Exoplanets*:
What We Know Now, What We Will Learn Before Your Grandchildren are Born, and Why We Should Care

**Exoplanet:* A planet in orbit around another star (not the Sun) or a planet not orbiting any star*

1

All the known planets in the entire universe when I was 18*:
My Very Earthly Mother Just Served Us Nine Pizzas

* in the 1970s

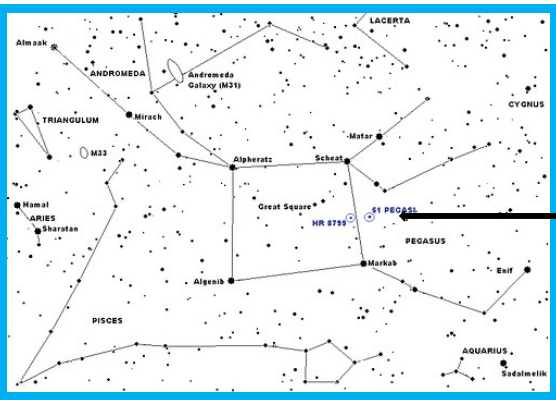
2

A revolution begins in 1995 …

NATURE · VOL 378 · 23 NOVEMBER 1995

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz



51 Pegasus

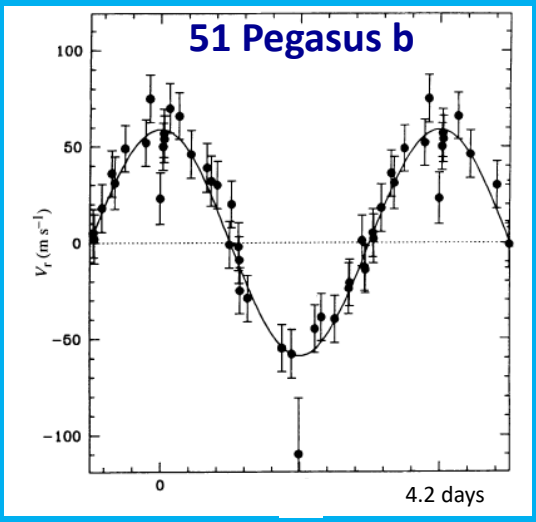
Distance from Sun = 50.9 light years
Mass = 1.06 solar masses (just 6% greater than the Sun)
Temperature 5,600 K (barely 4% less than the Sun)

3

The first exoplanet discovered around a normal sunlike star
--- using the 'radial velocity' method ---

Velocity of the star

Reveals the presence of a planet



Time →

4

Thirty Years Later … Sept 4, 2025: 6,070 known exoplanets*

* https://exoplanet.eu/catalog/
https://science.nasa.gov/exoplanets/
https://exoplanetarchive.ipac.caltech.edu/index.html

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Multiple Methods for Exoplanet Discoveries

1. **Radial Velocity method**: measure to/from motion of the star (caused by gravitational tugging of exoplanet)
2. **Transit method**: watch for the brightness of the star to dip during an eclipse (exoplanet passes in front of star)

Most Common

3. **Direct Imaging method**: take a picture (need to block the light of the star!)
4. **Astrometry method**: measure changing position of a star (as it orbits center-of-mass of star-planet system)
5. **Gravitational lensing method**: sudden increase of brightness of the star

6

The Pace of New Discoveries*

Week of	
June 12:	4 new exoplanet discoveries announced
June 26:	5 new exoplanet discoveries announced;
	8 new atmospheric spectra measured;
July 17:	7 new exoplanet discoveries announced;
	27 more exoplanet atmospheric spectra measured;
	(total as of now: more than 1,000)
July 29:	35 new exoplanet discoveries announced;
August 7:	5 new exoplanet discoveries announced;
August 14:	11 new exoplanet discoveries announced;
August 28:	6 new exoplanet discoveries announced;

* https://exoplanetarchive.ipac.caltech.edu/docs/exonews_archive.html

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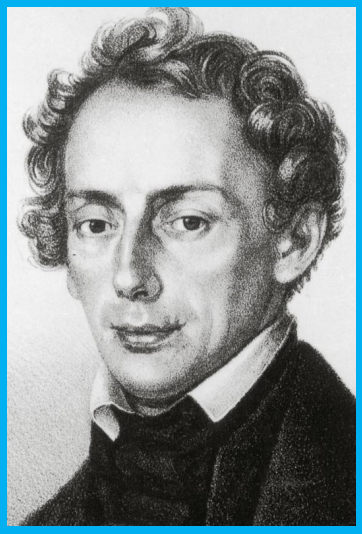
The Doppler Shift



