ASTR 620: Planetary Processes

Professor Eric Nielsen

Lecture 22: Exoplanets

Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 5 due on tonight at 11:59pm
- Order of Magnitude project written assignment due Monday, November 14 at the start of class

STUDENT:	First Question	Second Question	Presentation slot
Asif Abbas	19	24	Wednesday 1
Erick Aguirre	7	25	Monday 5
Neha Babbar	10	12	Wednesday 5
Kevin Brooks	5	9	Monday 3
Sarah Chinski	18	27	Monday 7
Anna Conly	15	23	Wednesday 7
Victoria De Cun	16	28	Monday 6
Dylan Gatlin	3	13	Monday 2
Daniel Godines Alcantara	1	17	Monday 1
Ezra Huscher	21	26	Wednesday 6
Khagendra Katuwal	4	22	Monday 4
Jessica Klusmeyer	14	20	Wednesday 2
Julio Morales	2	8	Wednesday 4
Annie Peck	6	11	Wednesday 3

Review of the last class

- In the core accretion model of planet formation:
  - (A) — Terrestrial planets form their atmosphere first, which allows them to accrete the solid material for their core from the disk
  - (B) — Terrestrial planets form their core first, which allows them to gravitationally pull in gas from the disk
  - (C) — Giant planets form their atmosphere first, which allows them to accrete the solid material for their core from the disk
  - (D) — Giant planets form their core first, which allows them to gravitationally pull in gas from the disk
  - (E) — Instabilities quickly form in the disk and grow into giant planets

Review of the last class

- Suppose we conducted a survey for exoplanets around 10 stars. 9 of these stars have 0 exoplanets, while the 10th star has 10 exoplanets. What is the planet occurrence rate and planet fraction we'd measure from this survey?
  - (A) — PO: 10%, PF: 100%
  - (B) — PO: 100%, PF: 10%
  - (C) — PO: 10%, PF: 10%
  - (D) — PO: 100%, PF: 100%

Review of the last class

- Radial velocity allows us to measure an exoplanet’s
  - (A) — mass, eccentricity, period
  - (B) — minimum mass, eccentricity, period
  - (C) — mass, radius, eccentricity, period
  - (D) — minimum mass, radius, eccentricity, period
  - (E) — period and eccentricity only

Review of the last class

- If (when observing from outside our Solar System) Jupiter transits the Sun, how much fainter does the Sun get?
  - (A) — 10% fainter
  - (B) — 1% fainter
  - (C) — 0.1% fainter
  - (D) — 0.01% fainter
  - (E) — 0.001% fainter

Review of the last class

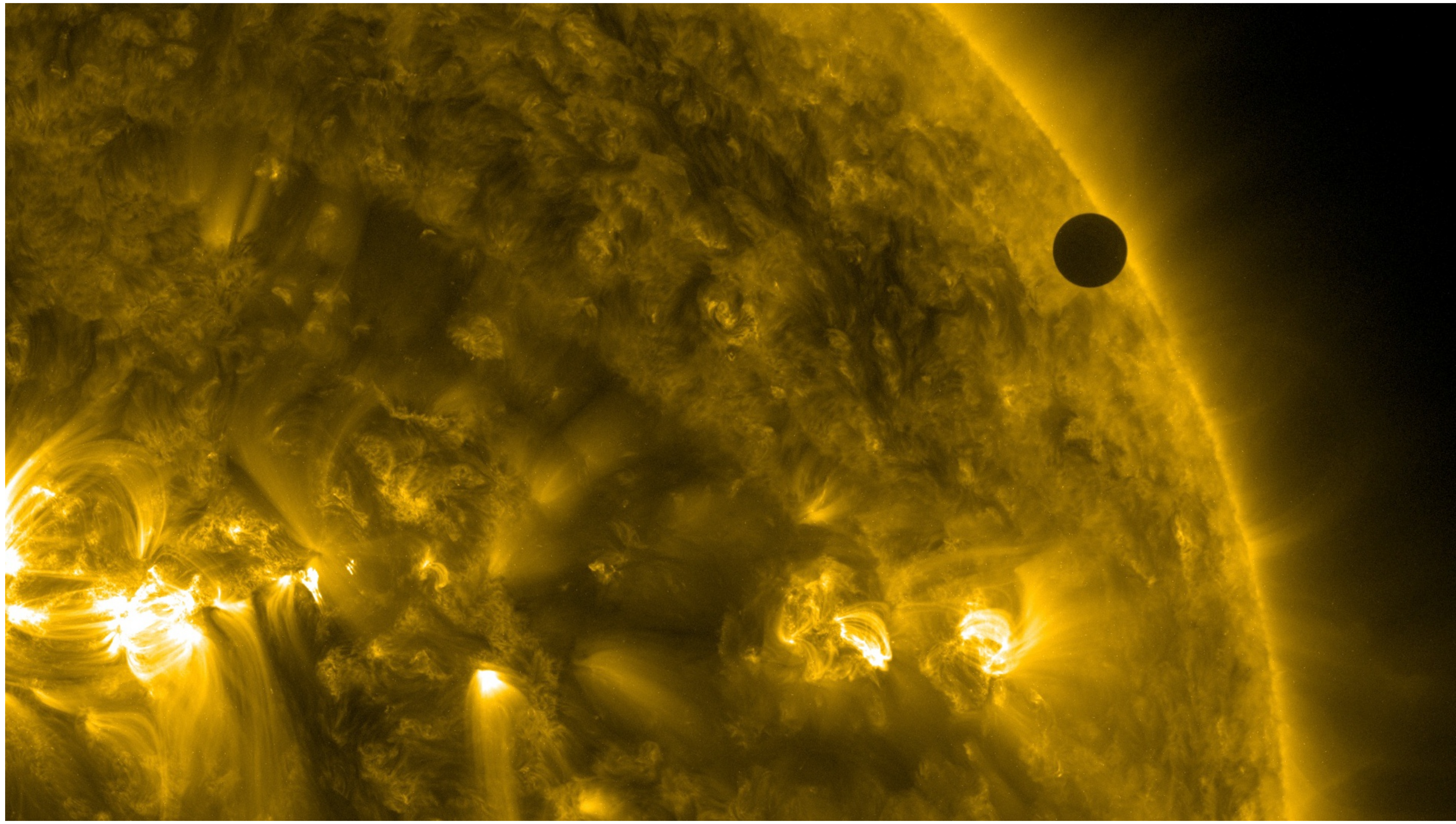
- Hot Jupiters were the first types of exoplanets to be detected with the radial velocity method because:
  - (A) — Pretty much every star has a hot Jupiter
  - (B) — Short-period, large radius planets are the easiest to detect with radial velocity
  - (C) — Short-period, massive planets are the easiest to detect with radial velocity
  - (D) — Long-period, large radius planets are the easiest to detect with radial velocity
  - (E) — Long-period, massive planets are the easiest to detect with radial velocity

The Transit Method

- For a small fraction of stars with planets in the galaxy, Earth happens to be aligned just right (inclination angle very close to 90 degrees) for the planet's orbit to take it in a line between the star and Earth

- We once again don't detect the planet directly, but rather indirectly detect it: light from the star dims when the planet is passing in front of the star

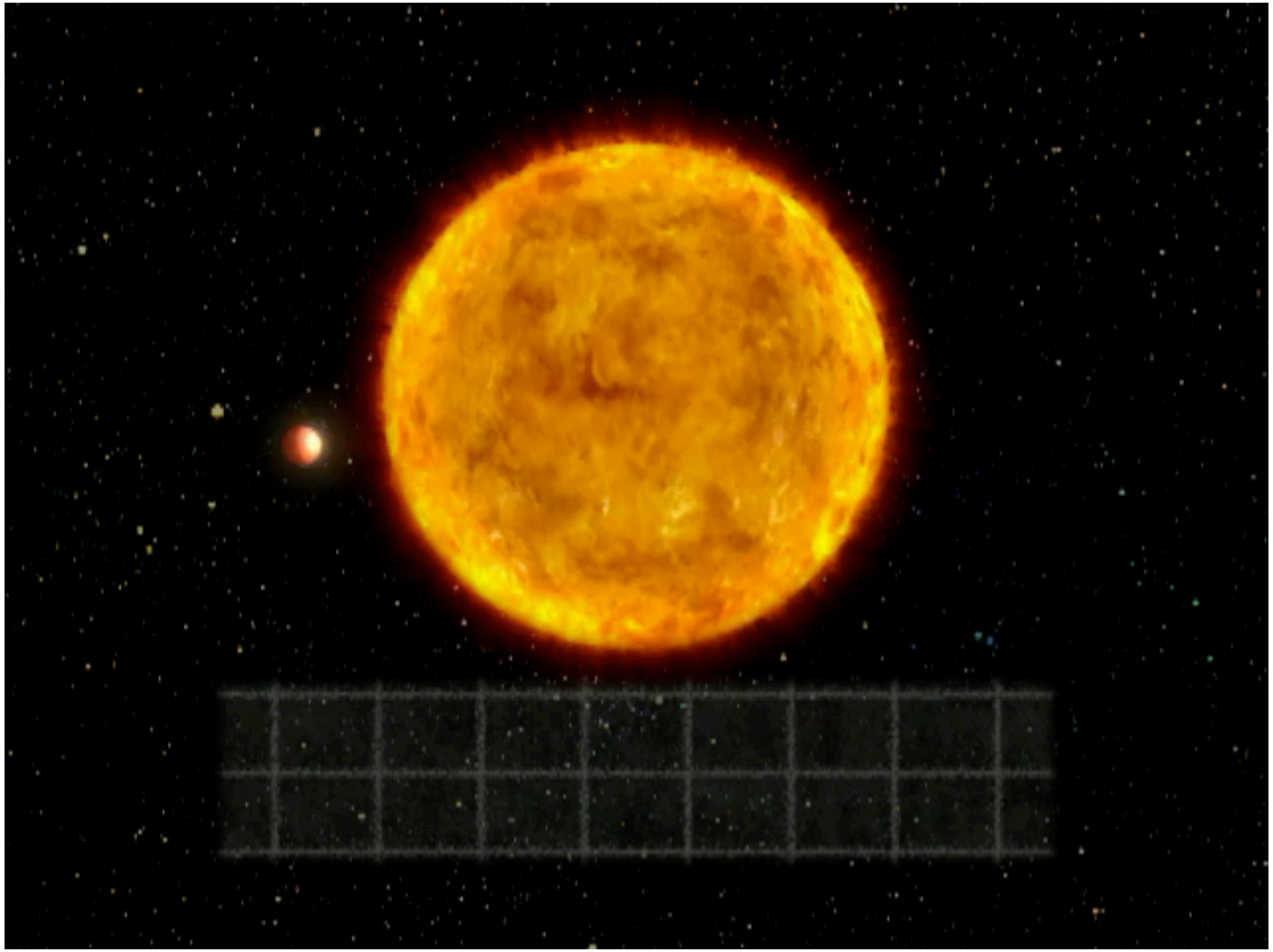
- By monitoring the brightness of stars, planets can be detected



