STRANGE NEW WORLDS: EXOPLANETS

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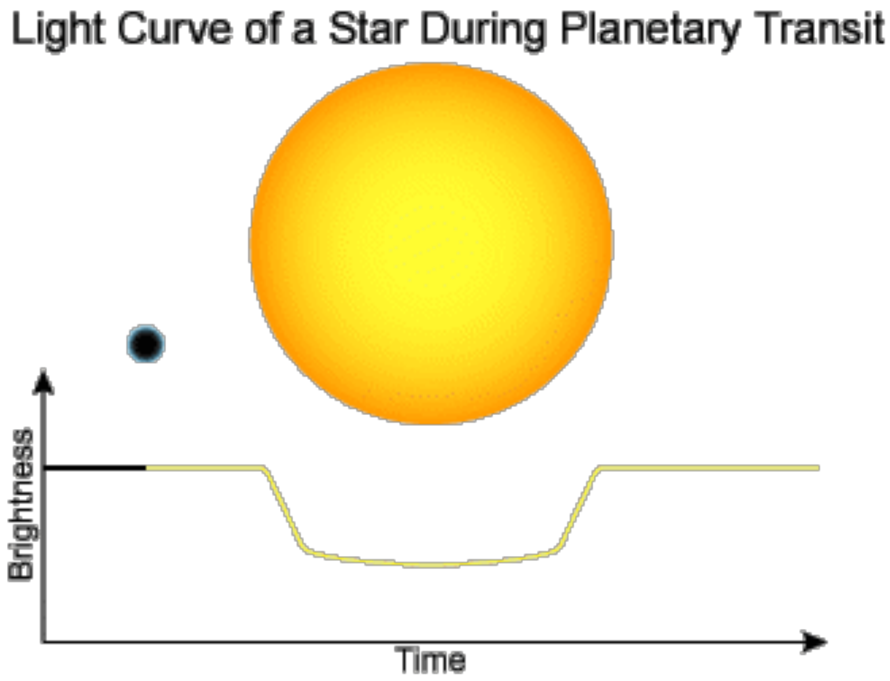
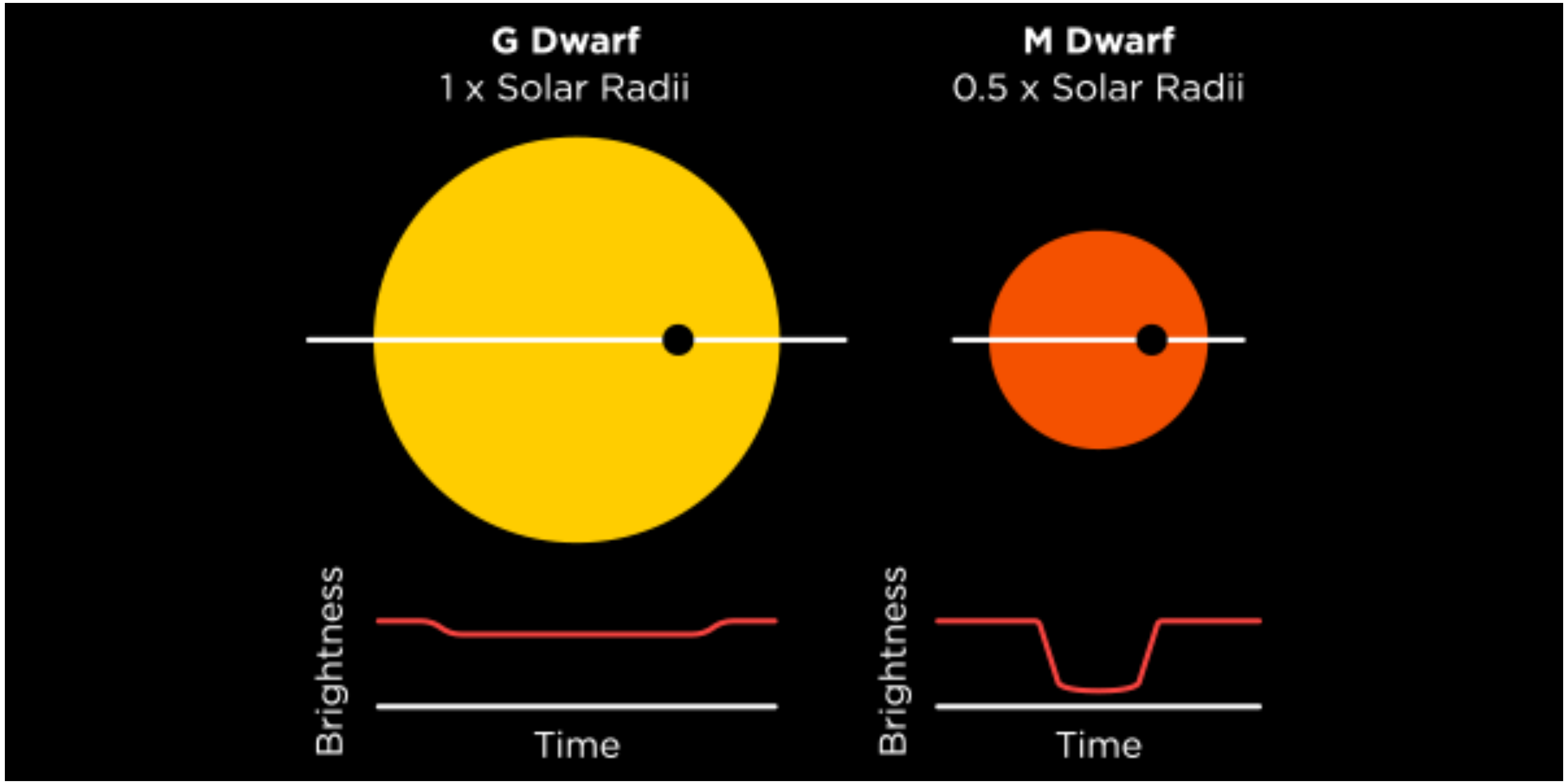
(WITH ACK to TIM HAMILTON)

Exoplanets	4,933	8,493	3,704
Last update: February 23, 2022	CONFIRMED	NASA CANDIDATES	PLANETARY SYSTEMS



When a planet crosses in front of or “transits” its host star, it blocks a tiny bit of its light. While we can’t see the shadow of the planet, we can see the starlight dim.

Transit Method



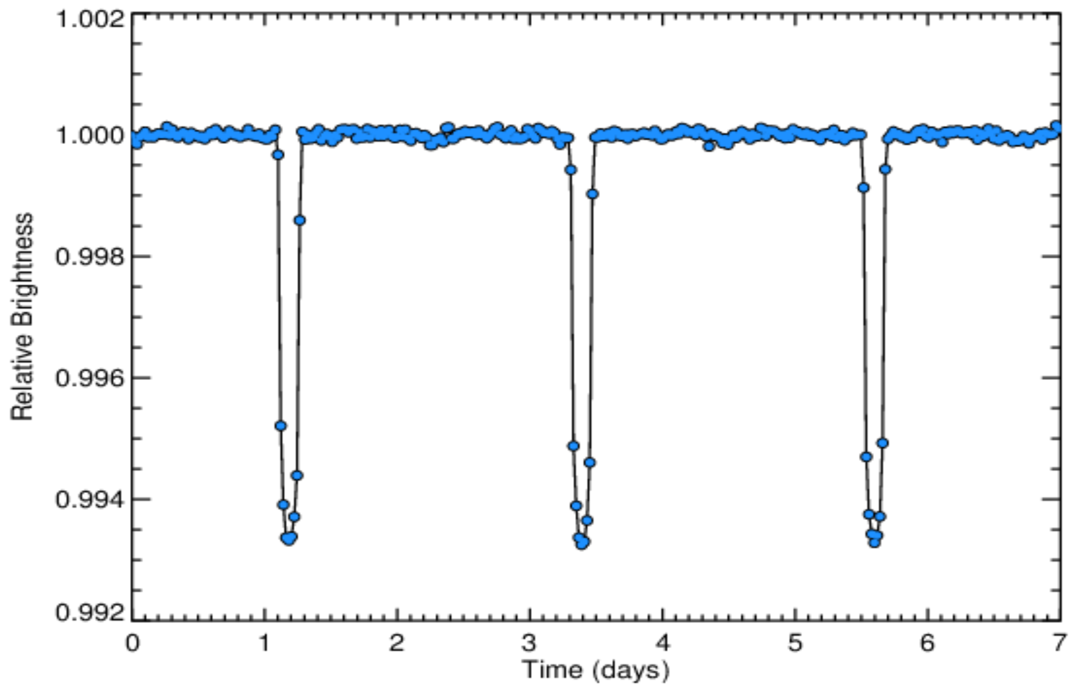
$$\text{Depth} = \left(\frac{R_p}{R_\star}\right)^2$$

$$R_p = R_\star\sqrt{\text{Depth}}$$

- For Sun & Earth:
- R ^2/R_planet^2
- =(7. 10^5)^2 / (6.4 *10^3)^2
- =10^4

Kepler light curve of an exoplanet called HAT-P-7 b

This planet is a hot Jupiter - one of the easiest types of planets to detect.



