Characterizing Transiting Exoplanet Atmospheres through 2025

"What Should NASA Do?"

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on behalf of ExoPAG SAG 10

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Study Analysis Group 10 (SAG-X)

1. What is the full diversity of planet properties needed to characterize and understand the climate of short-period exoplanets?
2. Which measurement suites and how much observing time are needed to characterize the climate of transiting planets?
3. **Will JWST be able to characterize the atmospheres of transiting terrestrial planets?**
4. **Which critical measurements will be too expensive or inaccessible to JWST**, and can these be obtained with planned observatories?

Controversial Statements

- JWST will be able to characterize the atmospheres of transiting temperate terrestrials (T^3)
  - ✓Detect Atmosphere
  - ✓Detect Greenhouse Gas
  - ✓Measure Emission Temperature
  - ❑Measure Atmospheric Mass
  - ❑Detect Water Vapor Clouds
- JWST will spend much of its time pursing these goals

Spoiler Alert!

Need a Dedicated Mission to Characterize the Atmospheres of Hot Jupiters and Warm Sub-Neptunes

- 10^0 meter aperture
- Optical-NIR Spectrograph
- 10^0 yr lifetime
- $\$10^0$B cost

Outline

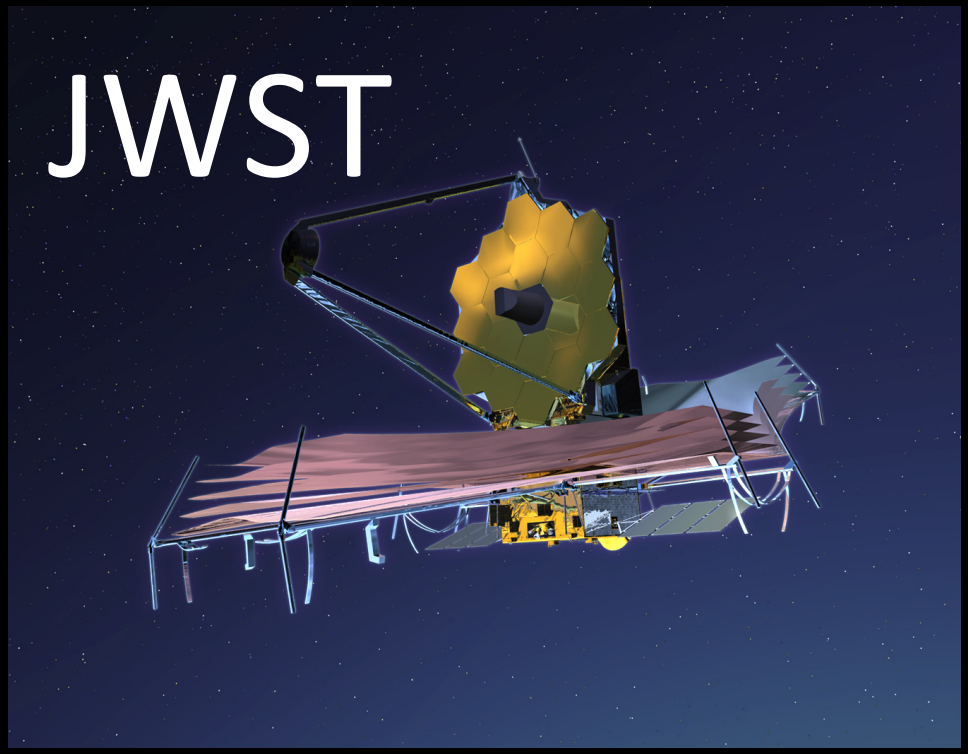
- Why Transiting Exoplanet Atmospheres?
- What Can JWST Do?
- What Will TESS Find?

Why Transiting Planets?