NASA/SDO

Transits

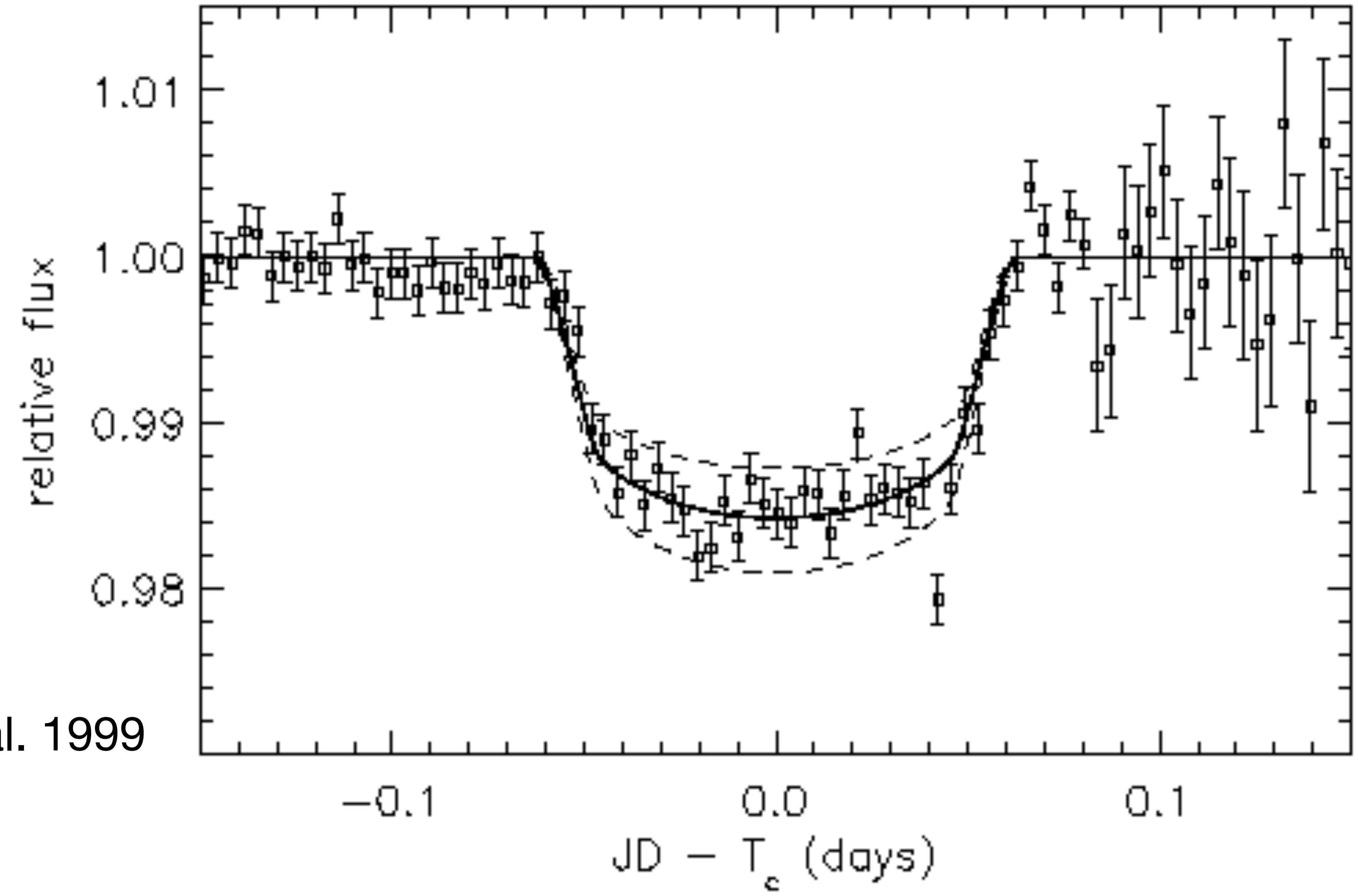
- For a Jupiter-sized planet, about 1% of the star's light will be blocked by the planet
- For a Hot Jupiter, a transit will happen once every few days, and last a couple of hours
- These are very feasible numbers for ground-based telescopes
- After the first Radial Velocity planets were discovered in 1995, astronomers began monitoring the brightness of their host stars, hoping some planets would transit



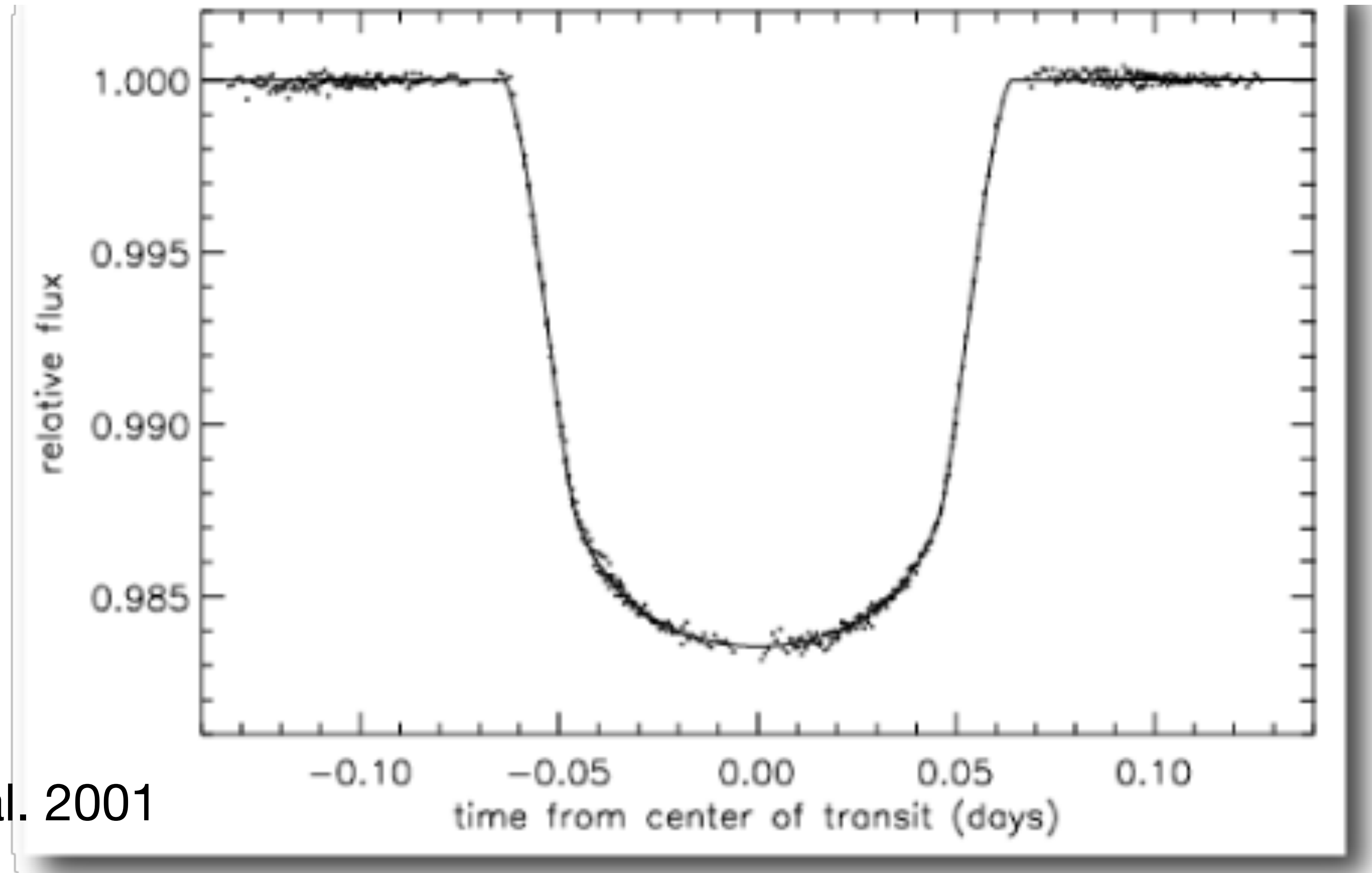
NASA/Hubble

HD 209458 b: the first Transit Detected

- In 1999, the first transiting planet was discovered, HD 209458 b, previously discovered by radial velocity
- “Light curve” shows brightness of the star over time
- Ground-based telescopes clearly showed the transit, though data got noisy as the star started to set
- Follow-up observations with the Hubble Space Telescope 2 years later showed the power of looking for transits from space