Notice:

1% dip

3 transits to confirm

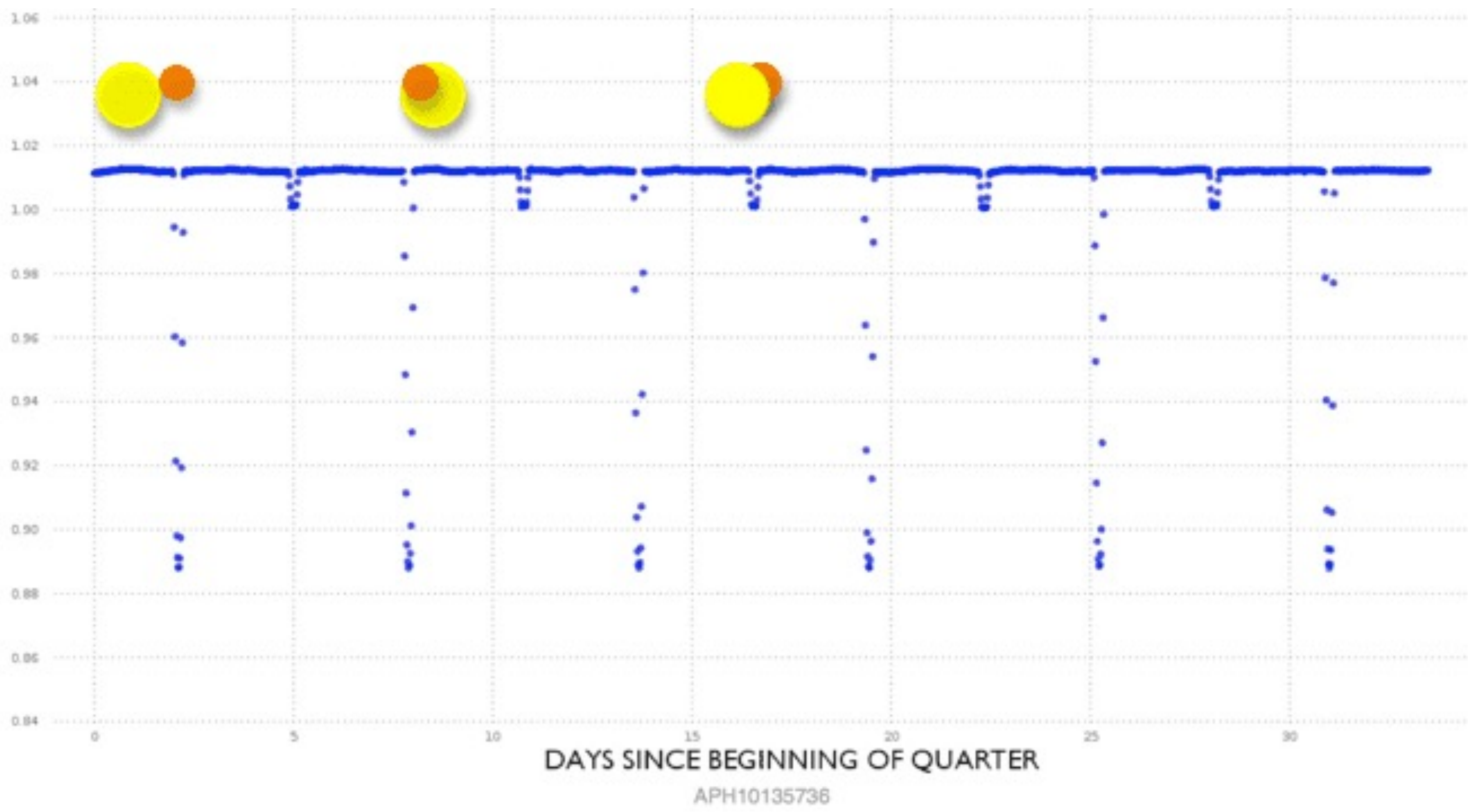
Size of planet

Number of planets

Orbital period

Inclination effect

In the case of binary stars….



Use Kepler data to find:

- a: orbital distance
- R: Radius of planet
- M: Mass of planet
- T: Temperature of planet
- Chem composition

https://archive.stsci.edu/prepds/kepler_hlsp/

Accessing Data:

Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

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Kepler HLSP

Below are README files describing version 1.0 HLSP data:

README_dtr.txt describing the files containing time series of detrended, normalized stellar fluxes of individual target stars as observed by NASA's Kepler Mission.

README_rvb.txt describing the files containing time series of radial velocity and spectral line bisector span for ground-based spectroscopic observations of individual target stars that have been observed by NASA's Kepler Mission.

Click on the target name to see more information and a quick-look plot. Click on the filenames to download txt files. You may also download via anonymous ftp from archive.stsci.edu. cd /pub/hlsp/kepler_hlsp/