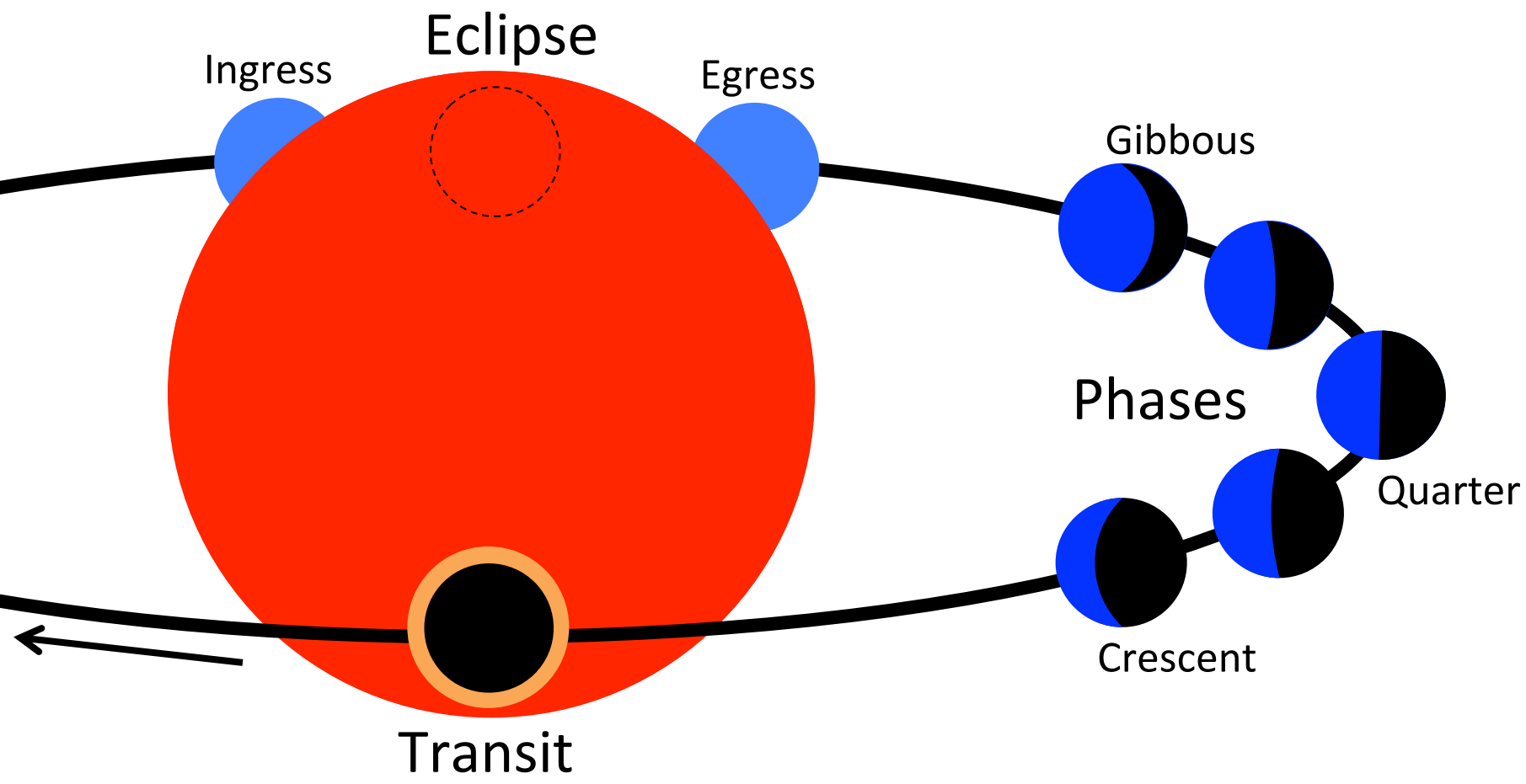
- Known **Mass** and **Radius**
  - Connect Atmospheric and Bulk Composition
- **Locked** and **Irradiated** Planets
  - Novel Atmospheric Physics
- Most **Temperate Terrestrials** Orbit M-Dwarfs
  - Habitable Worlds

“Play Your Stones to Make your Previous Stones Look Good”

NASA's Upcoming Major Commitments to Transiting Planets

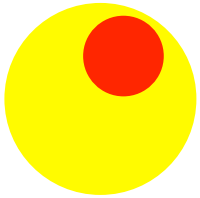


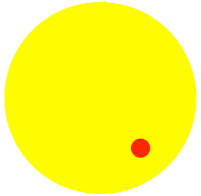
Characterizing Transiting Exoplanets



(Cowan, *Eos* 2014)

Archetypal Short-Period Planets

Hot Jupiter (HD 189733b) 

Hot Earth (Kepler 10b) 

Warm Neptune (GJ 1214b) 