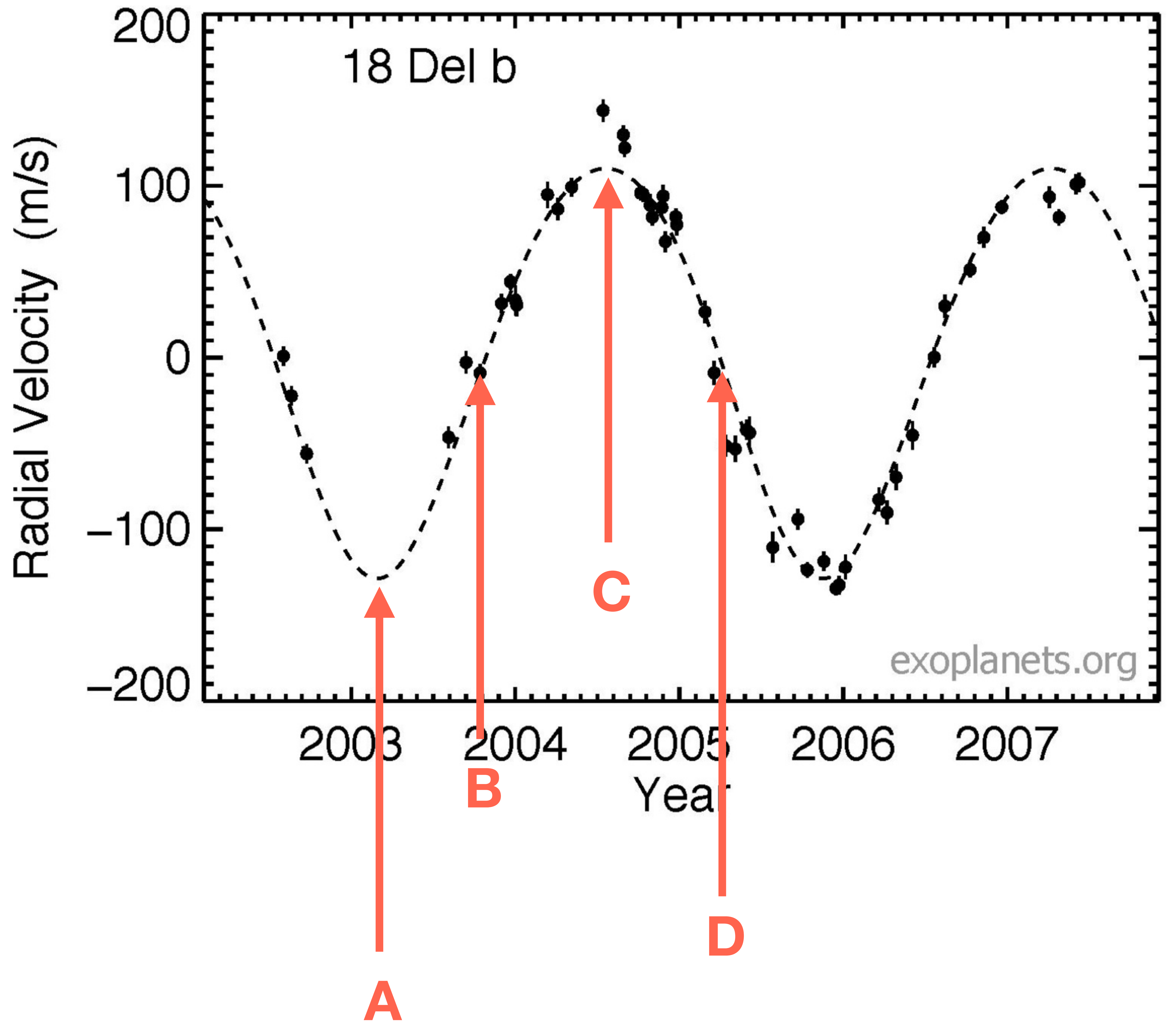
Charbonneau et al. 1999



Brown et al. 2001

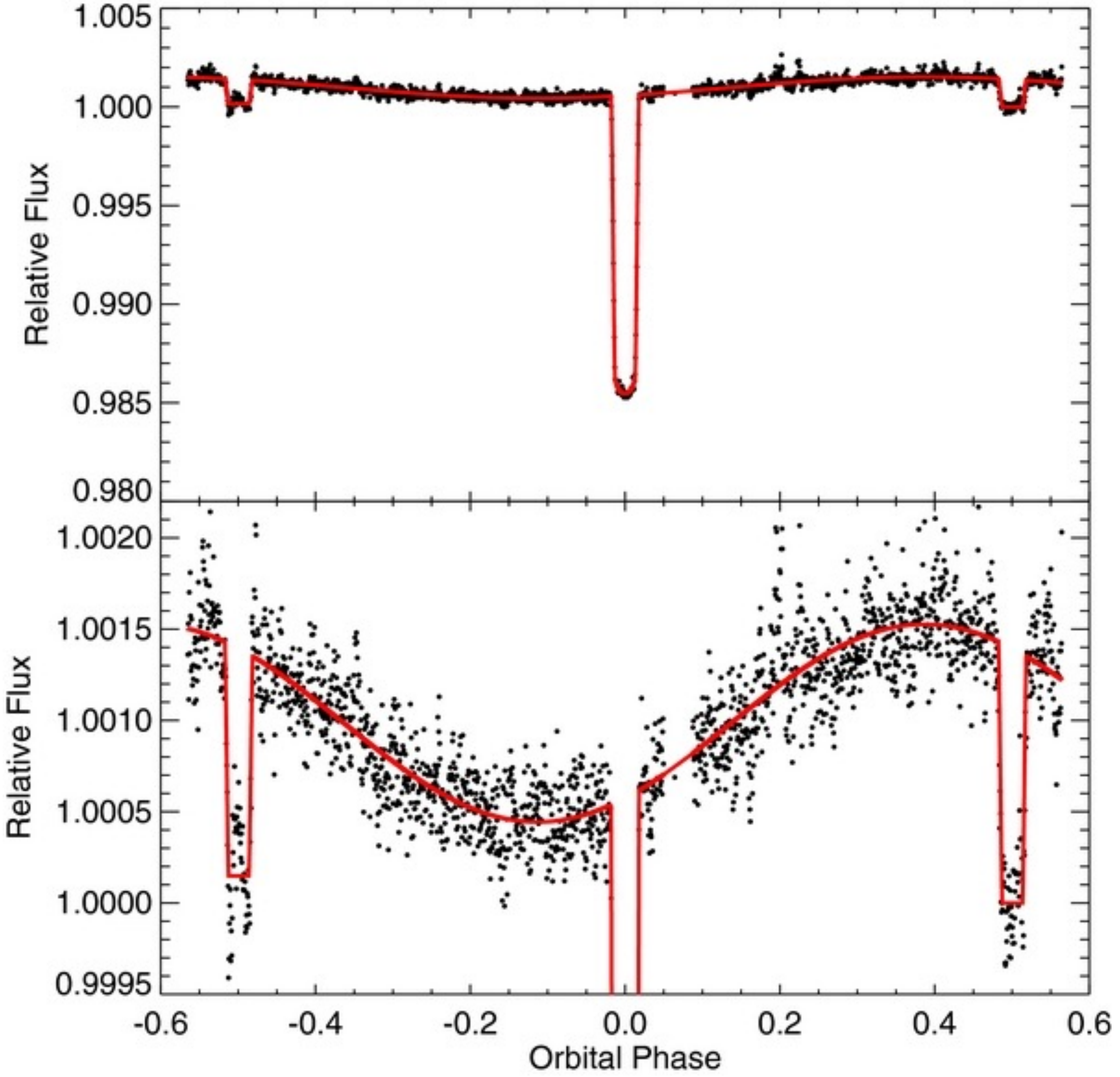
Response Card Question

- If 18 Del b transits its host star (it doesn't, sadly), when would we expect the transit to happen?
  - (A) — 2003.2
  - (B) — 2003.8
  - (C) — 2004.5
  - (D) — 2005.3
  - (E) — There's not enough information to narrow it down to one of these options



Transits, Secondary Eclipse, and Phase Curve

- Spitzer light curve of HD 209458 over a full orbit of HD 209458 b.
- Transit: when the planet is in front of the star, blocking out some light from the star
- Secondary eclipse: when the planet is behind the star, and the planet's light is blocked out
    - A hot Jupiter is hot enough (1000-2000K) to emit detectable light in the infrared, so that you can tell the difference between planet+star and just star



Zellem et al. 2014

Transits, Secondary Eclipse, and Phase Curve

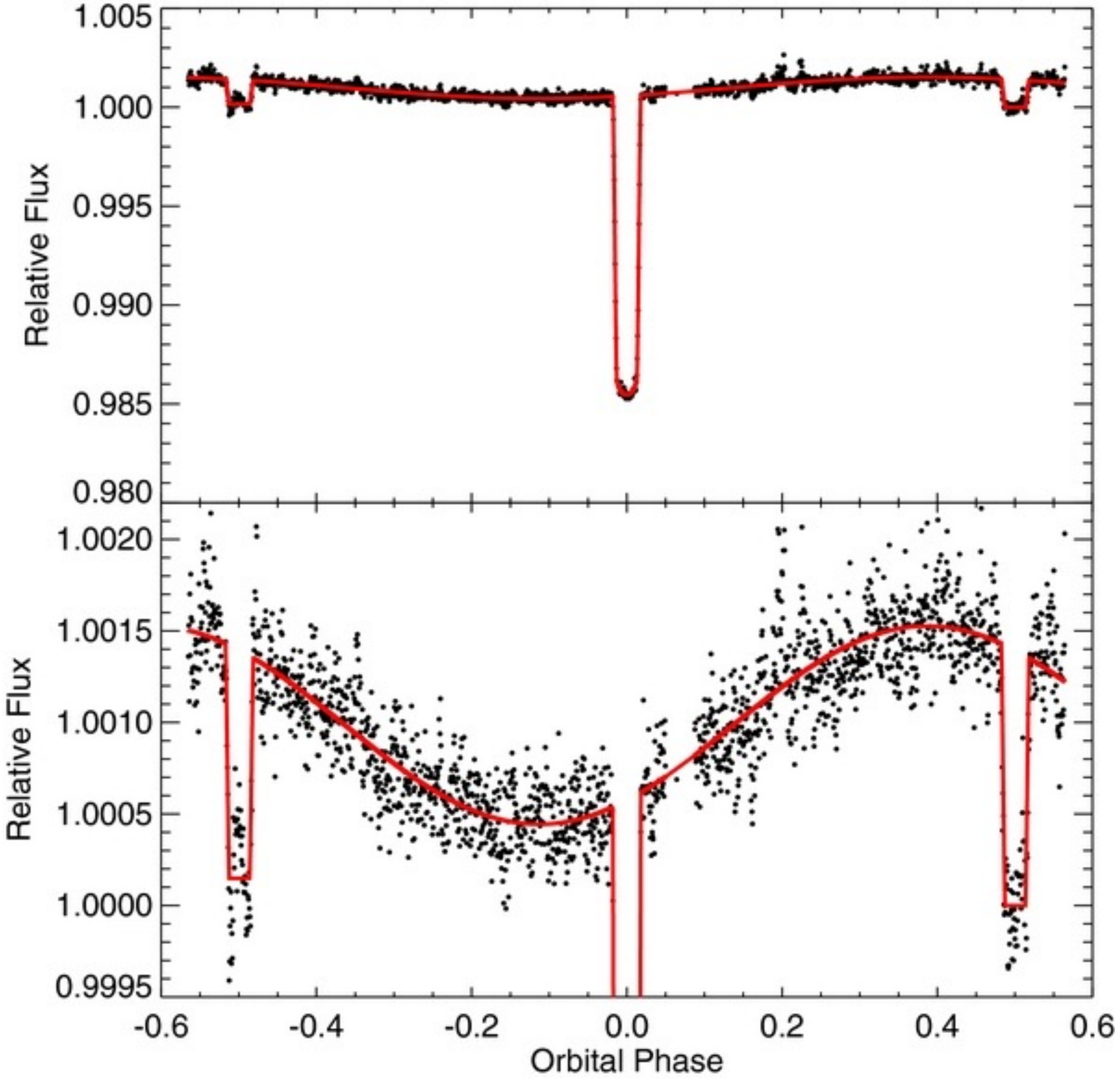
- Phase curve: planet is tidally locked, so rotates on its axis once an orbit around the star

- Expect "substellar point" to be the hottest, and so brightest (immediately before and after secondary eclipse)

    - Opposite side of planet from substellar point (immediately before and after transit) is expected to be coldest, and so faintest

- See a ~20 degree phase offset between secondary eclipse and brightest point, and between transit and faintest point

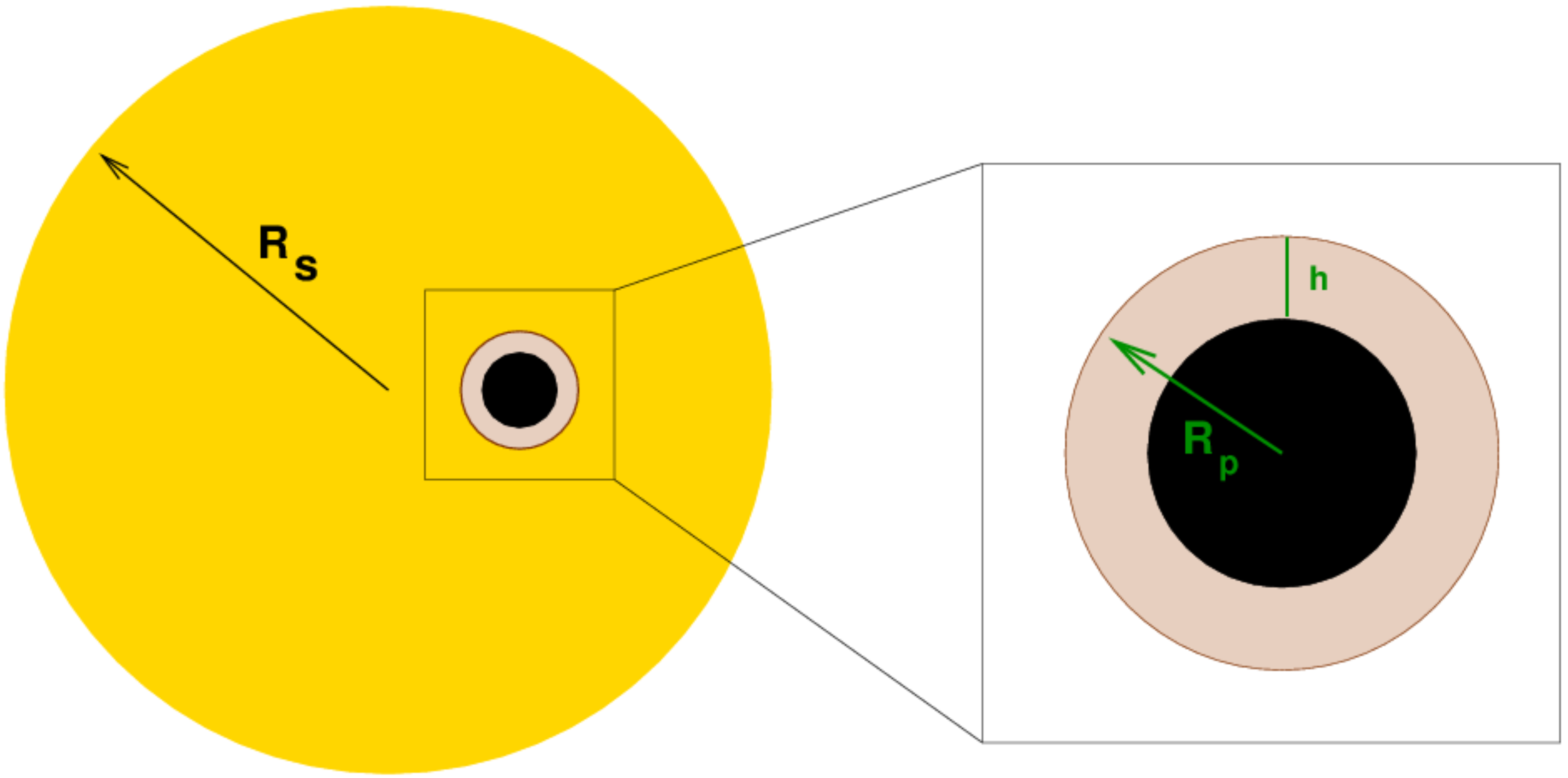
    - Consistent with a supersonic wind moving hot gas from substellar point eastward on the planet