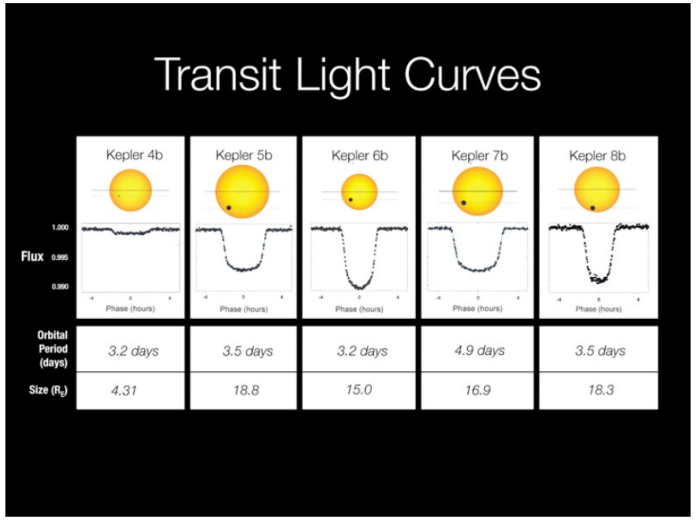


Illustration from Bill Borucki's Jan 2010 AAS Presentation

The First Five Targets

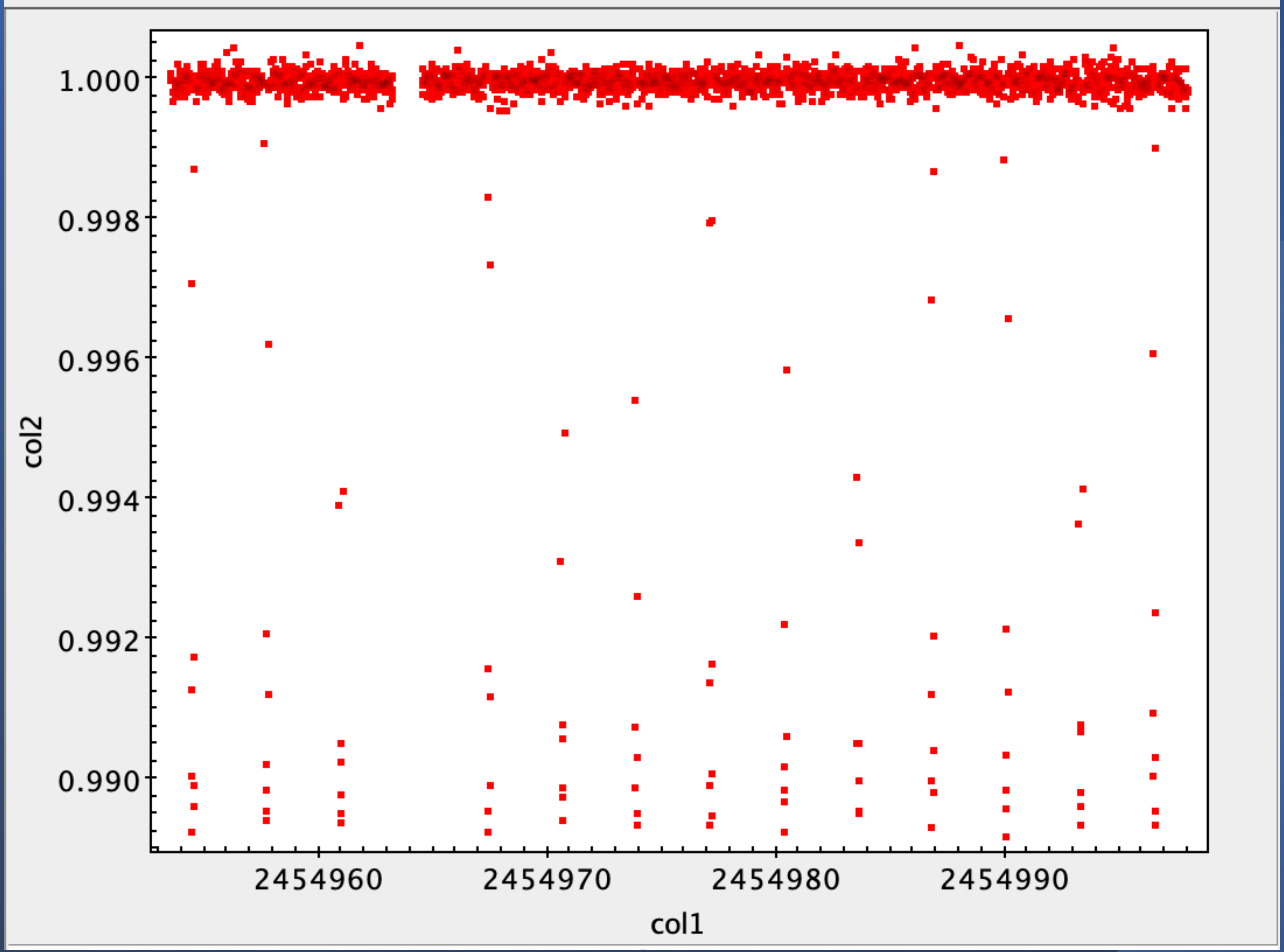
Target	Kepler Time Series	Ground Based Time Series
KPLR10874614 Kepler-6b	hlsp_exo_kepler_phot_KPLR10874614_kep_v1.0_dtr.txt	hlsp_exo_kepler_spec_KPLR10874614_wide_v1.0_rvb.txt
KPLR11853905 Kepler-4b	hlsp_exo_kepler_phot_KPLR11853905_kep_v1.0_dtr.txt	hlsp_exo_kepler_spec_KPLR11853905_wide_v1.0_rvb.txt
KPLR5780885		

Open in Topcat

- Julian Date
- Flux

	col1	col2
1	2.454954E6	1.00007
2	2.454954E6	0.99999
3	2.454954E6	0.99998
4	2.454954E6	0.99983
5	2.454954E6	0.99982
6	2.454954E6	0.99969
7	2.454954E6	0.99998
8	2.454954E6	0.99987
9	2.454954E6	0.99994
10	2.454954E6	0.99978
11	2.454954E6	0.99993
12	2.454954E6	0.99988
13	2.454954E6	1.00023
14	2.454954E6	0.99999
15	2.454954E6	0.99974
16	2.454954E6	0.99991

- The **Julian day number** (JDN) is the integer assigned to a whole solar day in the Julian day count starting from noon Universal Time, with Julian day number 0 assigned to the day starting at noon on Monday, January 1, 4713 BC, proleptic Julian calendar (November 24, 4714 BC, in the proleptic Gregorian calendar), a date at which three multi-year cycles started (which are: Indiction, Solar, and Lunar cycles) and which preceded any dates in recorded history.[a]
- For example, the Julian day number for the day starting at 12:00 UT (noon) on January 1, 2000, was 2 451 545.

