat redistribution.



Sing et al. 2018

3D simulations of GJ1214b



Charnay et al. 2015

<u>Interest of phase curves for low-mass planets:</u>

✓ High amplitude phase curves for high atmospheric metallicity

✓ Method little sensitive to clouds

Science questions for ARIEL phase curves

4) What is the albedo of exoplanets ?

- Measuring the bond albedo (from thermal emission) and geometric albedo (from reflected light) for a range of irradiation and metallicity.
- Cloud longitudinal distribution and transition

Advantages of ARIEL:

✓ Several channels for deciphering reflected light and thermal emission

✓ Broad spectral cover for thermal emission

5) What is the time variability of the thermal structure and cloud distribution ?

- Measuring variation of phase-curve amplitude and off-set

→ Constraints for 3D climate models.

Science questions for ARIEL phase curves

Requirements

1) How efficient is the atmospheric heat redistribution and which parameters control it ?

→ photometric phase curves; precision: 10% for amplitude and 5° for phase

2) How the atmospheric composition and thermal structure change from dayside to nightside ?

→ spectroscopic phase curves; precision: 0.5 on mean abundance (log)

3) What is the atmospheric composition of low-mass planets ?

→ photometric phase curves; precision: 0.5 on log(metallicity) → precision of 10% for amplitude

4) What is the albedo of exoplanets ?

→ photometric phase curves; precision: 10% on the geometric albedo and Bond albedo

5) What is the time variability of the thermal structure and cloud distribution ?

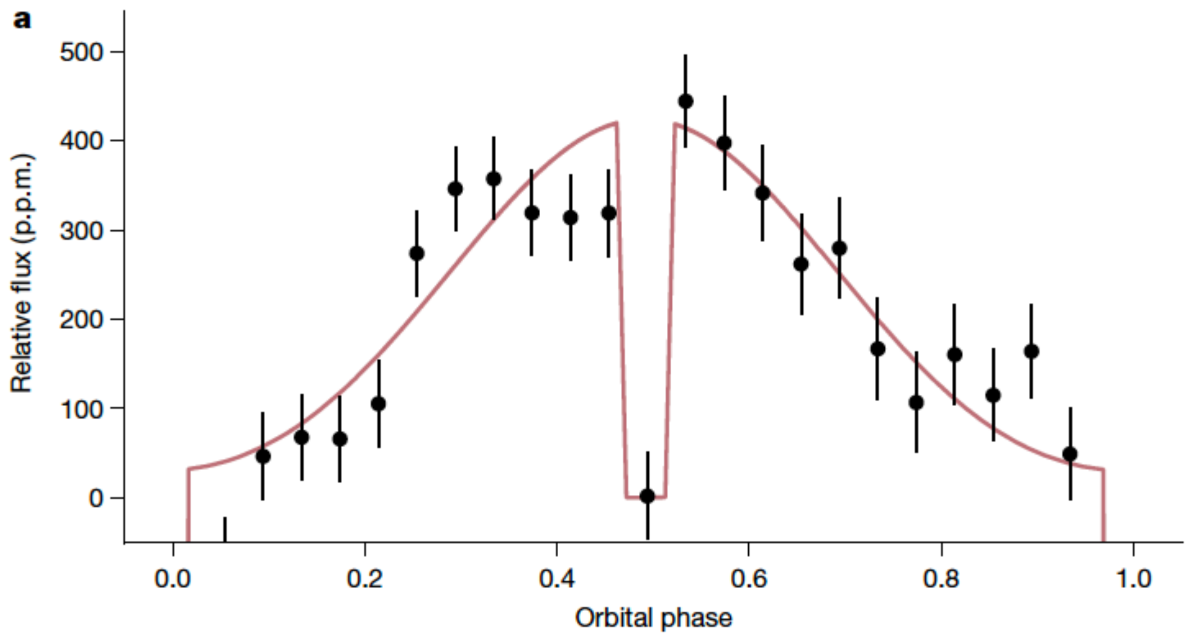
→ multiple photometric phase curves; precision: 2% for amplitude and 1° for phase

Requirements: SNR>10 for maximal amplitude (no heat redistribution)