Zellem et al. 2014

Transit Spectroscopy

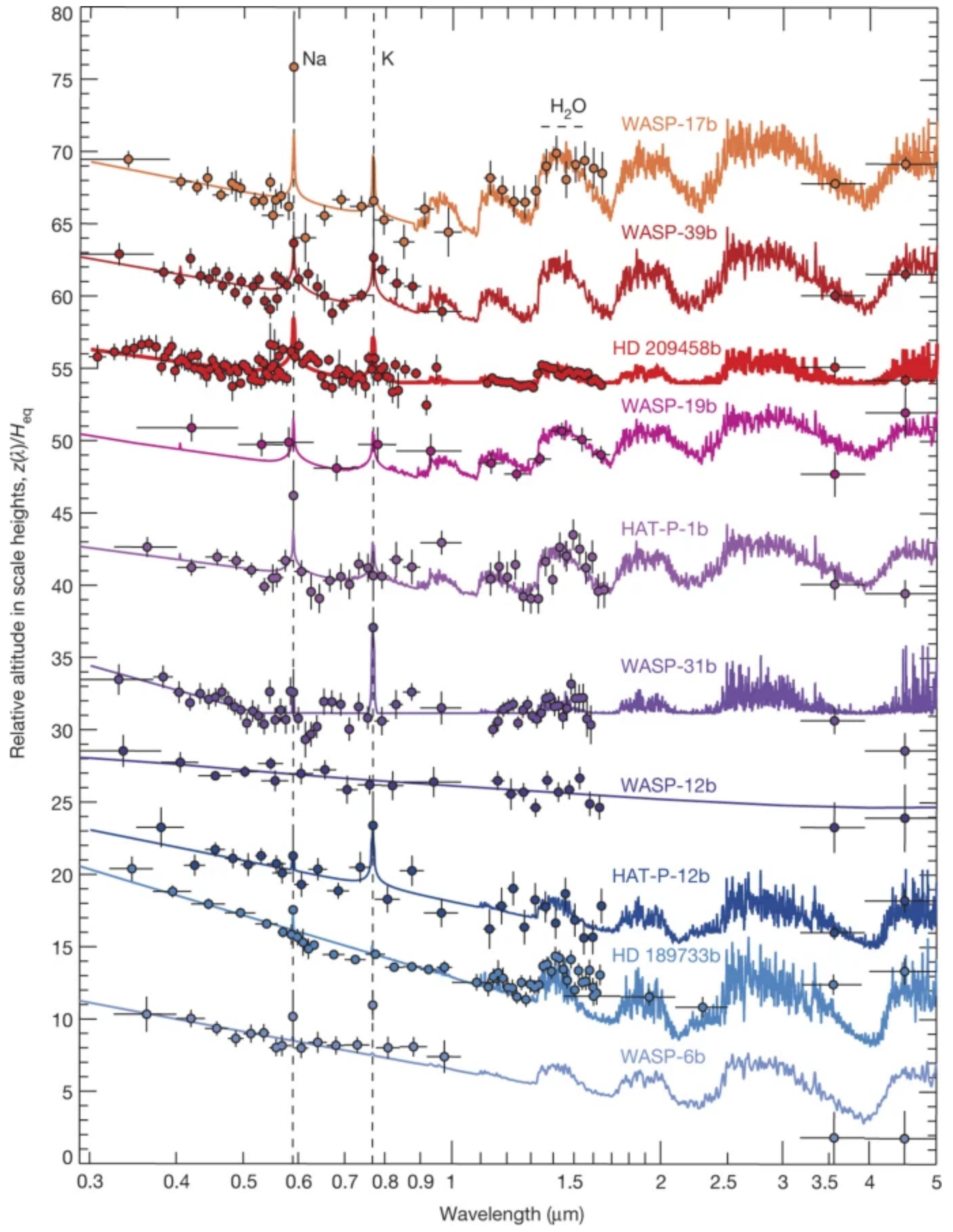
- The transit method is one of two ways to get spectra of exoplanets (the other is direct imaging)
- Take spectra of star before, during, and after a transit, then subtract in-transit spectra from out-of-transit spectra
- Can determine atmospheric composition and structure with the right resolution and SNR
- Need high precision: geometrically, giant planet upper atmospheres are a few percent the area of the planet



Michael Richmond

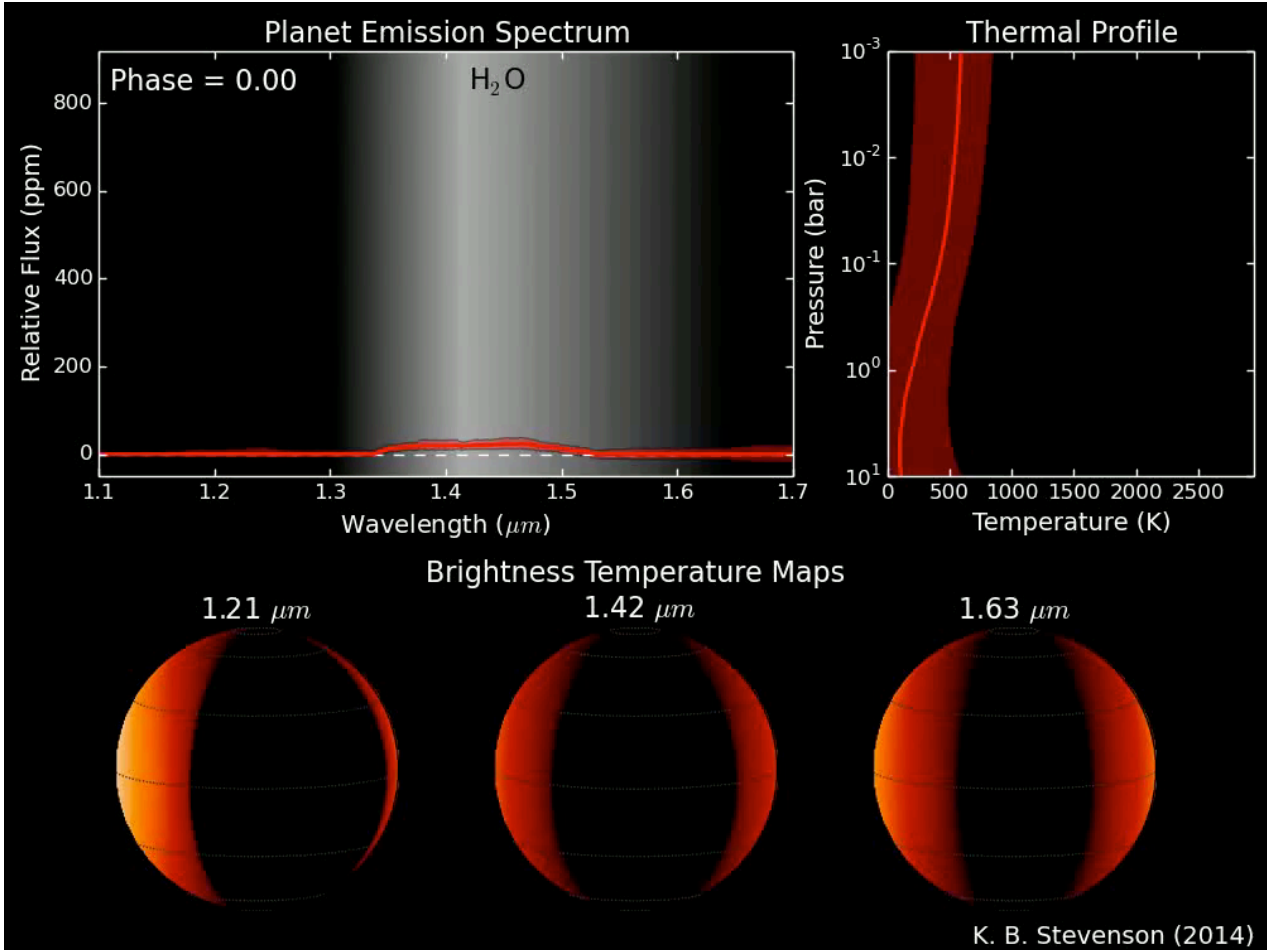
Transit Spectroscopy

- Most transit spectroscopy of hot Jupiter in the visible showed mostly flat spectra
    - Hazes and clouds meant starlight was only probing the uppermost layers of the atmosphere
- Hubble was able to observe in the NIR, and detect a water feature in many hot Jupiter atmospheres



Sing et al. 2015

Phase Curve Spectroscopy



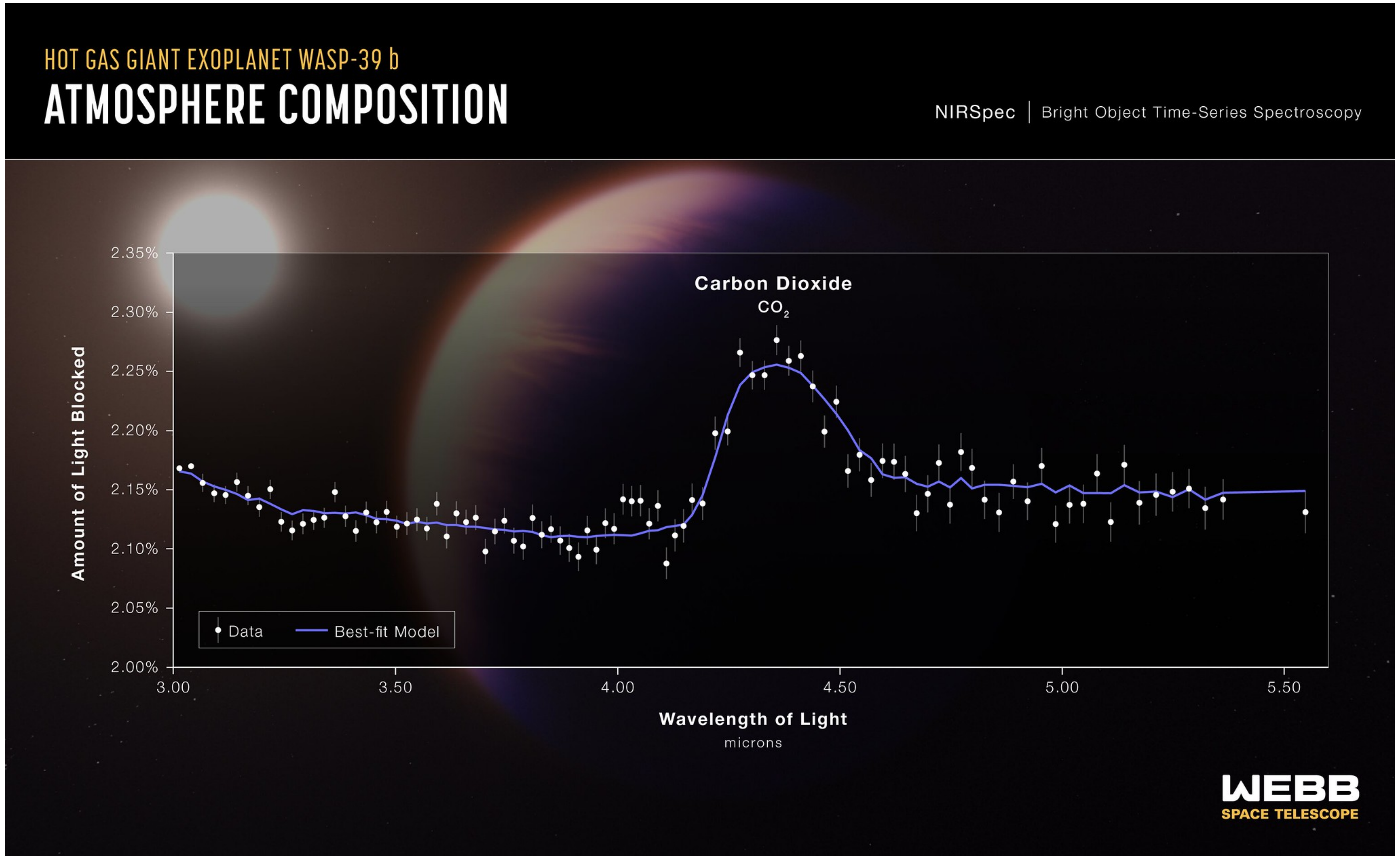
WASP-43b, Stevenson et al. 2014

Transit Spectroscopy

- JWST is able to do precision transit spectroscopy into the mid-infrared, where most molecular features are

- These wavelengths are less obscured by hazes, allowing for better characterization of the atmospheric composition

- Requires a lot of space telescope time (usually multiple transit observations of each planet) to get the SNR required