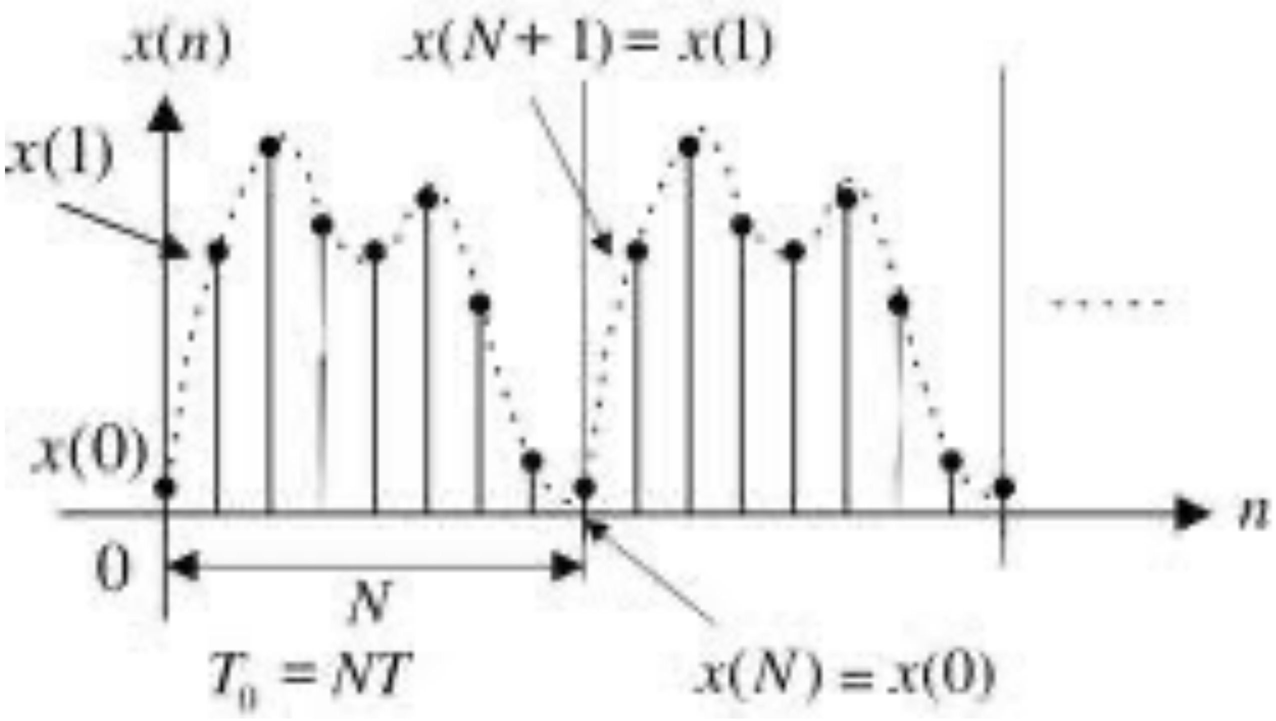


1.000
0.998
0.996
0.994
0.992
0.990
col2
2454960
2454970
2454980
2454990
col1

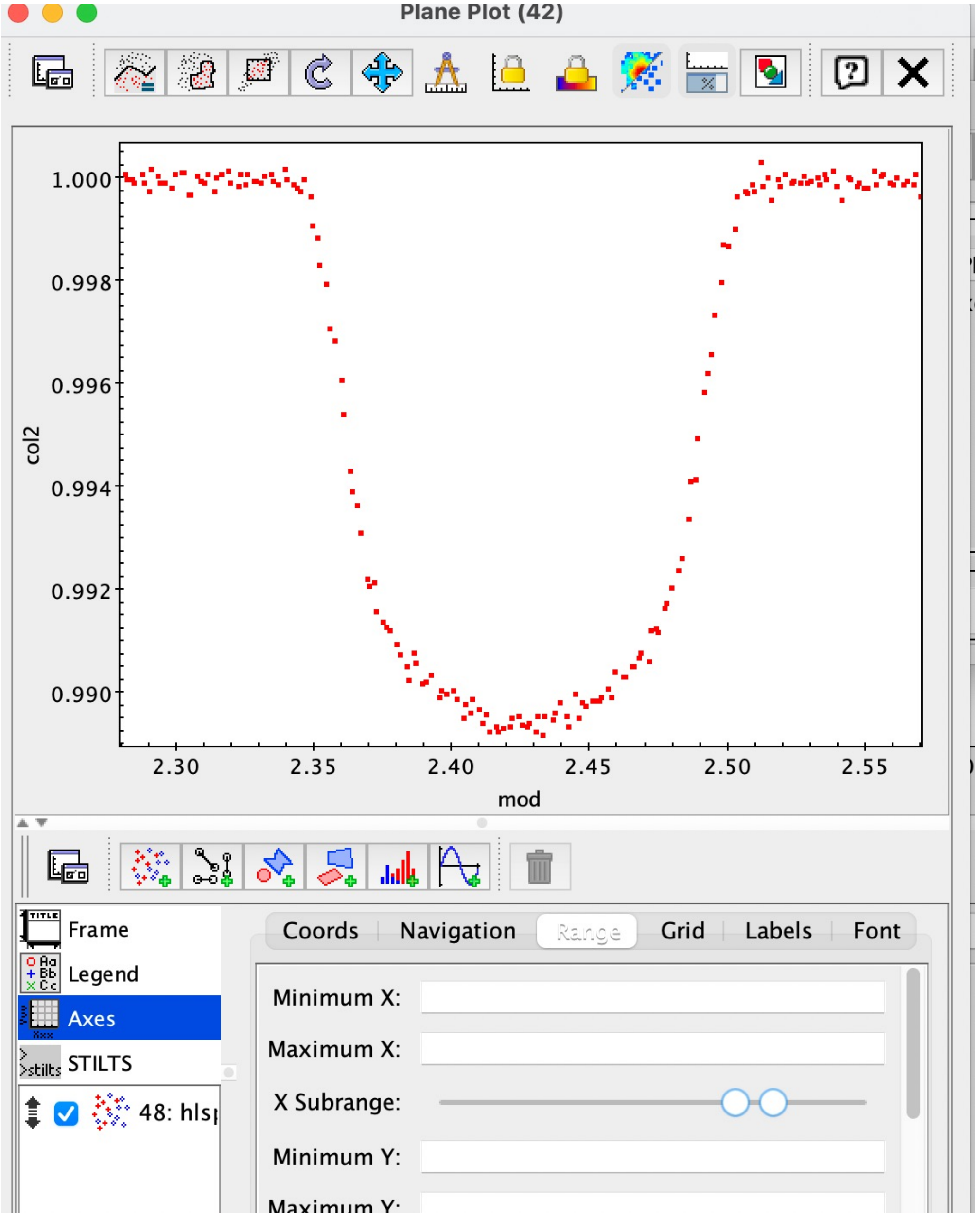
Folding functions mod(y,P)

C6 =MOD(A6,B6)

Number	Divisor	MOD Result
12	3	0
12	5	2
15	-3	0
-10	3	2
23	-5	-2



# Light curve (folded)
P=3.2346
mod(col1,3.2346)



Measuring the Distance from the Star to the Planet

Recall Kepler's Third Law,

$$P^2 \propto a^3,$$

where P is the planet's orbital period, and a is its semi-major axis (for a circular orbit, this will be the orbital radius).

$$\frac{a^3}{P^2} = \frac{G(\mathcal{M}_* + \mathcal{M}_\mathrm{p})}{4\pi^2},$$

where $\mathcal{M}_*$ is the mass of the host star, $\mathcal{M}_\mathrm{p}$ is the mass of the planet, and G is Newton's gravitational constant.

If $\mathcal{M}_\mathrm{p} << \mathcal{M}_*$ (the star is much more massive than the planet), then $\mathcal{M}_* + \mathcal{M}_\mathrm{p} \approx \mathcal{M}_*$, and

$$\frac{a^3}{P^2} = \frac{G\mathcal{M}_*}{4\pi^2}$$

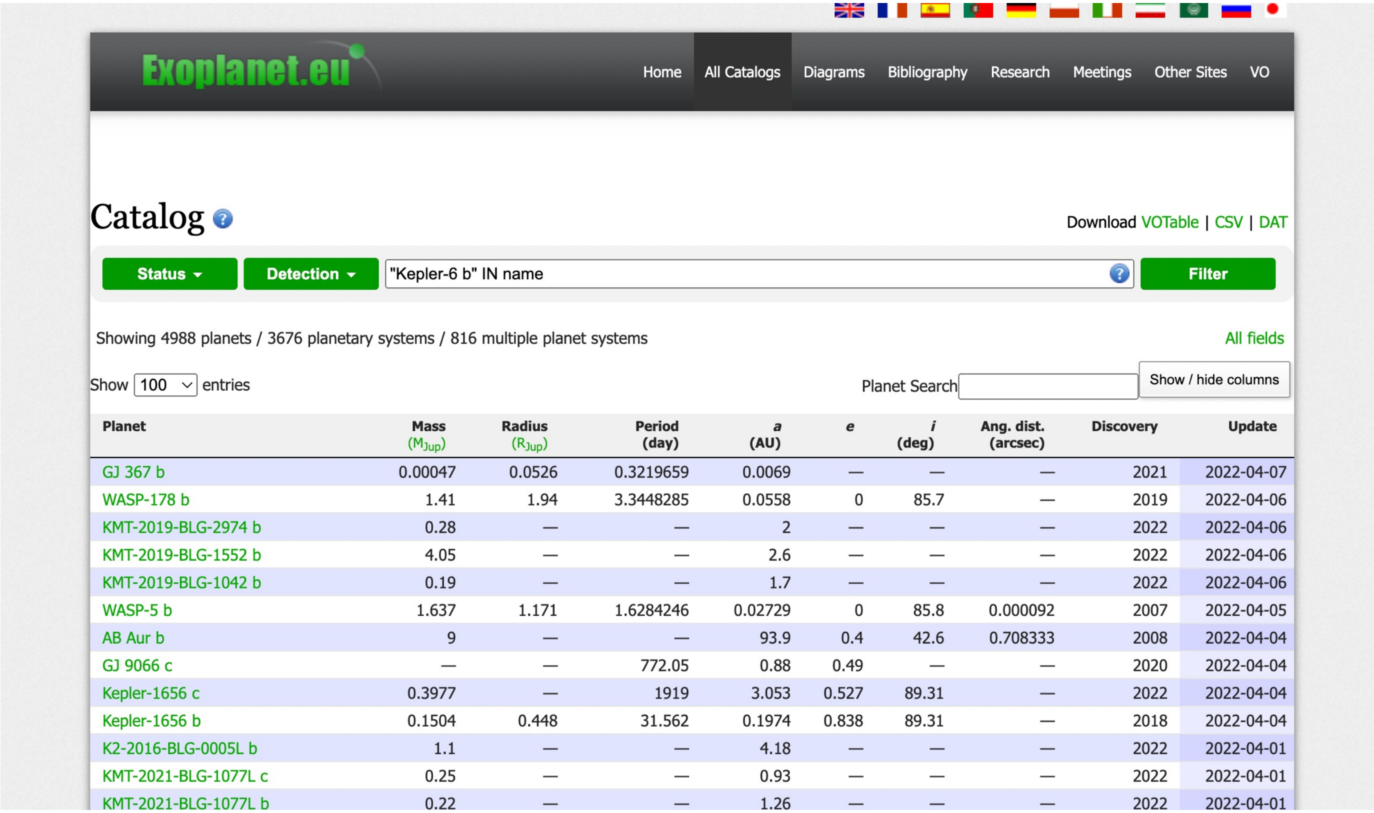
$$a^3 = G\mathcal{M}_* \frac{P^2}{4\pi^2}$$

$$a^3 = G\mathcal{M}_* \left(\frac{P}{2\pi}\right)^2$$

$$\boxed{a = \left[G\mathcal{M}_* \left(\frac{P}{2\pi}\right)^2\right]^{\frac{1}{3}}}$$