Temperate Super-Earth (GJ 163 c) 

Getting Quantitative

FIDUCIAL TRANSITING PLANET PARAMETERS

Planet Type	Stellar Temp.	Stellar Radius	Planetary Radius	*Transit Depth*[a]	$a/R*$	*Dayside Temp.*[a]	Mean Mol. Mass	Planet Gravity
Hot Jupiter	5000 K	$0.75R_\odot$	1.10 R_J	2.2×10^{-2}	5	1787 K	2 μ	20 m/s^2
Hot Super-Earth	5000 K	$0.75R_\odot$	1.50 $R_\oplus$	2.9×10^{-4}	3	2308 K	140 μ	12 m/s^2
Warm Sub-Neptune	3000 K	$0.20R_\odot$	0.24 R_J	1.4×10^{-2}	15	619 K	2 μ	9 m/s^2
Temperate Super-Earth	3000 K	$0.20R_\odot$	1.50 $R_\oplus$	4.1×10^{-3}	90	253 K	28 μ	12 m/s^2

What JWST Can Do (in photon-counting limit)

Easy (>10σ in single occultation)

Planet Type	Reflected Contrast	Transit Feature	Planet Peak Contrast	Rayleigh-Jeans Contrast
Hot Jupiter	$\mathbf{2.6 \times 10^{-4}}$	$\mathbf{8.3 \times 10^{-4}}$	$\mathbf{7.4 \times 10^{-4}}$	$\mathbf{7.7 \times 10^{-3}}$
Hot Super-Earth	$\mathbf{9.8 \times 10^{-6}}$	$\mathbf{3.0 \times 10^{-6}}$	$\mathbf{1.8 \times 10^{-5}}$	$\mathbf{1.4 \times 10^{-4}}$
Warm Sub-Neptune	1.9×10^{-5}	$\mathbf{2.0 \times 10^{-3}}$	1.8×10^{-4}	$\mathbf{3.0 \times 10^{-3}}$
Temperate Super-Earth	1.5×10^{-7}	2.3×10^{-5}	1.5×10^{-5}	3.5×10^{-4}

Hard (<10σ in single occultation)

Impossible? (<1σ in single occultation)

Photon-Counting Noise?!?

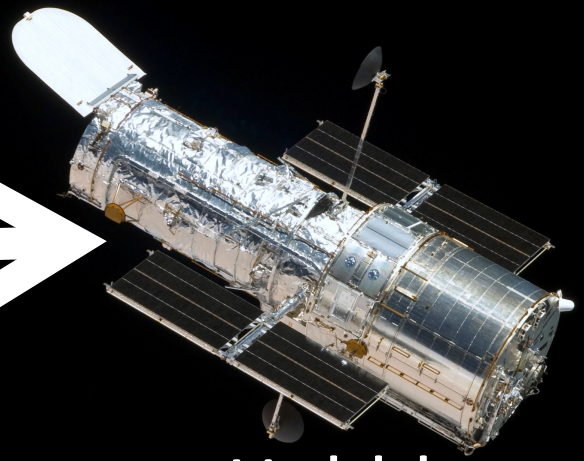
- 3×10^{-5} with HST WFC3 (Kreidberg+2014)
- 5×10^{-5} with *Spitzer* IRAC (Knutson+2012)
- 3×10^{-4} with *Spitzer* MIPS (Crossfield+2012)

In any case, our photon-counting estimates are not terribly different from more detailed studies of JWST (Deming+2009, Batalha+2014)

What TESS Will Find
(Easy to Predict thanks to *Kepler*)

- Some Hot Jupiters
- A Lot of Warm Sub-Neptunes
- A Few Transiting Temperate Terrestrials (t^3)

Spitzer

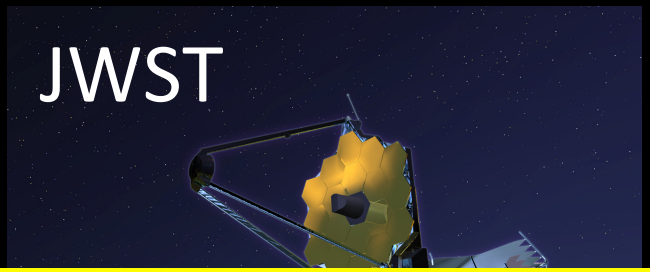


Hubble

10 Bright Targets

RV

Transits



10^3 Bright Targets?!?