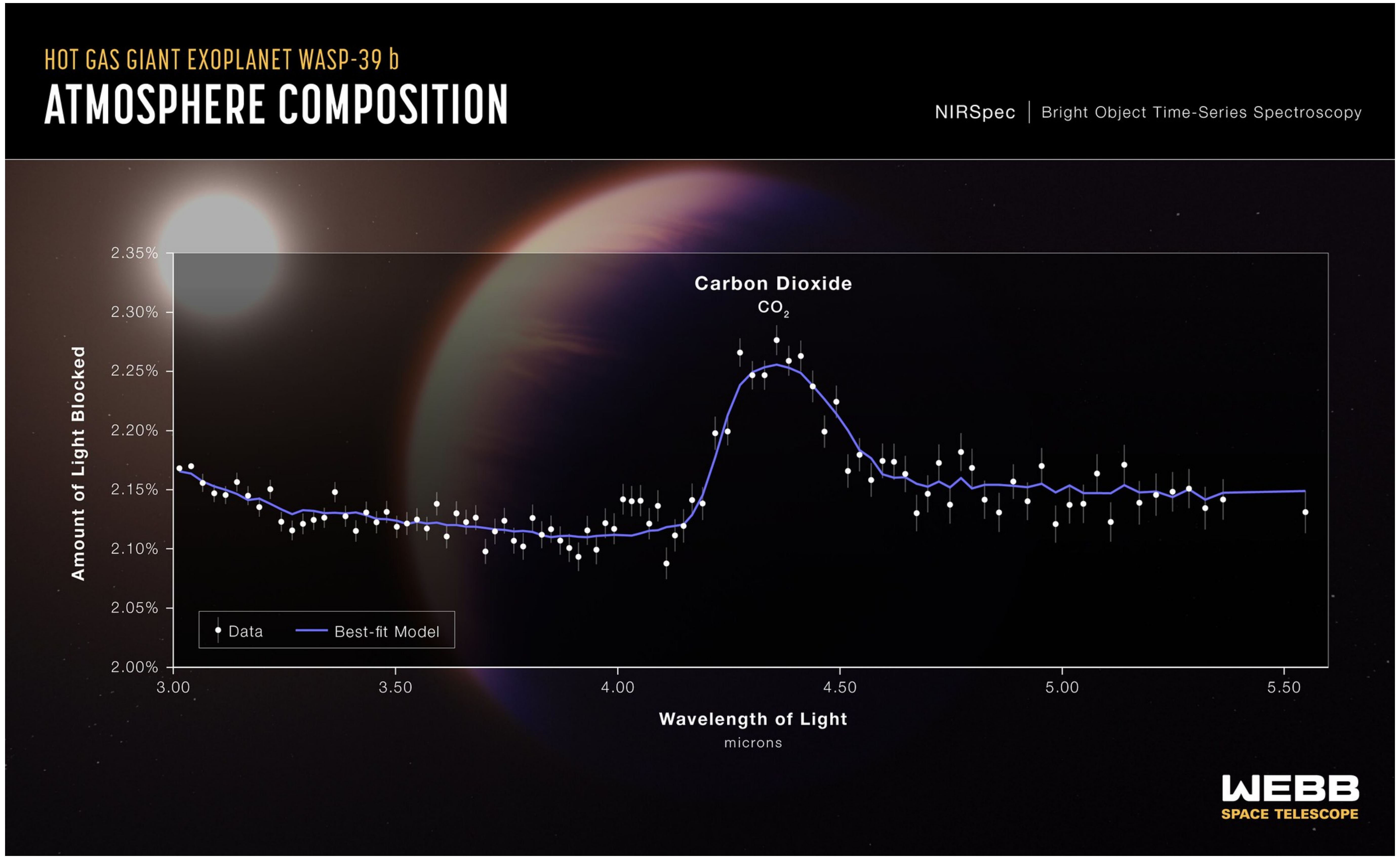
Order of Magnitude: Transit Spectroscopy

- Suppose at some point in the future, JWST is trying to take a spectrum of an Earth twin (same atmospheric and orbital properties of the Earth, orbiting a Sun-like star) via transit spectroscopy

- Most of the mass of Earth's atmosphere is in the troposphere and stratosphere, 50 km above the surface. Suppose the atmosphere is completely transparent at one wavelength (W1), and completely opaque at a nearby wavelength (W2) due to water absorption.

- (1) What is the transit depth (in percent of the star's flux) at W1?

- (2) What is the extra transit depth (in percent of the star's flux) at W2, compared to W1?



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- (1) What is the transit depth (in percent of the star's flux) at W1?

- Ok, here we can just ignore the atmosphere, and compare areas of circles, remembering that Earth's radius is 1/100 of the Sun's radius

$$T_D = \frac{A_P}{A_S} = \frac{\pi R_P^2}{\pi R_S^2} = \left(\frac{1}{100}\right)^2 = \frac{1}{10000} = 10^{-4} = 0.01\,\%$$

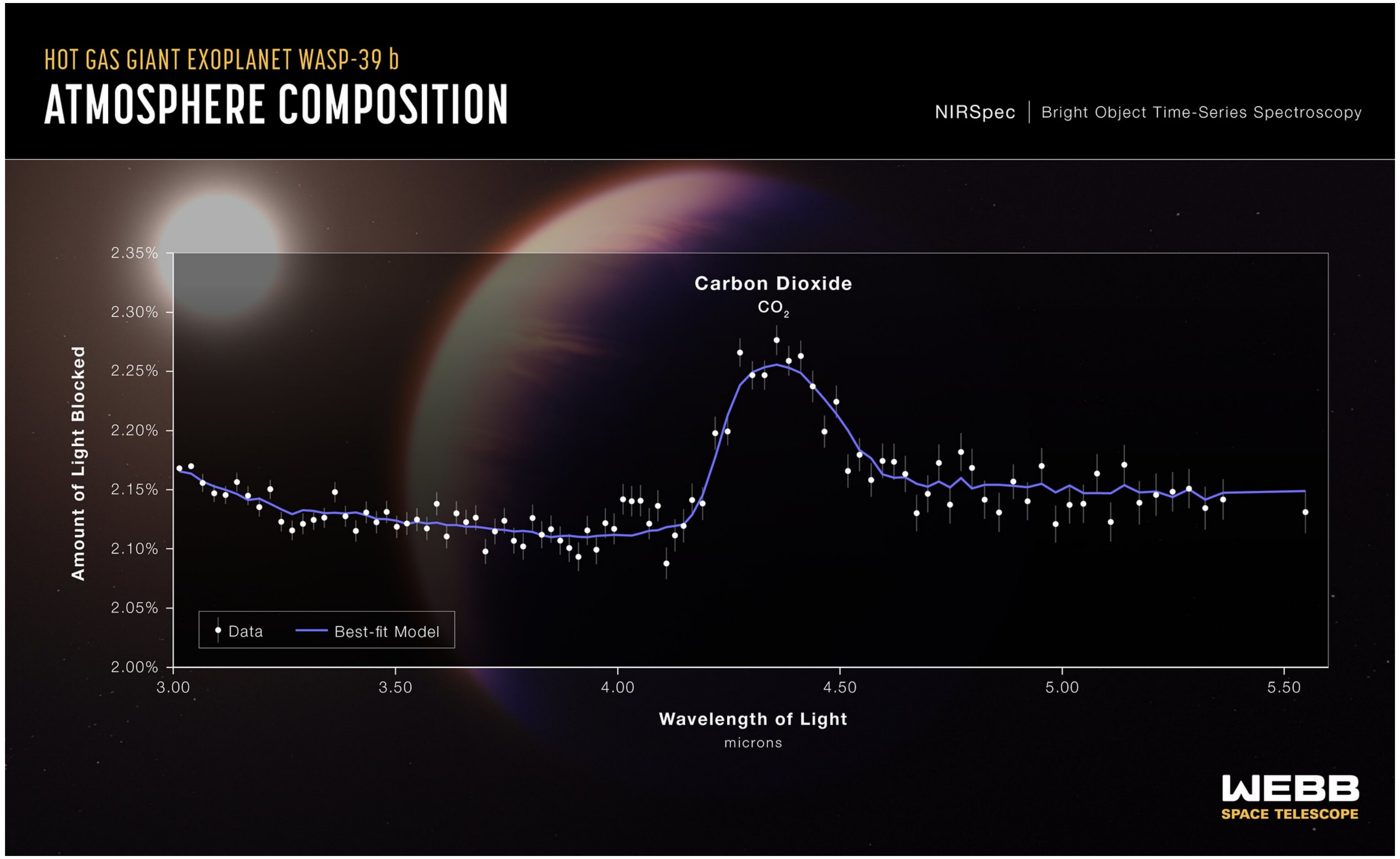
Order of Magnitude: Transit Spectroscopy

- (2) What is the extra transit depth (in percent of the star's flux) at W2, compared to W1?
- So the radius of the planet gets 50km bigger at this wavelength, which is about a 1% change from the radius of the planet without the atmosphere. Since we want the extra transit depth, we care about the area of the atmosphere, since that's the extra obstruction for the star's light. Since the atmosphere is so much smaller than the planet, we can approximate the atmosphere as a rectangle, with length equal to the circumference of the planet, and height equal to the atmosphere's height:
- $$T_{D,A} = \frac{A_{atmos}}{A_S} = \frac{2\pi R_E H}{\pi R_S^2} = \frac{2R_E H}{(100R_E)^2} = \frac{2H}{10^4 R_E} = \frac{2x50km}{10^4(6000km)} = \frac{100km}{6x10^7 km} = 0.2x10^{-5} = 2x10^{-6}$$
- So, 2 parts per million. Or, converting to percent: 0.0002%

Transit Spectroscopy

- Early results will come from hot Jupiters: frequent transits, large planets, large atmospheres

- Rocky planets are trickier: close-in planets are easier (more frequent transits, more likely to have puffier atmospheres), but also more likely to have lost their atmospheres