For M*: The Extrasolar Planets Encyclopaedia

http://exoplanet.eu/



Planet	Mass (M_{Jup})	Radius (R_{Jup})	Period (day)	*a* (AU)	*e*	*i* (deg)	Ang. dist. (arcsec)	Discovery	Update
GJ 367 b	0.00047	0.0526	0.3219659	0.0069	—	—	—	2021	2022-04-07
WASP-178 b	1.41	1.94	3.3448285	0.0558	0	85.7	—	2019	2022-04-06
KMT-2019-BLG-2974 b	0.28	—	—	2	—	—	—	2022	2022-04-06
KMT-2019-BLG-1552 b	4.05	—	—	2.6	—	—	—	2022	2022-04-06
KMT-2019-BLG-1042 b	0.19	—	—	1.7	—	—	—	2022	2022-04-06
WASP-5 b	1.637	1.171	1.6284246	0.02729	0	85.8	0.000092	2007	2022-04-05
AB Aur b	9	—	—	93.9	0.4	42.6	0.708333	2008	2022-04-04
GJ 9066 c	—	—	772.05	0.88	0.49	—	—	2020	2022-04-04
Kepler-1656 c	0.3977	—	1919	3.053	0.527	89.31	—	2022	2022-04-04
Kepler-1656 b	0.1504	0.448	31.562	0.1974	0.838	89.31	—	2018	2022-04-04
K2-2016-BLG-0005L b	1.1	—	—	4.18	—	—	—	2022	2022-04-01
KMT-2021-BLG-1077L c	0.25	—	—	0.93	—	—	—	2022	2022-04-01
KMT-2021-BLG-1077L b	0.22	—	—	1.26	—	—	—	2022	2022-04-01

Star data

Star

Kepler-6

Name	**Kepler-6**
Distance	**597.14 ($_{-5.16}^{+5.16}$) pc**
Spectral type	—
Apparent magnitude V	—
Mass	**1.21 ($_{-0.04}^{+0.04}$) M_{Sun}**
Age	**3.8 (± 1.0) Gyr**
Effective temperature	**5647.0 (± 44.0) K**
Radius	**1.39 ($_{-0.03}^{+0.02}$) R_{Sun}**
Metallicity [Fe/H]	**0.34 (± 0.04)**

Measuring the Size of the Planet

- R_p=factor * R_*

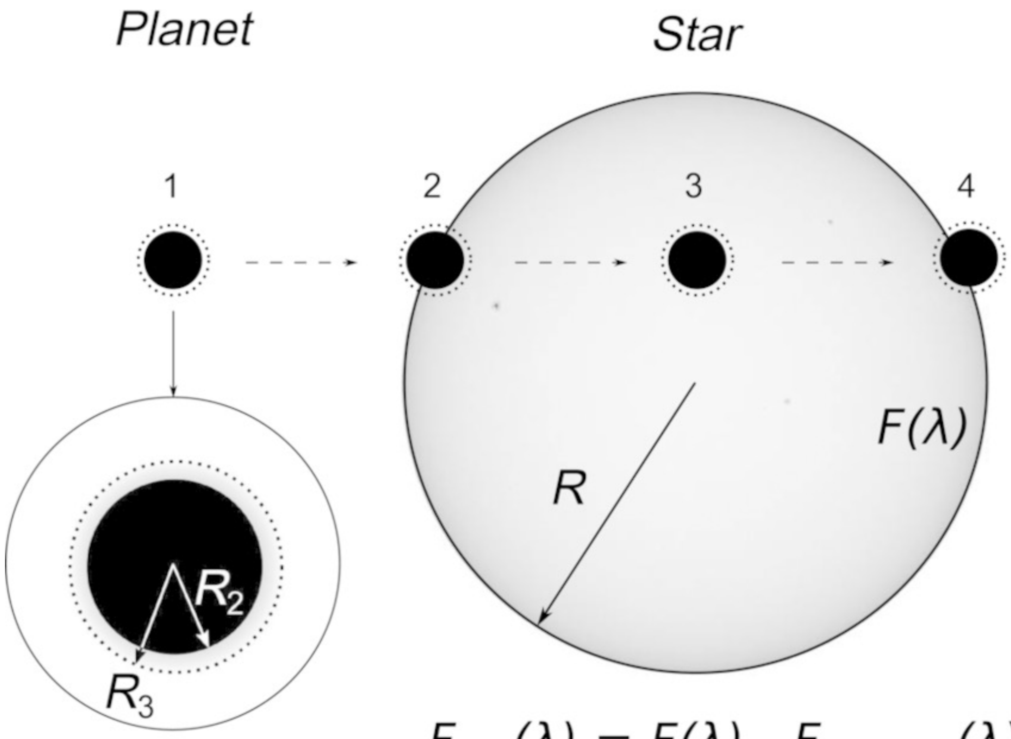
$$\frac{F_{\mathrm{tot}} - F_{\mathrm{trans}}}{F_{\mathrm{tot}}} = \frac{A_{\mathrm{p}}}{A_*}.$$

Since both the star and the planet are circular, we can write their area in terms of radius, $A = \pi r^2$. Substituting this in and simplifying the left hand side,

$$1 - \frac{F_{\mathrm{trans}}}{F_{\mathrm{tot}}} = \frac{\pi R_{\mathrm{p}}^2}{\pi R_*^2}$$

$$\boxed{R_{\mathrm{p}} = R_* \sqrt{1 - \frac{F_{\mathrm{trans}}}{F_{\mathrm{tot}}}}}$$

Calculating the Temperature of the Planet



$F_{obs}(\lambda) = F(\lambda) - F_{occulted}(\lambda)$

$$L_{\rm em} = \sigma T_{\rm p}^4 \; 4\pi R_{\rm p}^2. \qquad L_{\rm abs} = (1-\alpha)\sigma T_*^4 \frac{R_*^2}{a^2}\,\pi R_{\rm p}^2$$

$L_{\rm abs} = (\text{absorption coefficient}) \times F_{\rm inc} A_{\rm cross}$

$$L_{\rm em} = L_{\rm abs}$$

$$\sigma T_{\rm p}^4 \; 4\pi R_{\rm p}^2 = (1-\alpha)\,\sigma T_*^4 \,\frac{R_*^2}{a^2}\pi R_{\rm p}^2$$

The σ and $\pi R_{\rm p}^2$ cancel out on both sides.

$$T_{\rm p}^4 = \frac{1}{4}(1-\alpha) T_*^4 \,\frac{R_*^2}{a^2}$$

Solving for $T_{\rm p}$,

$$\boxed{T_{\rm p} = T_* \left[(1-\alpha)\,\frac{R_*^2}{a^2}\right]^{\frac{1}{4}}},$$