Science questions for ARIEL phase curves

Requirements

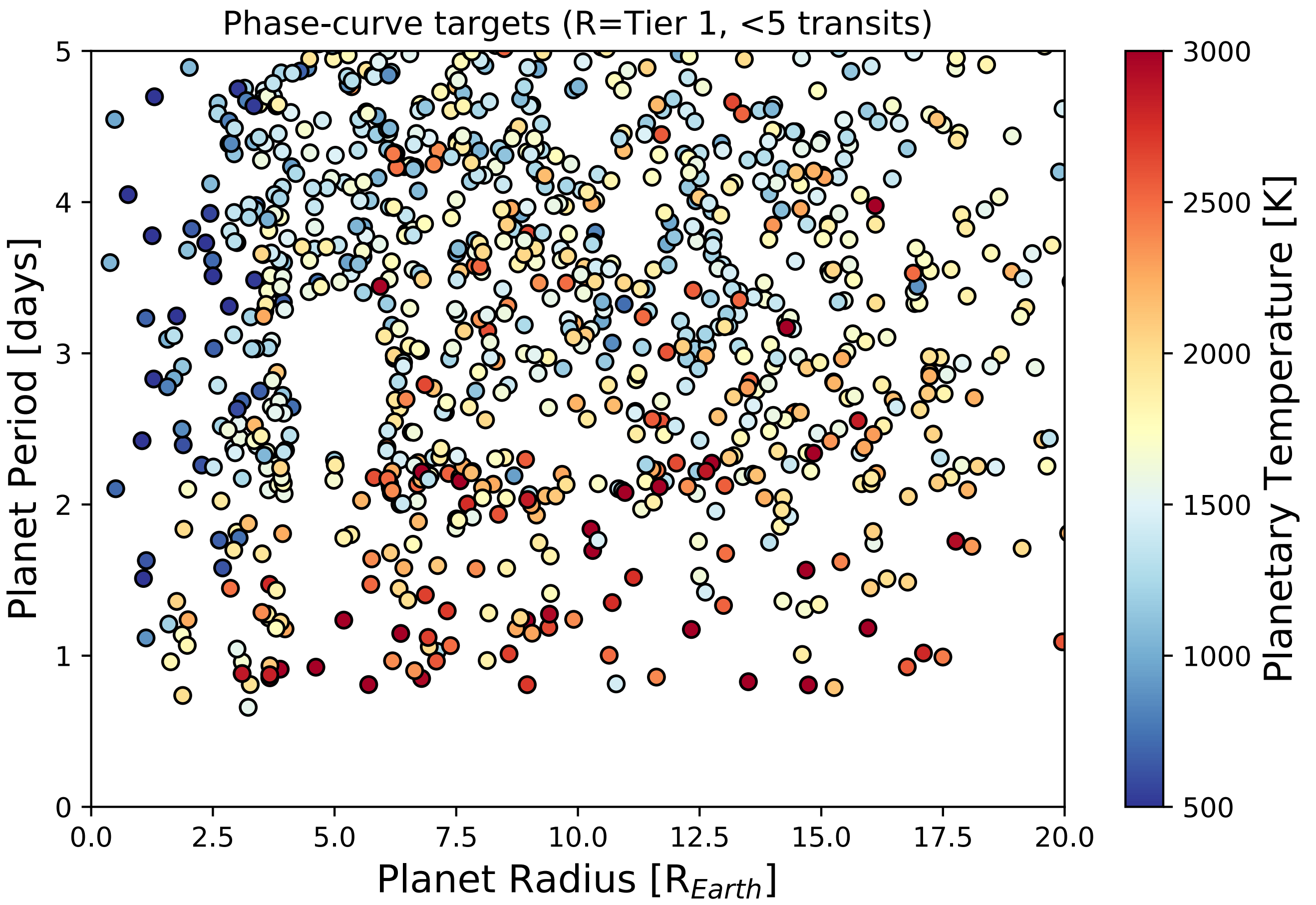
Spitzer's phase curve of LHS3844b (SNR~14)



Kreidberg et al. (2019)