Christian Doppler (1803 – 1853)
Austrian mathematician and physicist

Louis Fizeau (1819 – 1896)
French physicist

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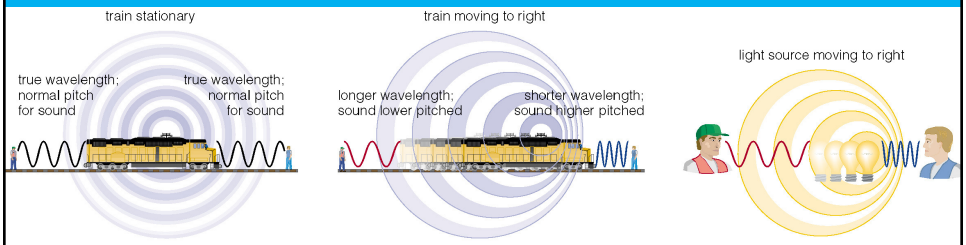
How does light tell us the speed of a moving object?



- **1842: Doppler predicted that frequency (or wavelength) of a sound wave would be affected by motion of source of the sound toward or away from the observer of the sound**

- **1848: Fizeau made a similar prediction for light --- wavelengths (or colors) at which starlight arrives in our telescopes will be affected by the motion of the star toward or away from the Earth.**

9

Doppler Shift

The wavelength (of light or sound) you observe depends on the relative motion of you and the wave source[1].

If you and the source are moving *toward* each other, the light is blueshifted[2].

If you and the source are moving *away* from each other, the light is redshifted[3].

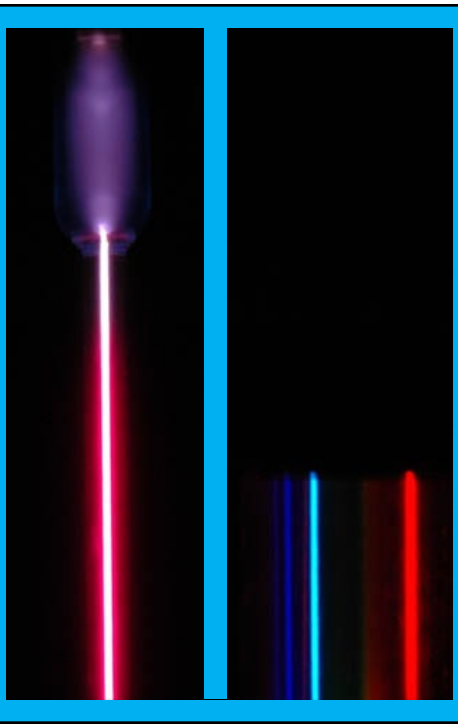
[1] Doesn't matter which object is moving and which is still or if both are moving
[2] Toward the blue from the middle (yellow) of the visible spectrum
[3] Toward the red, from the middle (yellow) of the visible spectrum

10

Left: a hydrogen spectral tube excited by a 5000 volt transformer.

It appears to emit a purplish light.

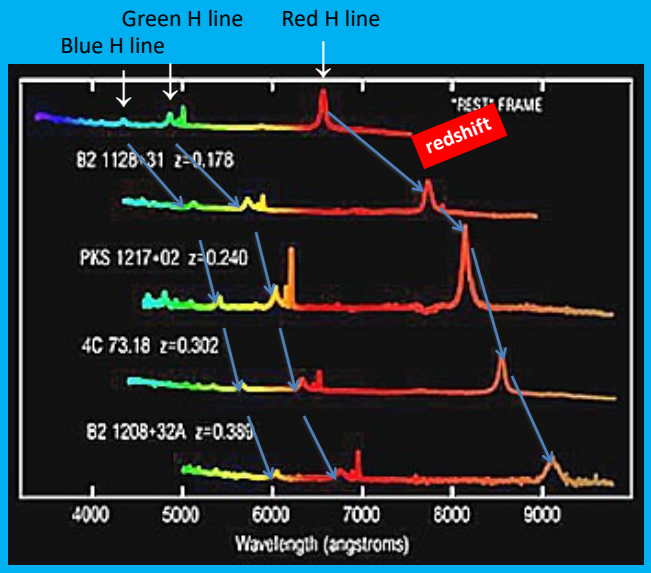
But that color is actually the combined effect of blue, green and red colors.



Right: After the light from the spectral tube passes through a diffraction grating (acts like a prism), we see that the purplish glow breaks up into three prominent hydrogen emission lines (blue, green, red).