Getting the Planet’s Mass and density From Radial Velocity

$$\mathcal{M}_p = \frac{v_{*,\,\mathrm{max}}}{\sin i}\sqrt{\frac{a\,\mathcal{M}_*}{G}}$$

$$P^2 = \frac{4\pi^2}{GM_*}a^3$$

from P, we get a and (knowing M_*) V_p:

$$V_p = \sqrt{\frac{GM_*}{a}}$$

then, conservation of momentum:

$$M_pV_p = M_*V_*$$

we can get M_p

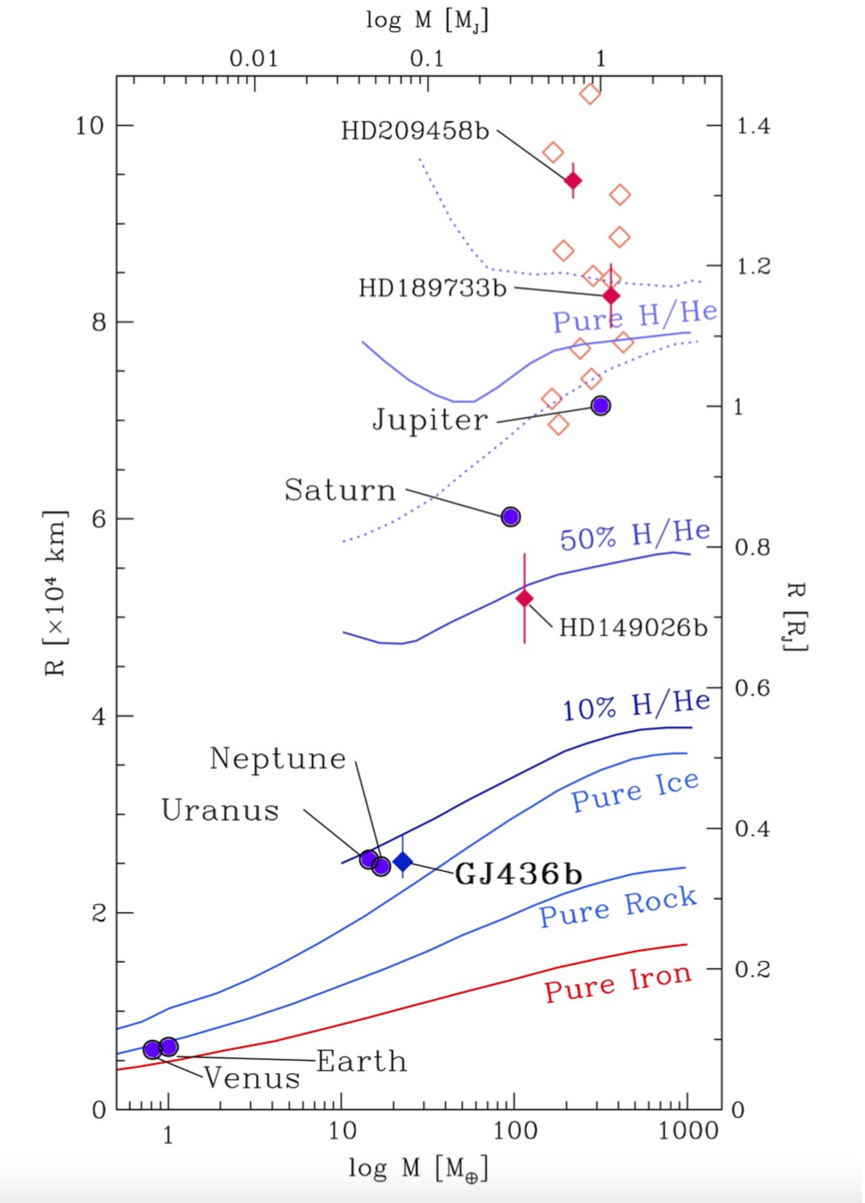
$$M_p = M_*\left(\frac{V_*}{V_p}\right)$$

but we really get $M_p\sin(i)$

Density

$$\rho_p = \frac{\mathcal{M}_p}{(4/3)\,\pi\, r_p^3}.$$

Planet composition
Gillon 2007



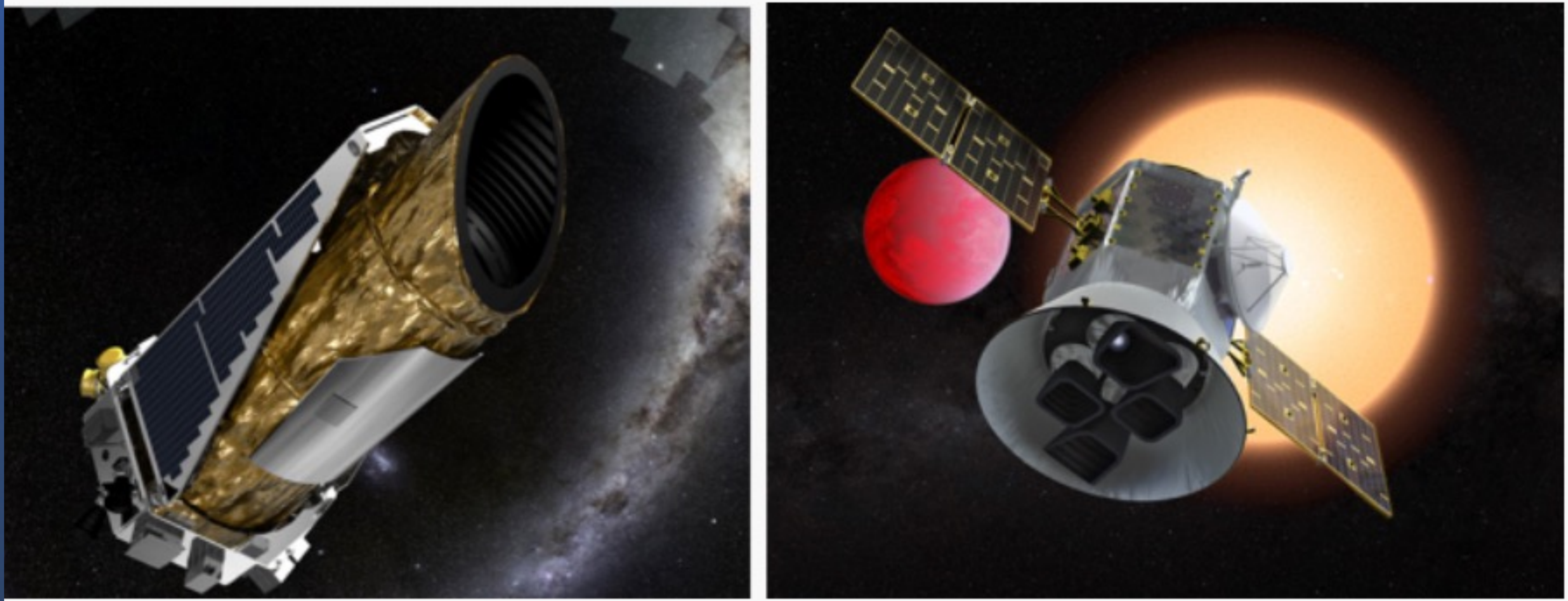
Hot Jupiter!!!

Assignment

Common Name	Kepler Catalog #
Kepler-4 b	KPLR11853905
Kepler-5 b	KPLR8191672
Kepler-6 b	KPLR10874614
Kepler-7 b	KPLR5780885
Kepler-8 b	KPLR6922244

Level 1: Repeat procedure for any of the above targets

Level 2: Analysis with Jupyter notebook



st impression of NASA’s planet-hunting Kepler spacecraft (left) and TESS satellite (right). *Image credit: NASA Ames/JPL-Caltech/T Pyle*