Target list for ARIEL phase curves

Selection of potential targets

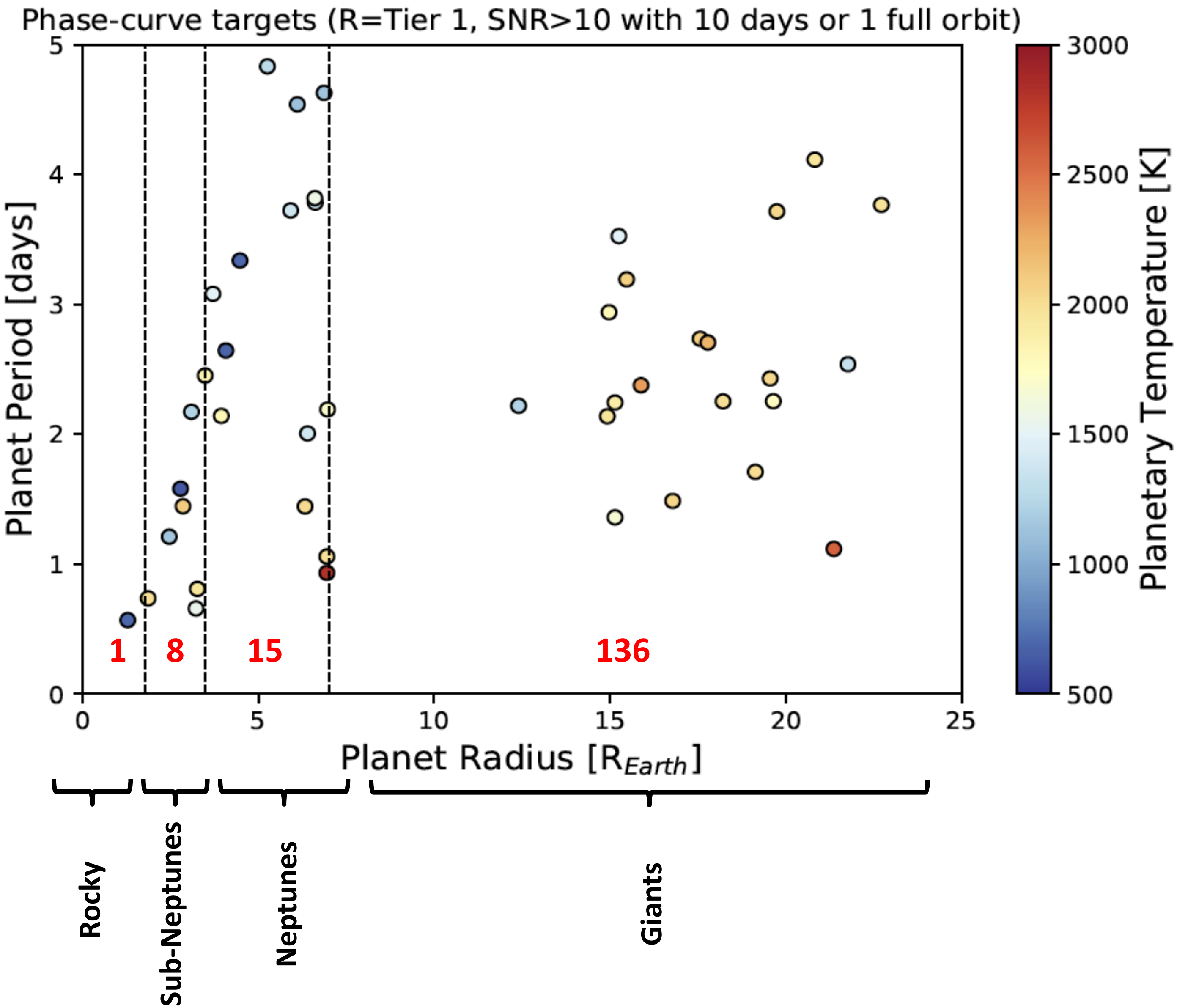


➢ Divide the list in 4 radius bins and choose the best targets per bin having:

1) SNR>10 for photometric phase curves for super-Earths and sub-Neptunes (<10 days)
2) SNR>10 for photometric phase curves for Neptunes (1 orbit)
3) SNR>10 for spectroscopic phase curves for Giants (observation of 0.1 orbit)

Target list for ARIEL phase curves

Selection of potential targets



Target list for ARIEL phase curves

Selection of potential targets

- **$R < 1.8R_E$ (rocky):**

1 targets reach SNR>10 with 5 days

- **$1.8 < R < 3.5R_E$ (sub-Neptunes):**

1 targets reach SNR>10 with 1 orbit
4 targets reach SNR>10 with 5 days
8 targets reach SNR>10 with 8 days