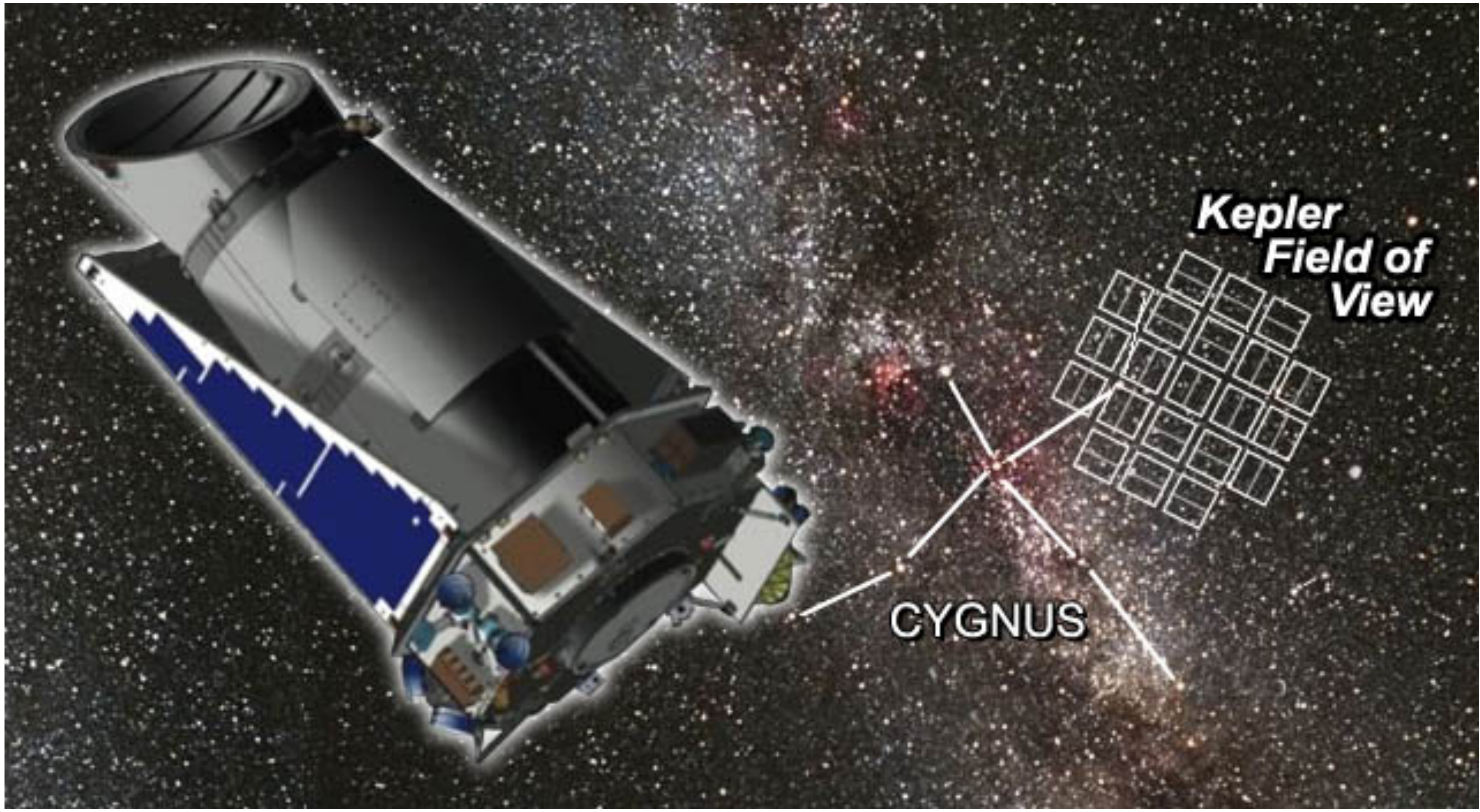
Break

Planet Discoveries over Time

wikipedia

Kepler

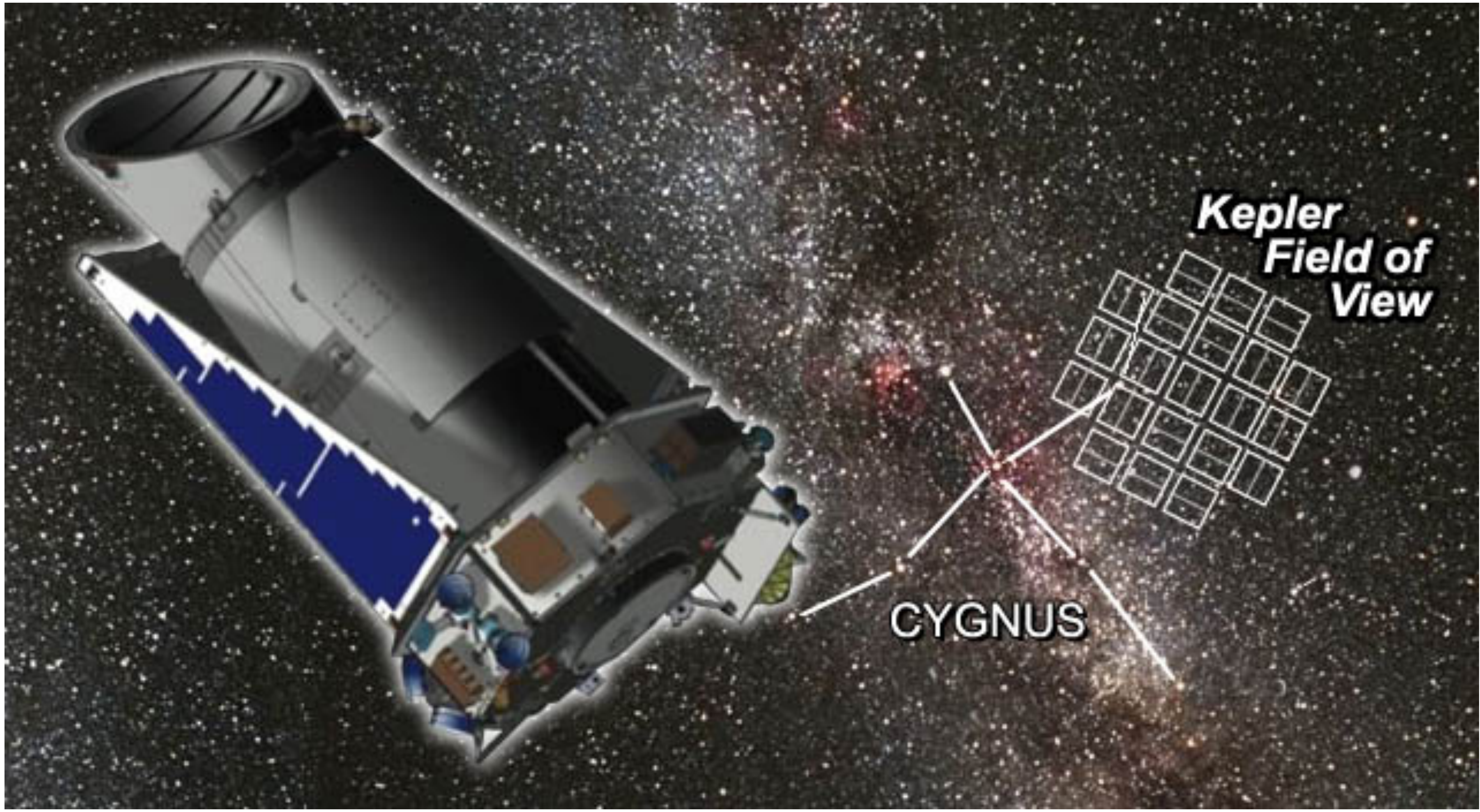
- The Kepler Space Telescope is the most prolific planet-finder ever built
- Kepler monitored the brightness hundreds of thousands of stars in one part of the sky for four years



NASA/Kepler

Kepler

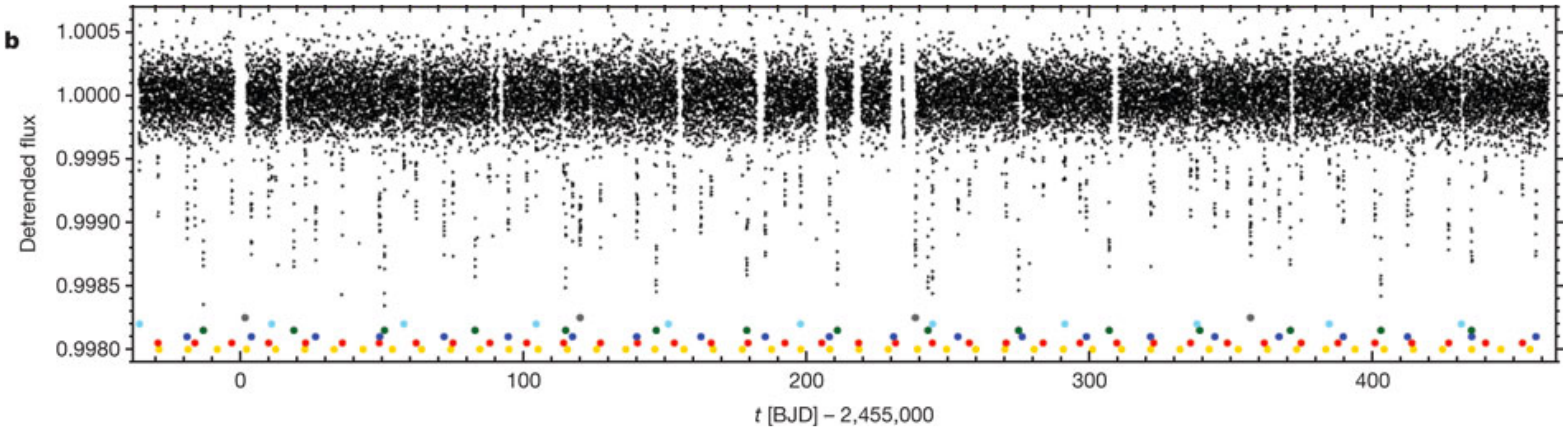
- Kepler could measure brightnesses much more precisely than any ground-based telescope, and didn't have to contend with weather
- Kepler launched in 2009, took data until 2018
- Over 2800 confirmed planets from Kepler, with more still being found as astronomers analyze the data



NASA/Kepler

Kepler

- Jupiter-sized planets block about 1% of the light from a Sun-like star
- Earth-sized planets block about 0.01% of the light from a Sun-like star
- Kepler was the first telescope to have the precision needed to make transit detections of Earth-sized planets
- Kepler was very sensitive to planets with orbital periods shorter than 100 days, and sizes down to about the size of the Earth

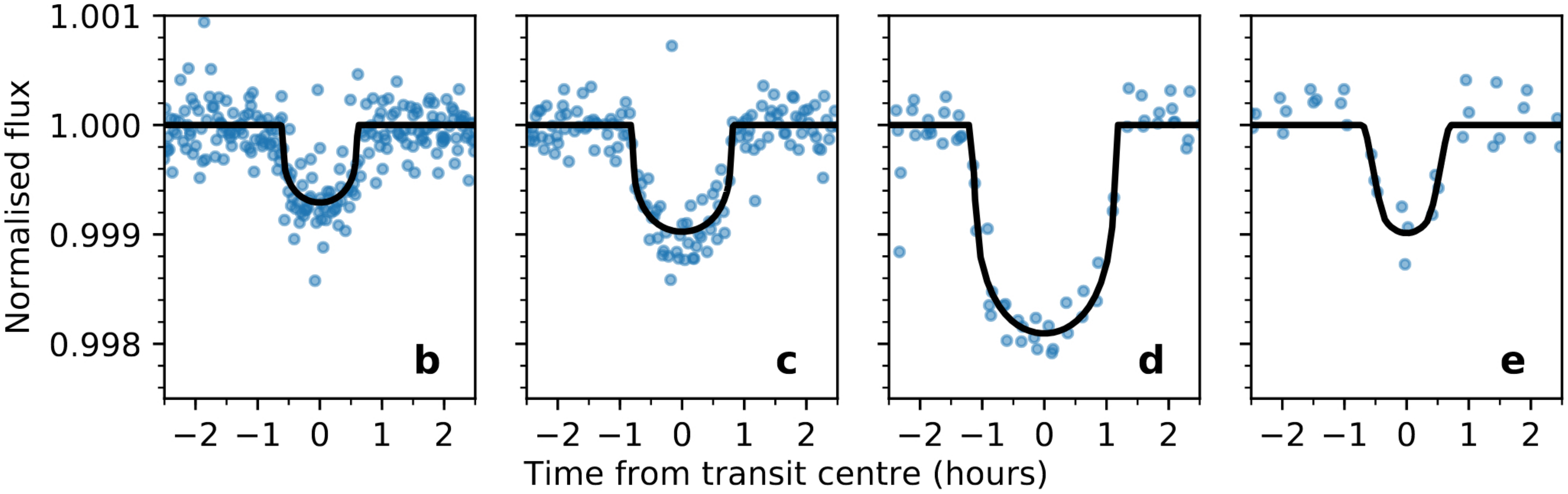


Lissauer et al. 2011

Response Card Question

- These four planets orbit the same star, and were detected by the transit method. Which of these planets has the largest size (radius)?

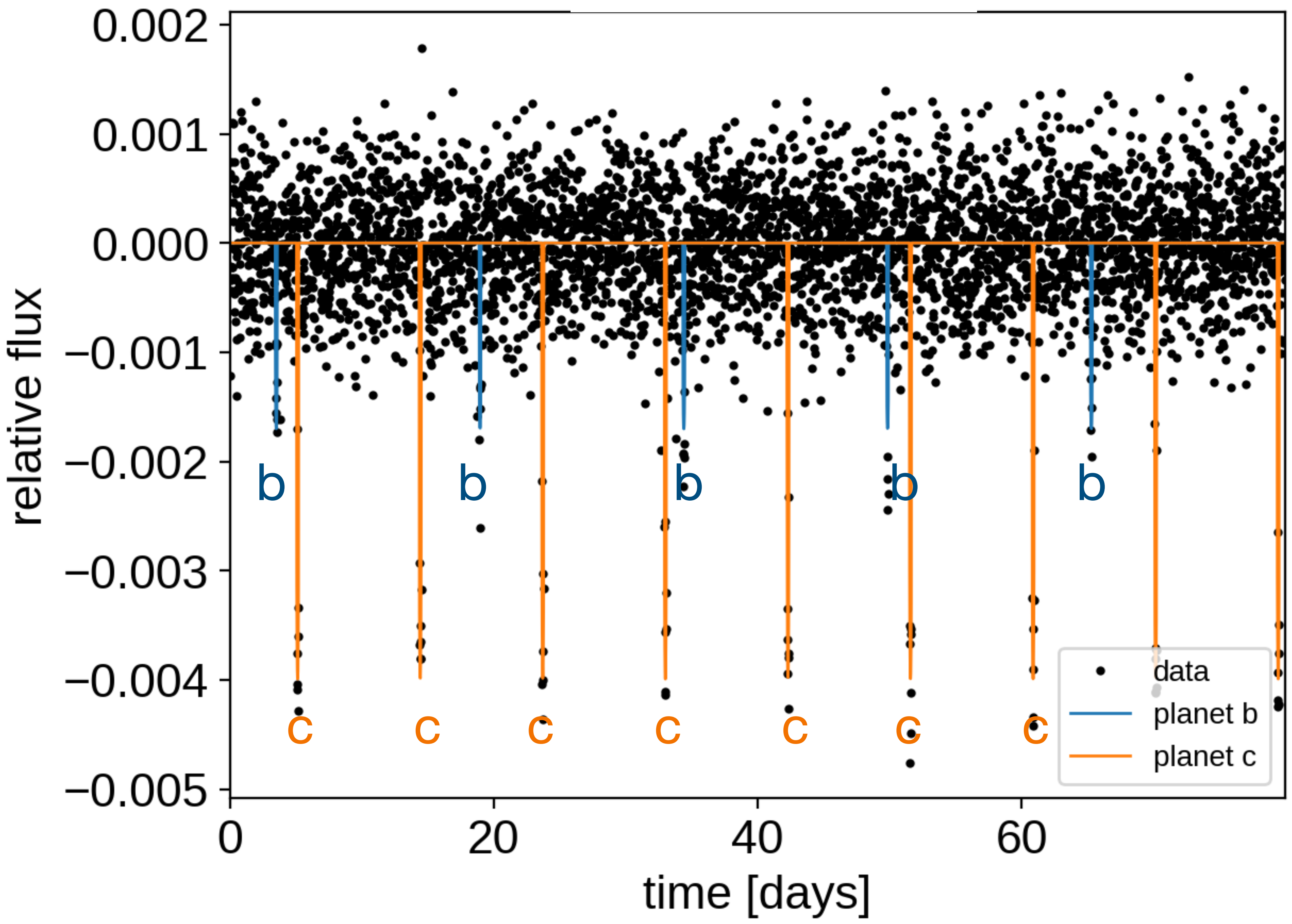
  - (B) — planet b
  - (C) — planet c
  - (D) — planet d
  - (E) — planet e