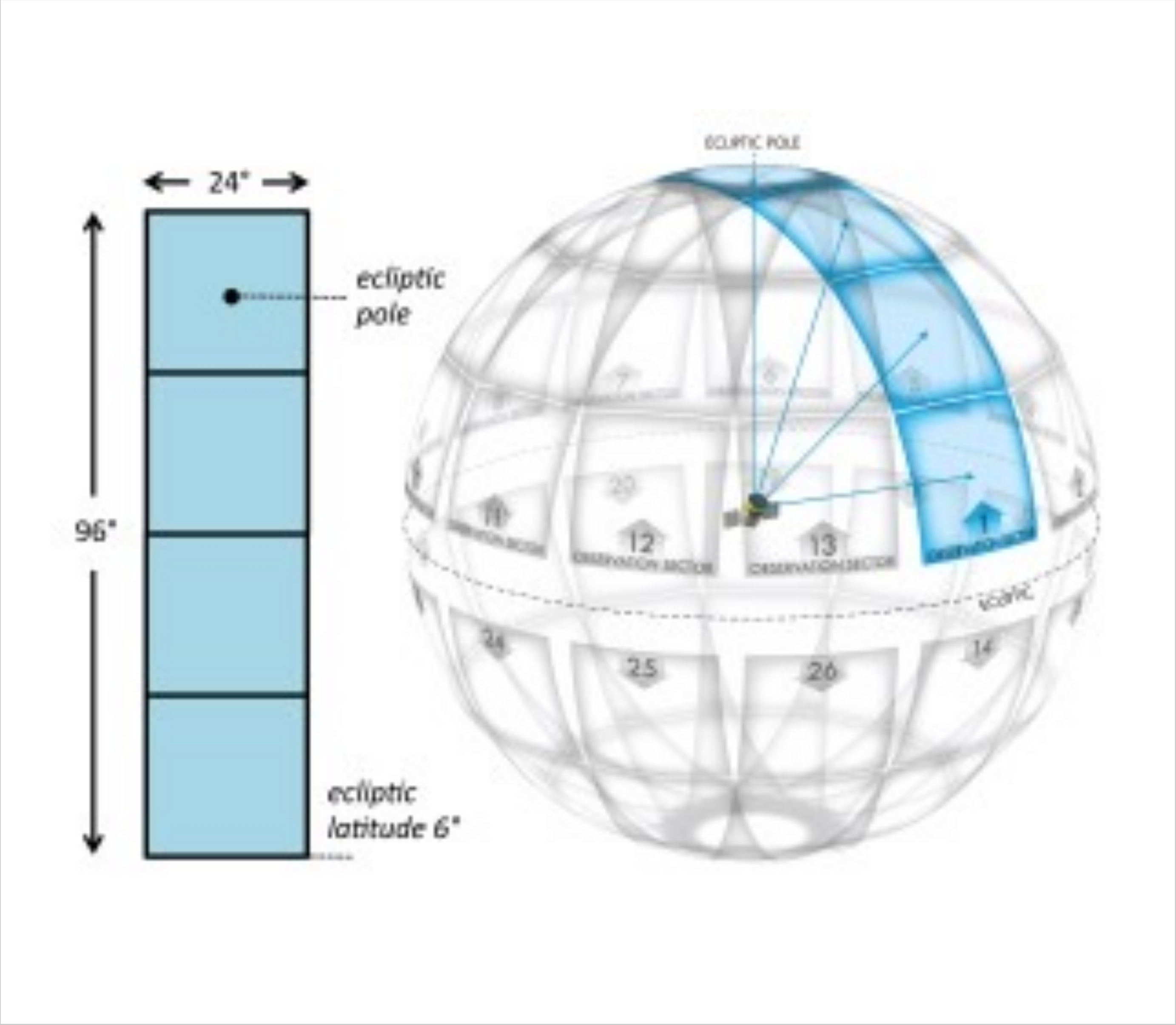
Kepler /K2Kepler/K2
Launched in March 2009, 1.4-m primary mirror, observed a 12×12 degree patch of sky Kepler could find exoplanets as small as half the size of the Earth

TESS

TESS will survey the entire sky, looking at 400 times more stars than Kepler did throughout its lifetime. TESS will do this with four identical telescopes, which, combined, observe a 24-degree patch of sky at any one point. Each 27 days, TESS changes direction and looks for planets around a different set of stars in a new ‘sector’. The entire sky has been split into 26 overlapping sectors, and TESS will visit each one over the course of the next 2 years.

Kepler Vs TESS

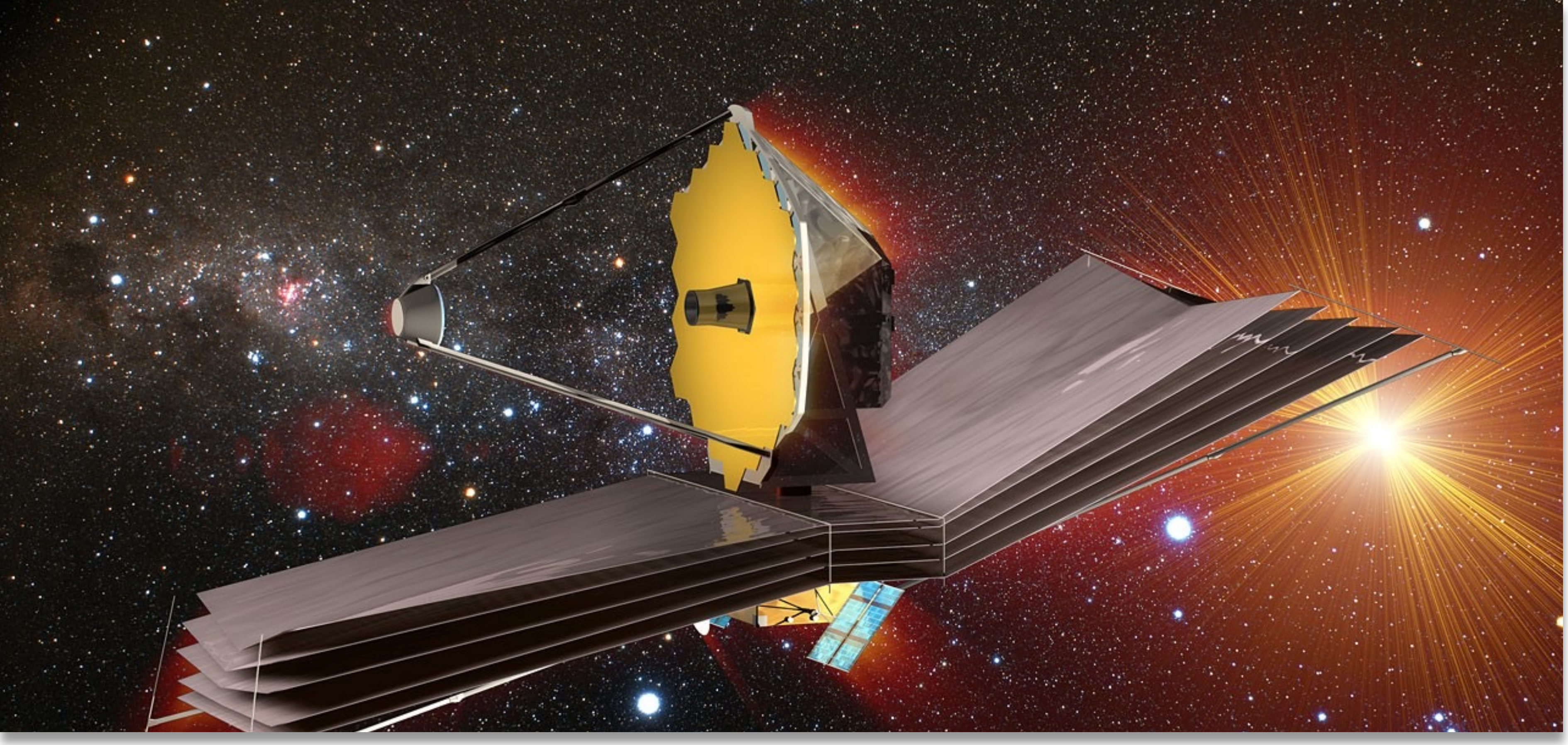
- The two satellites also differ in their observing strategy and the types of stars that they focus on. Whilst Kepler observed one patch of sky for a long period of time, TESS will only spend a month looking at each sector. The long exposure times of Kepler allowed it to find the dimmer and more distant stars, whereas TESS will monitor the nearby, and brightest targets. Stars observed by TESS are 10 times closer and 100 times brighter than the Kepler target stars! Observing brighter and closer stars has the advantage that any planet candidates that we find will be easier to observe using ground based telescopes.



Future Plans

- Exploring Exoplanet samples
- Identifying target objects for ground-based observatories
- JWST, E-ELT, GMT

IAU Name ExoWorlds 2022



WHAT IS JWST?

The James Webb Space Telescope is an infrared space telescope

Carina Nebula

This image is of the edge of a nearby stellar nursery called NGC 3324 at the northwest corner of the nebula. Young stars are born in such environments. The ultraviolet radiation from young stars is shown in blue. Huge pillars rise above the glowing wall of gas, resisting this radiation. The "steam" that seems to rise from the "mountains" is actually hot, ionized gas and hot dust streaming away from the nebula due to the relentless radiation.