- **$3.5 < R < 7R_E$ (Neptunes):**

15 targets reach SNR>10 with 1 orbit
6 planets reach SNR>5 for spectroscopic phase curves (e.g. GJ436b)

- **$7R_E < R$ (giants):**

136 targets reach SNR>10 for spectroscopic phase-curves

Photometric phase curve (Science questions 1, 3 & 4)

Spectroscopic phase curve (Science question 2 and the others)

Only giant planets are expected to reach a SNR sufficient to detect reflected light and to measure the geometric albedo (precision $\sim$ 0.03-0.1)

Target list for ARIEL phase curves

Possible target samples

Tier 4 : ~10% of ARIEL Science Time, mostly for phase curves

Priority 1 (7% ST):
- 1 rocky
- 3 sub-Neptunes
- 8 Neptunes
- 10 Giants

Priority 2 (15% ST):
- 1 rocky
- 7 sub-Neptunes
- 15 Neptunes
- 15 Giants

(1 multi phase curves)

Priority 3 (19% ST):
- 1 rocky
- 8 sub-Neptunes
- 15 Neptunes
- 20 Giants

(2 multi phase curves)

In average, the equivalent of 28% of phase-curve observations is dedicated to transit and eclipses

Known potential targets

Rocky planets (0): none

Sub-Neptunes (3): GJ1214b, K2-266b, 55Cnce

Neptunes (3): GJ436b, GJ3470b, HAT-P-26b

Giant planets (83): HD189733b, KELT-7b, WASP-74b, WASP-77Ab, HD209458b, WASP-82b, XO-3b, KELT-14b, WASP-14b, KELT-4Ab, WASP-167b, HAT-P-32b, WASP-93b, KELT-3b, WASP-43b, HAT-P-41b, HAT-P-7b, TrES-3b, K2-31b, WASP-54b, WASP-173Ab, KELT-18b, HAT-P-67b, CoRoT-2b, HAT-P-49b, KELT-2Ab, WASP-79b, KELT-11b, KELT-8b, HAT-P-57b, WASP-100b, WASP-95b, HAT-P-30b, WASP-4b, K2-237b, HAT-P-56b, HAT-P-8b, WASP-104b, WASP-127b,WASP-3b, WASP-52b, HAT-P-33b, WASP-85Ab, WASP-97b, Qatar-2b, WASP-94Ab, WASP-90b, WASP-140b, HAT-P-22b, KELT-15b, WASP-75b, WASP-101b, WASP-13b, HD149026b, HAT-P-16b, WASP-26b, WASP-7b, TrES-2b, HAT-P-6b, WASP-69b, WASP-145Ab, WASP-123b, WASP-62b, HAT-P-1b, WASP-35b, WASP-31b, KELT-10b, WASP-17b, HAT-P-14b, WASP-50b, WASP-49b, WASP-2b, WASP-20b, WASP-10b, WASP-80b, WASP-41b, WASP-168, TrES-1b, HAT-P-20b, WASP-16b, K2-29b, XO-1b, WASP-34b

Target list for ARIEL phase curves

Strategy of observation and scheduling

Tier 4 : ~10% of ARIEL Science time, mostly for phase curves

Priority 1 (7% ST):
- 1 rocky
- 3 sub-Neptunes
- 8 Neptunes
- 10 Giants

Priority 2 (15% ST):
- 1 rocky
- 7 sub-Neptunes
- 15 Neptunes
- 15 Giants

(1 multi phase curves)

Priority 3 (19% ST):
- 1 rocky
- 8 sub-Neptunes
- 15 Neptunes
- 20 Giants

(2 multi phase curves)

In average, the equivalent of 28% of phase-curve observations is dedicated to transit and eclipses

- **Observations should start and end with the secondary eclipse**, which represents the reference for the phase curve.
- **They should keep a margin of 7% of the period before and after** not to miss the eclipse. It corresponds to a maximal error of 0.1 on the eccentricity.
- **Continuous observations will be performed even for multiple orbits**