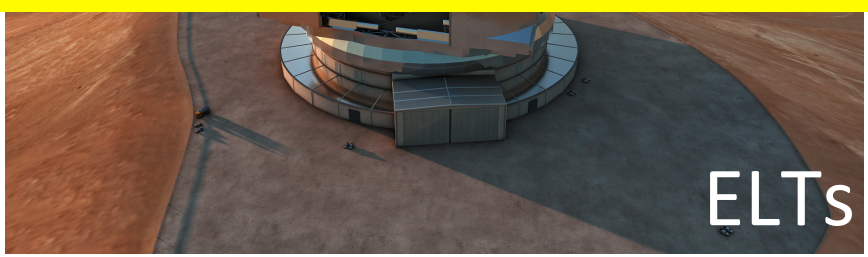
2 hours in transit

+ 4 hours out of transit

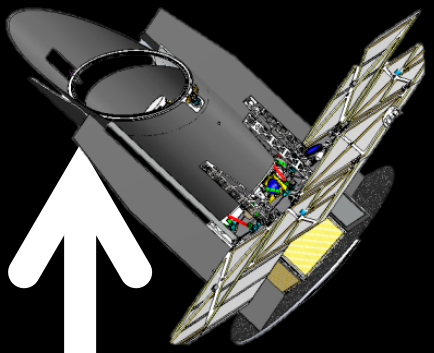
6 hours per planet

= 4 planets per day

= 10^3 planets per year

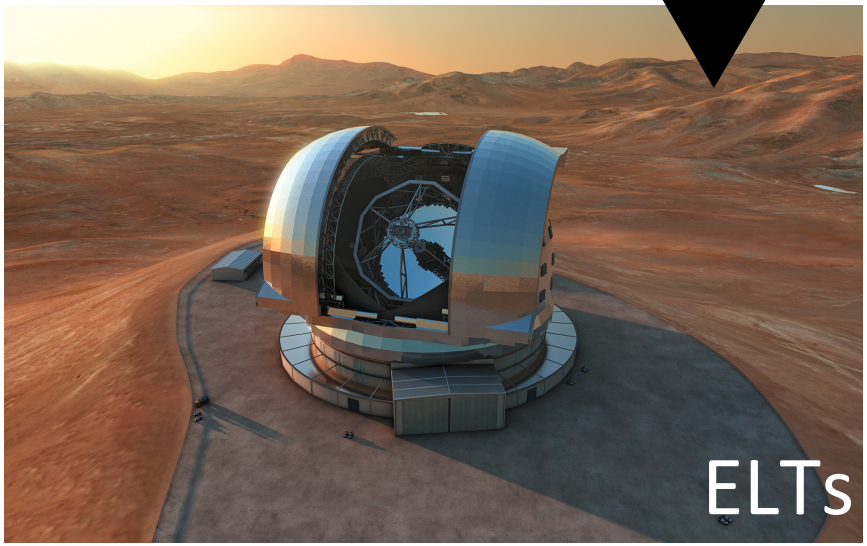


1m Vis-NIR



10^3 Bright Targets

10 Best Targets



Other Observatories

UV Environment of TTTs

- Atmospheres of TTTs
  - HST, ELTs (transit spectroscopy)
- Warm Sub-Neptunes
  - 10m telescopes (transit spec., thermal eclipses)
- Low S/N Surveys of hot Jupiters
  - 4m telescopes, SOFIA, *Spitzer* (transit spectroscopy, thermal eclipses & phases)

The Obvious Next Step

Kepler: Warm Sub-Netunes and temperate terrestrials orbiting M-Dwarfs are common

TESS: Find nearest transiting examples of WSN and TTT

JWST: Capable of characterizing the Atmospheres of WSNs and TTTs, but insufficient time to do both

Exoplanet Atmosphere Survey Telescope

- Obtain good S/N for transit spectroscopy of Warm Sub-Neptunes in single occultation
  - ≈1 meter aperture
- Detect Greenhouse Gases (H_2O, CO_2, CO, CH_4)
  - – Optical-NIR Spectrograph
- Launch into Earth Orbit
  - ≈$1B cost
- Perform survey of 10^{2-3} planets
  - – 1-2 yr lifetime