Wells, Poppenheagar, and Watson 2017

Response Card Question

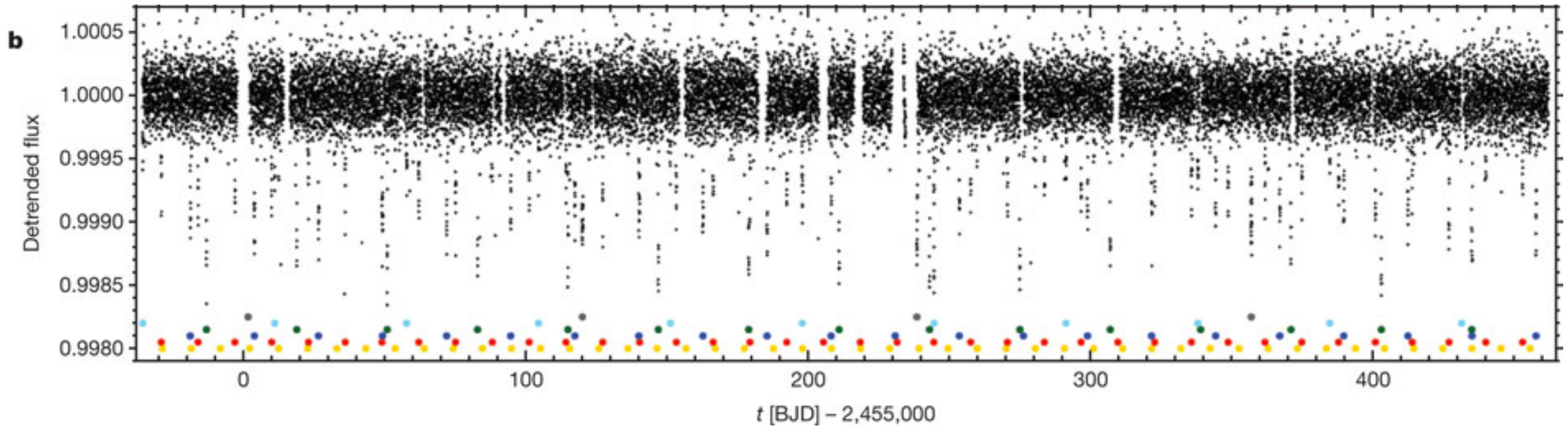
- Two planets orbit the same star. Which has the larger orbital period?
  - (A) — They have the same period
  - (B) — planet b
  - (C) — planet c
  - (D) — there's no way to tell



Foreman-Mackey 2020

Transits

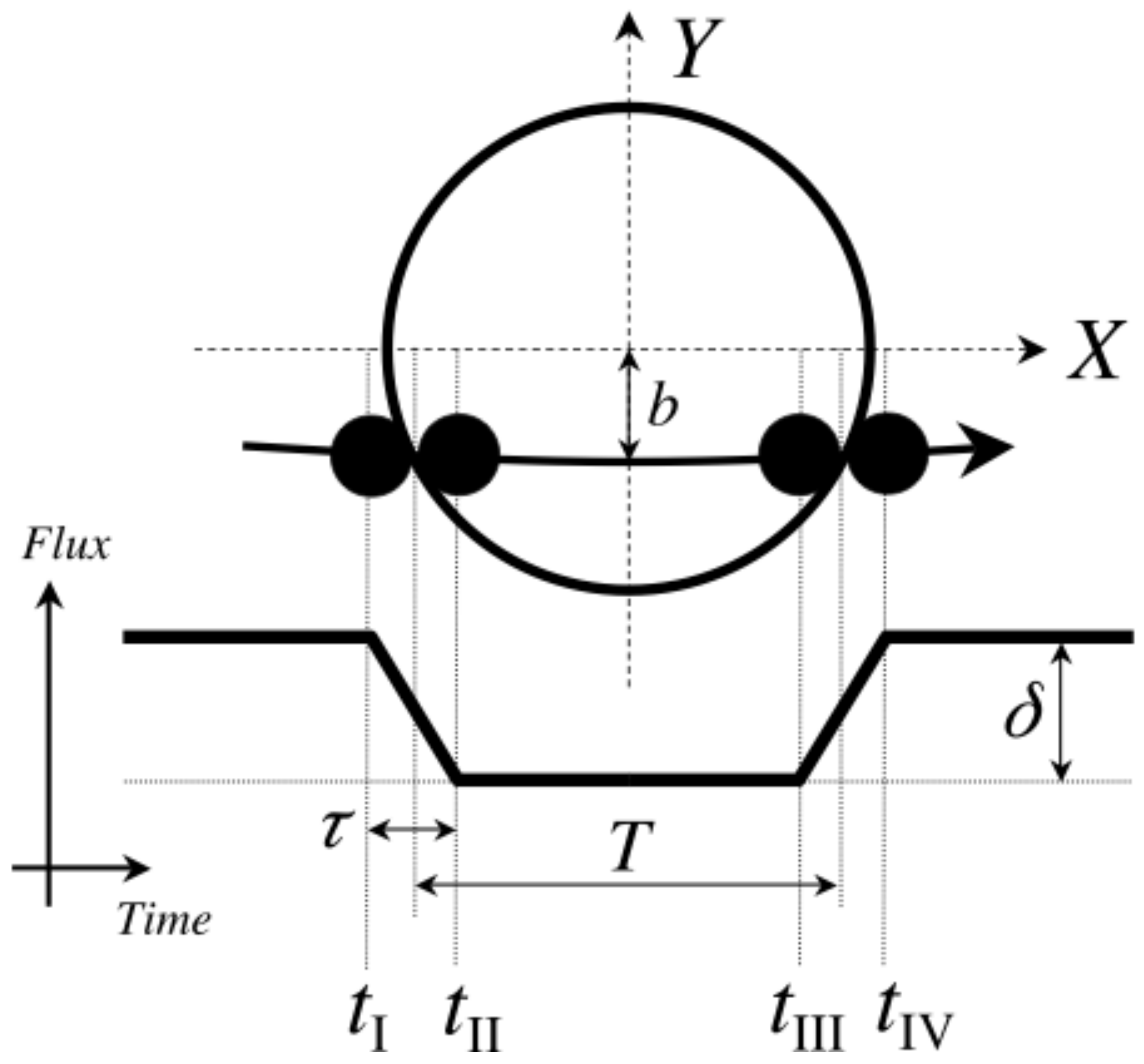
- From a transit light curve, can get orbital period for each planet (time between transits)
- Can get transit depth, which is area of the planet divided by area of the star
    - Converting transit depth to physical size requires that we know stellar radius: can infer this from observations+models



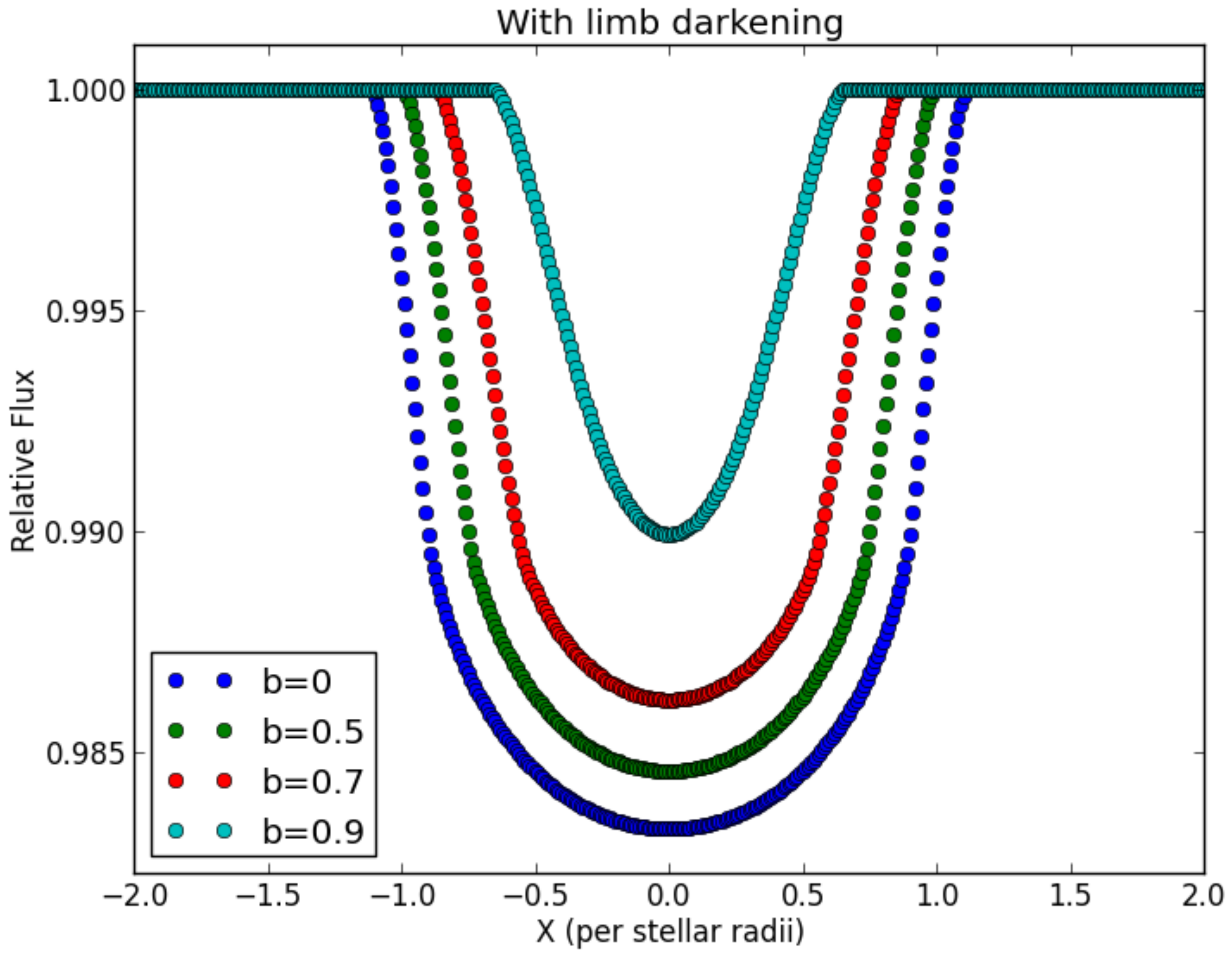
Lissauer et al. 2011

Transits

- "Impact parameter," how close the transit is to the center of the star
  - b=0: center of planet passes through center of star, as seen from Earth
  - b=1: center of planet just grazes the top of the star, as seen from Earth
- Can determine impact parameter from the shape of the transit light curve
  - Can solve for inclination angle if you know impact parameter
- Also need to account for limb darkening: stars are brighter in the center of the disk than at the edges