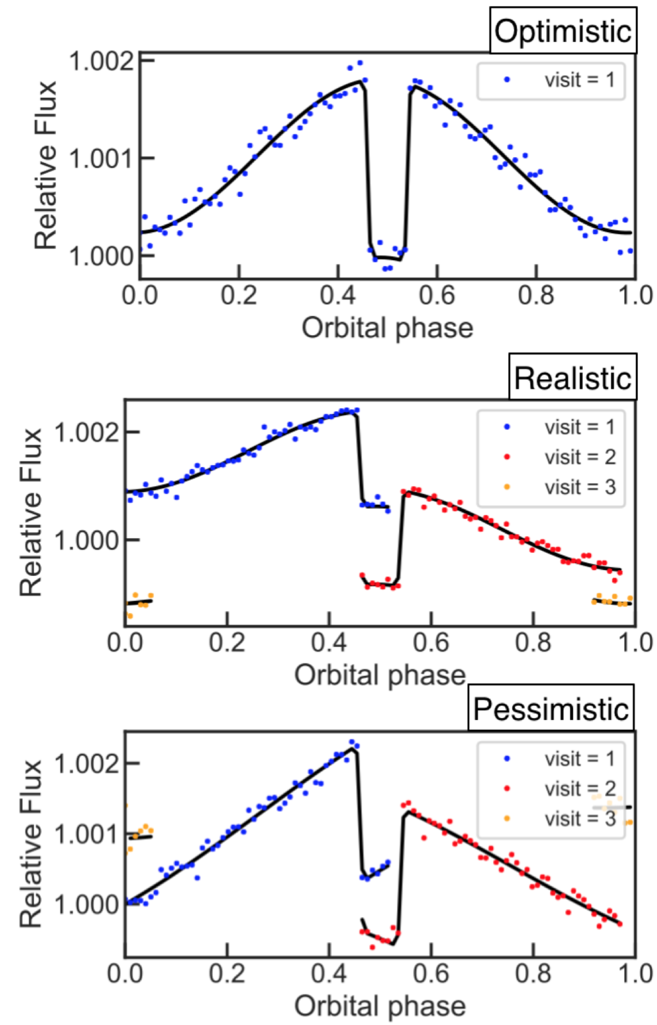
Strategy of observations

Testing multi epoch phase curves

Fitting WASP-43b simulated light curve with multi-epoch phase curves

WASP-43b	Amplitude (ppm)	Hotspot offset (degrees)
1. Optimistic	1560 +/- 30	4.2 +/- 1.0
2a. Realistic (10% overlap)	1560 +/- 30	4.3 +/- 2.1
2b. Realistic (25% overlap)	1560 +/- 30	3.9 +/- 1.8
3a. Pessimistic (10% overlap)	990 +/- 250	5.9 +/- 3.5
3b. Pessimistic (25% overlap)	1520 +/- 150	4.6 +/- 3.2

- **Effects of systematics can strongly limit amplitude and phase retrieval**
- **Need to be tested early on the mission**