Carina Nebula: NGC 3372 (2600 pc)

NASA’s James Webb Space Telescope reveals emerging stellar nurseries and individual stars in the Carina Nebula that were previously obscured

Images of “Cosmic Cliffs” showcase Webb’s cameras’ capabilities to peer through cosmic dust, shedding new light on how stars form

Objects in the earliest, rapid phases of star formation are difficult to capture, but Webb’s extreme sensitivity, spatial resolution, and imaging capability can chronicle these elusive events

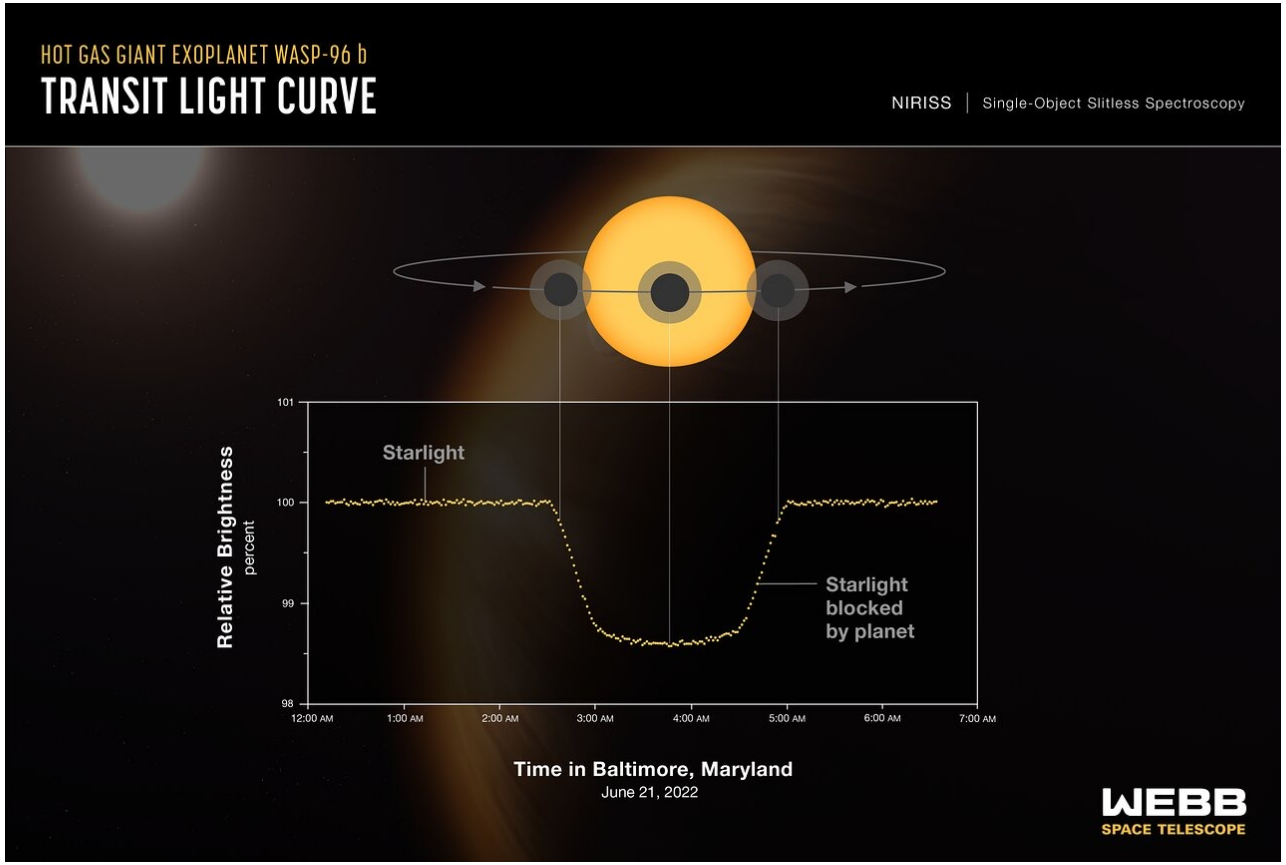
Open Questions

- Protostellar jets, t from some of these young stars.
- The youngest sources in the earliest, rapid phases of star formation are difficult to observe
- Process of star formation. Star birth propagates over time, triggered by the expansion of the eroding cavity. As the bright, ionized rim moves into the nebula, it slowly pushes into the gas and dust. If the rim encounters any unstable material, the increased pressure will trigger the material to collapse and form new stars.
- What determines the number of stars that form in a certain region? Why do stars form with a certain mass?

Exoplanet WASP-96 b (NIRISS Transit Light Curve) Near-Infrared Imager and Slitless Spectrograph

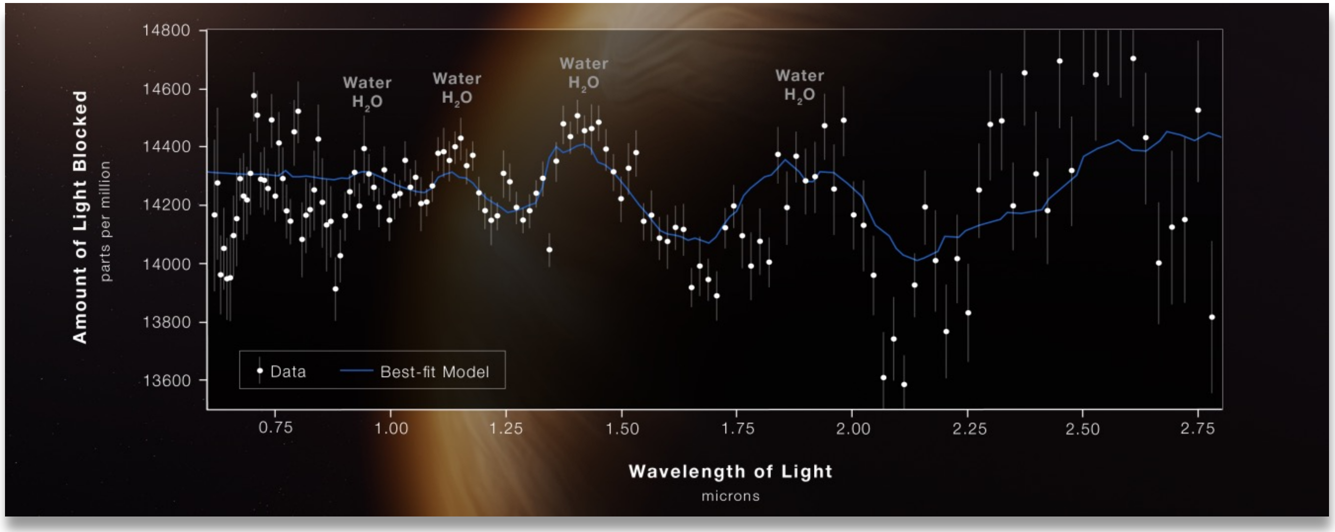
WASP-96 b is a hot gas giant exoplanet of a Sun-like star roughly 1,150 light years away, in the constellation Phoenix. It is extremely close to its star (less than 1/20th the distance between Earth and the Sun) and completes one orbit in less than 3½ Earth-days. The planet's discovery, from ground-based observations, was announced in 2014.

Webb observed WASP-96 star system for 6 hours 23 minutes: 2½ hours before the transit and ending about 1½ hours after the transit was complete. The transit itself lasted for just under 2½ hours. The curve includes a total of 280 individual brightness measurements – one every 1.4 minutes. (1.5 % dimming)



The last image is actually a graph.

- The JWST telescope has detected the distinct signature of water, along with evidence for clouds and haze, in the atmosphere surrounding a hot, puffy gas giant planet **WASP 96b** orbiting a distant Sun-like star.



https://www.nameexoworlds.iau.org/2022exoworlds


Around PSR 1257+12 are the first three exoplanets found orbiting a neutron star.
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