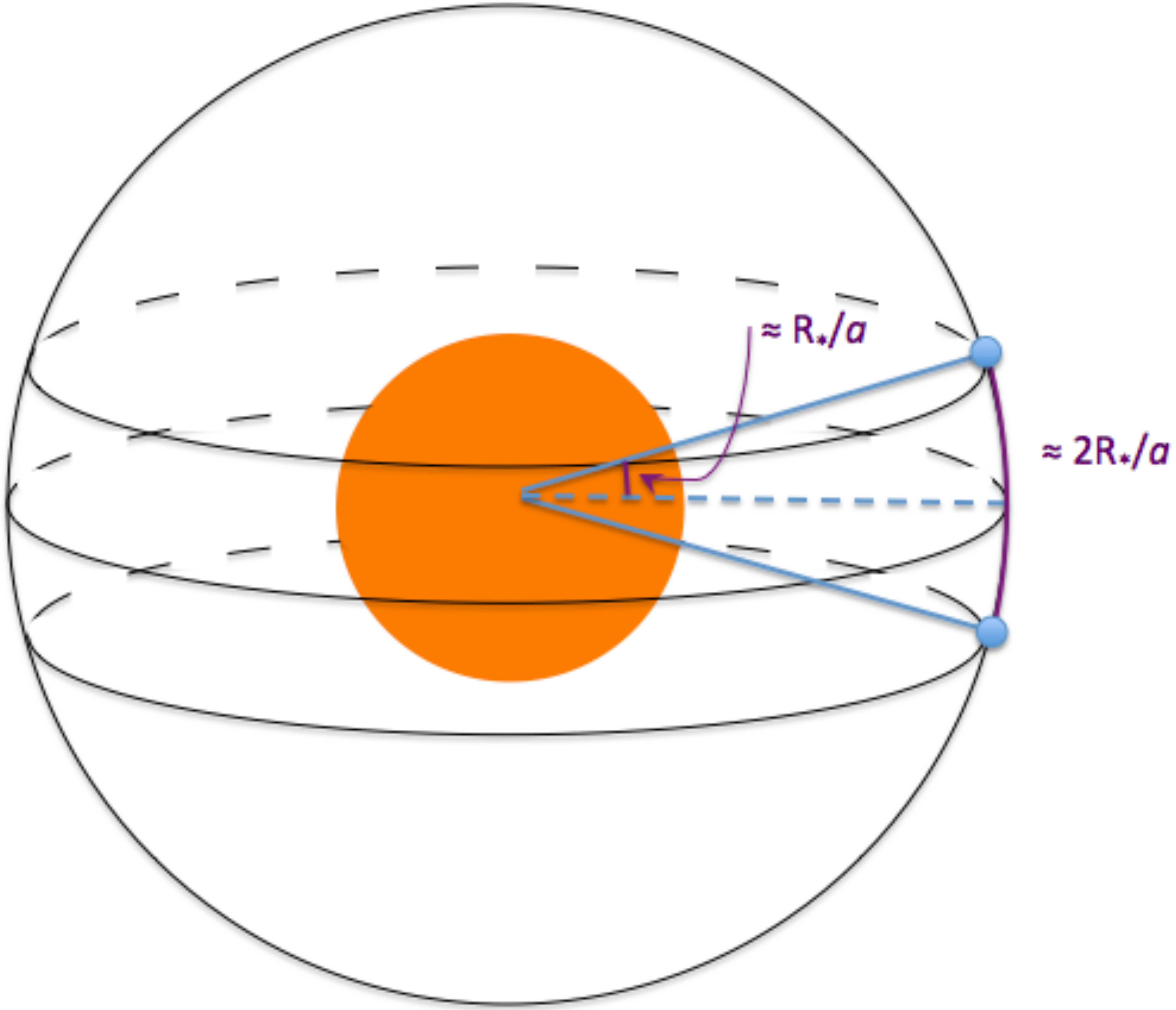
Winn et al. 2011



planethunters.org

Transits

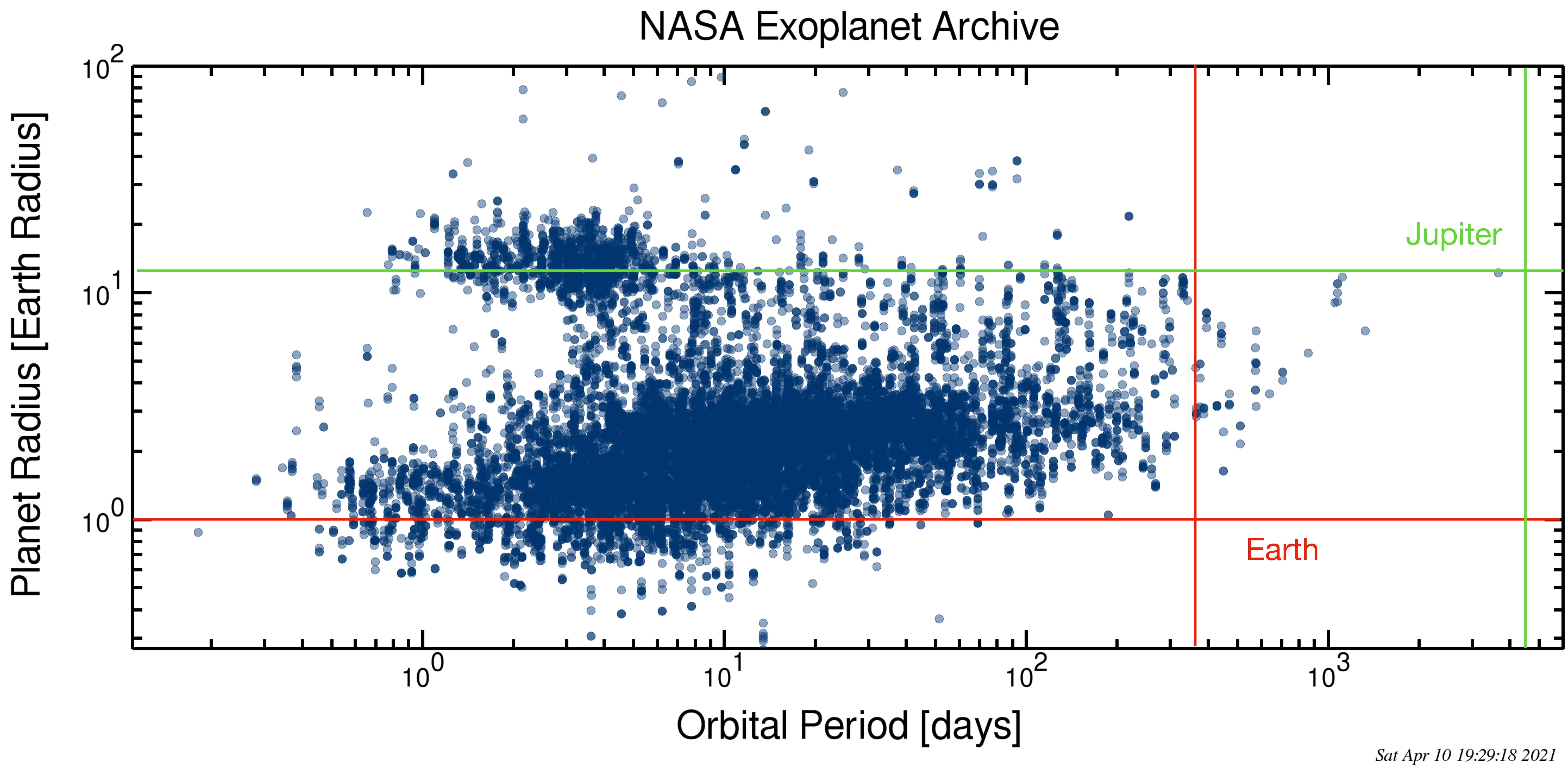
- A planet close to the star (smaller semi-major axis) is more likely to transit than a more distant planet (larger semi-major axis)
- A planet orbiting a Sun-like star will transit:
  - $85^\circ < i < 95^\circ$ at 0.05 AU (9% of all cases)
  - $89.5^\circ < i < 90.5^\circ$ at 0.5 AU (0.9% of all cases)
  - $89.95^\circ < i < 90.05^\circ$ at 5 AU (0.09% of all cases)



John Johnson

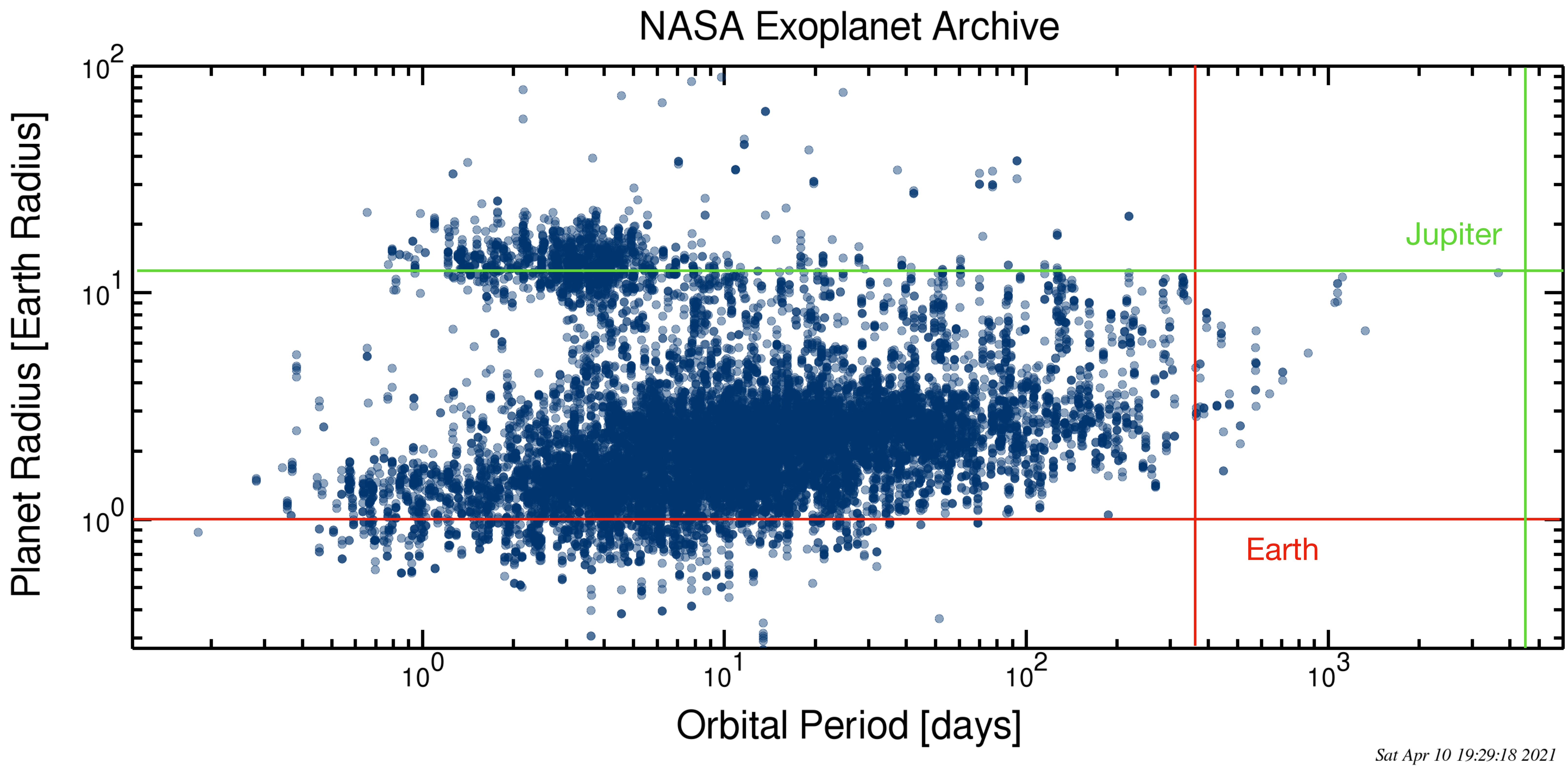
The Transit Method

- Can measure:
  - orbital period and inclination angle
  - planet size
  - spectra of atmosphere (for the best cases)



The Transit Method

- Biases:
  - Close-in planets are most likely to transit, and are easier to detect (more transits during your observing window)
  - Larger planets are much easier to detect (block out more light)
  - Planets are easier to detect around smaller stars
  - Non-transiting planets (inclination not near 90 degrees) can't be detected



For next time

- Reading: Planetary Science, 12.2.6-12.2.9
- Homework 5 due TONIGHT at 11:59pm
- Order of Magnitude project, written assignment due Monday, November 14 at start of class