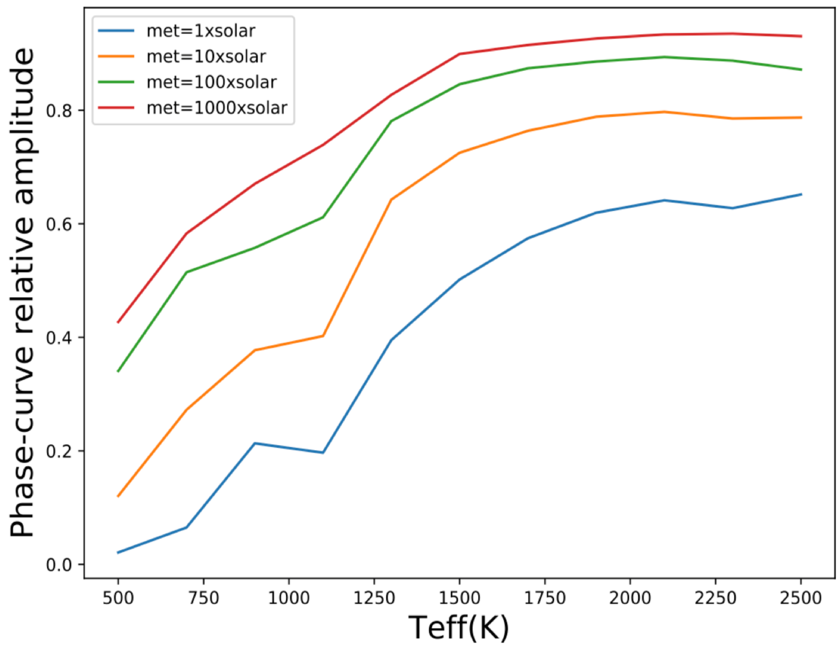
Summary

- We defined 5 sciences questions to be investigated with phase curves
- We plan to realize photometric and spectrally resolved phase curves
  Requirement: SNR>10
- We determined target lists of 20 to 40 planets divided into 4 planet size bins, which can fit into the Tier 4 Science Time
- Spectroscopic phase curves for all gaseous giants and half of Neptunes
- Effects of systematics can strongly limit amplitude and phase retrieval
  → need continuous full phase curves and tests early on the mission
- Reflected light curves can only be performed for giant planets
  → possibility to choose targets for which we have many reflected light curves from TESS, CHEOPS and PLATO (strong synergy)

Science questions for ARIEL phase curves

Requirements

Relative amplitude of phase curve in AIRS-CH1 (3.9-7.8 microns)
Simulated with 2D ATMO



Precision of 0.5 on log(metallicity) → precision of 10% on the maximal amplitude

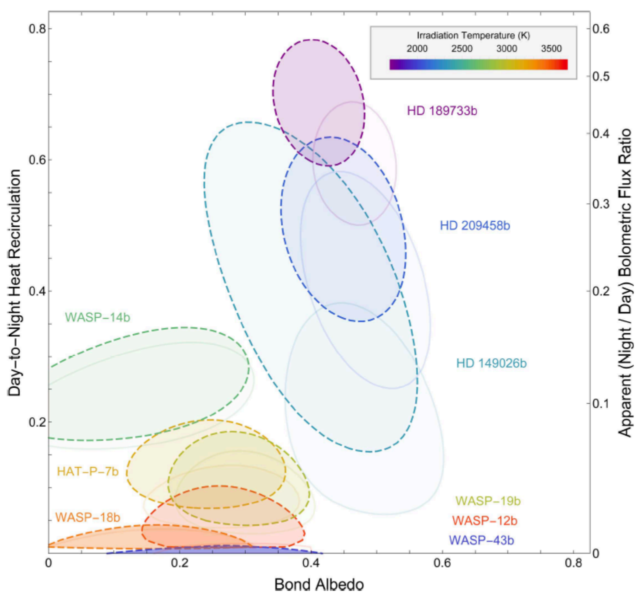
<u>Requirements:</u> SNR>10 for maximal amplitude

Science questions for ARIEL phase curves

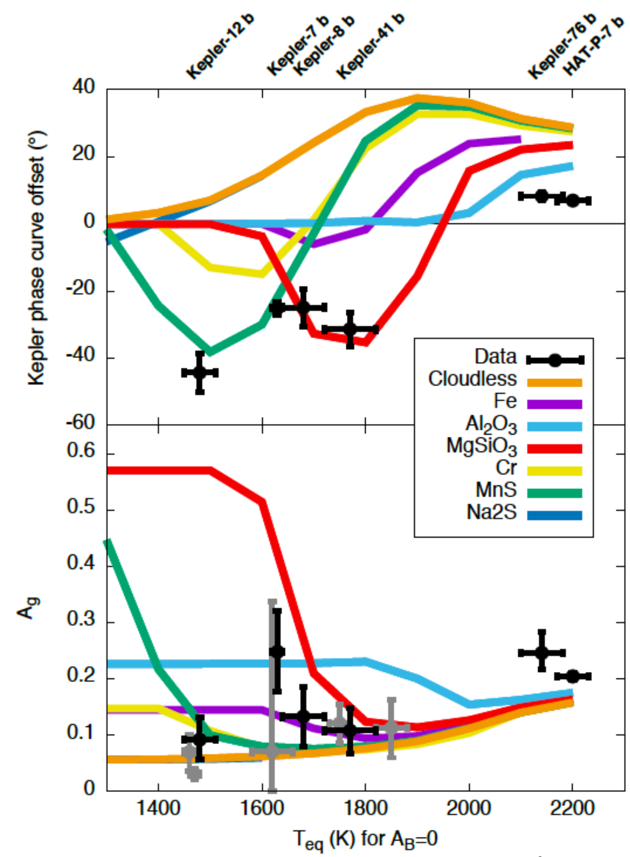
4) What is the albedo of exoplanets ?

- Measuring the bond albedo (from thermal emission) and geometric albedo (from reflected light) for a range of irradiation and metallicity.
- Cloud longitudinal distribution and transition

→ Requires photometrics phase curves



Schwartz et al. 2017



Parmentier et al. 2016

Advantages of ARIEL:

✓ Several channels for deciphering reflected light and thermal emission

✓ Simultaneous observations

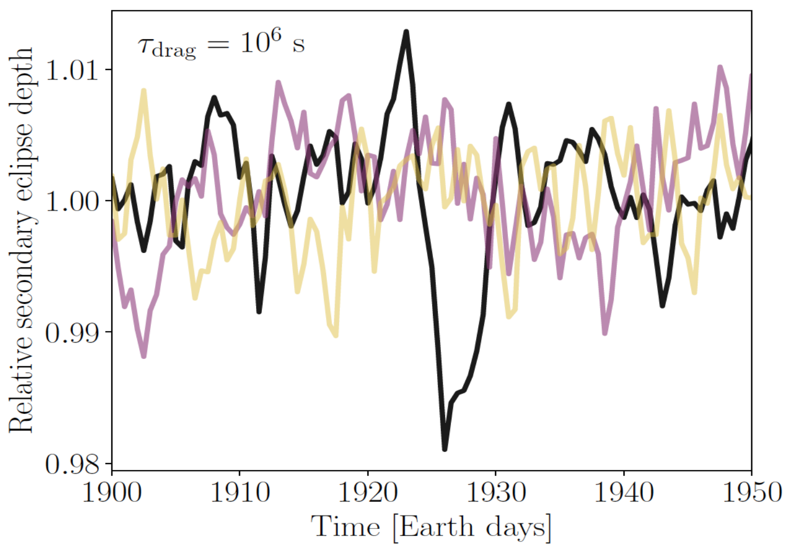
Science questions for ARIEL phase curves

5) What is the time variability of the thermal structure and cloud distribution ?

- Measuring variation of phase-curve amplitude and off-set

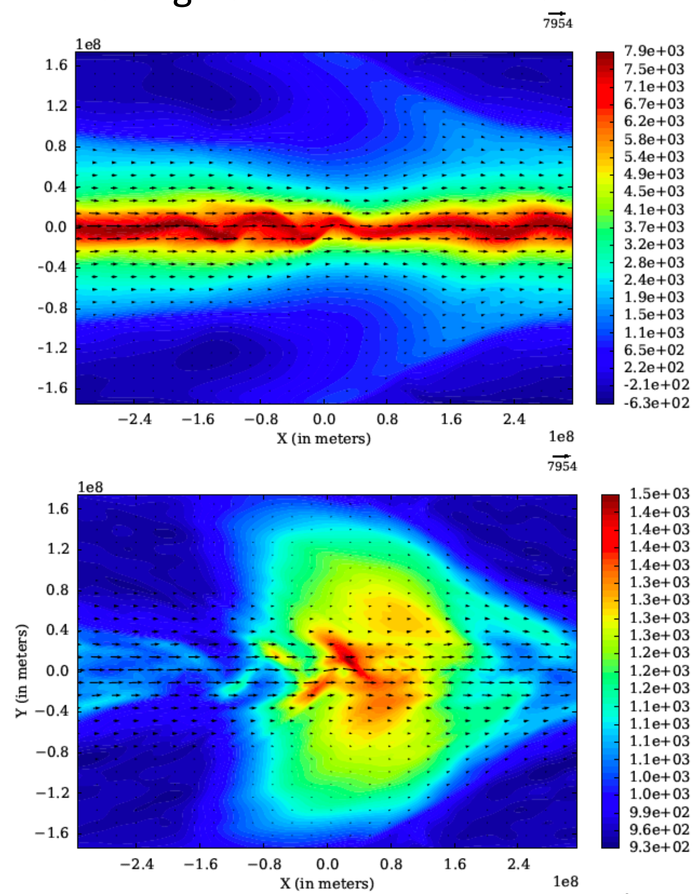
→ Constraints for 3D climate models.

→ Requires multiple photometric phase curves



Komacek & Showman (2019)

Variability and instability at high 3D model resolution



Fromang et al. (2016)

Retrieval of GJ1214b phase curves (AIRS-CH1, 5 days of observations)