Because hydrogen is the most abundant element in the universe, astronomers often observe these three hydrogen spectral lines when observing astrophysical sources

11



"rest" frame (in the lab, not moving)

Moving away from us

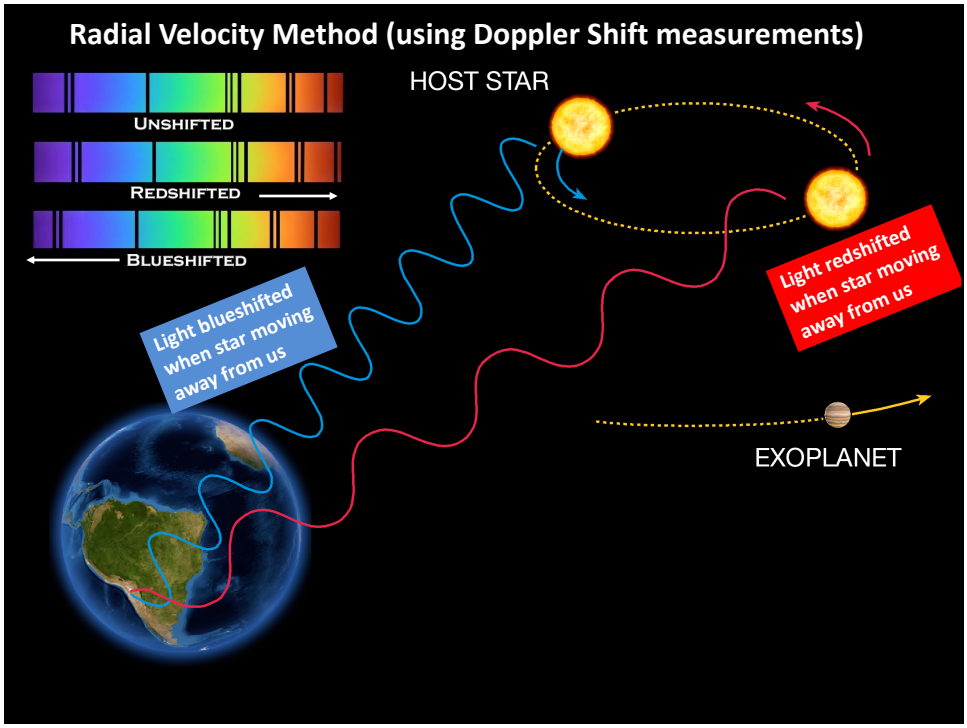
Moving away faster

Moving away even faster

Moving away the fastest

A spectrogram recorded by a Kitt Peak National Observatory telescope in which the top spectrum (obtained at rest in the laboratory) has peaks for three hydrogen lines in the blue, green, and red. The next four are spectra from distant quasars moving away from the Sun at progressively higher velocities (all are "redshifted")

12


Radial Velocity Method (using Doppler Shift measurements)
HOST STAR
UNSHIFTED
REDSHIFTED
BLUESHIFTED
Light blueshifted when star moving away from us
Light redshifted when star moving away from us
EXOPLANET

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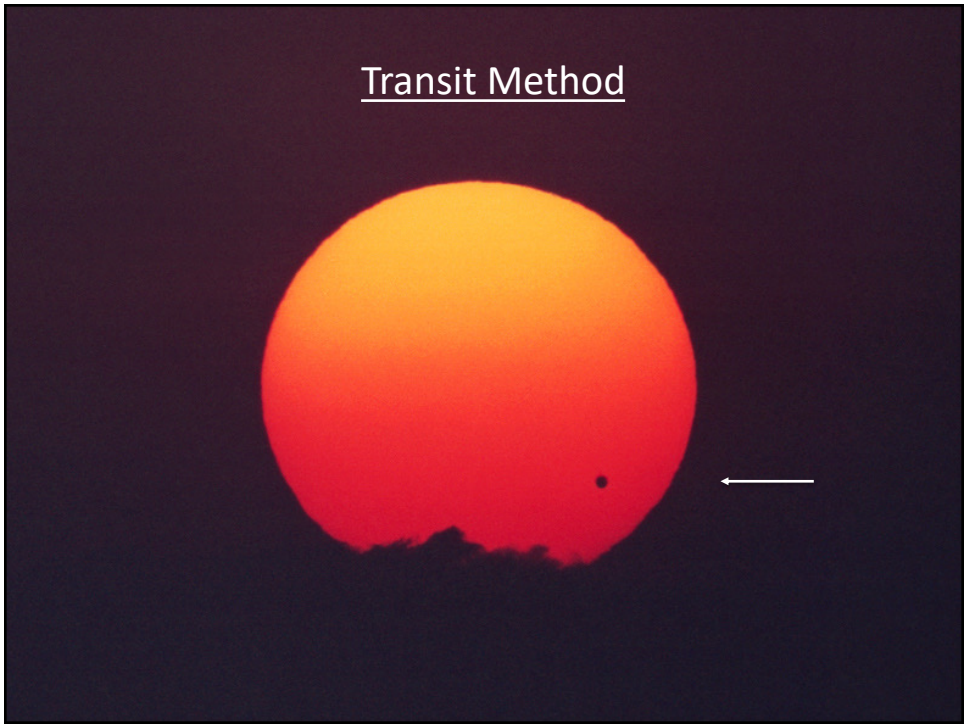
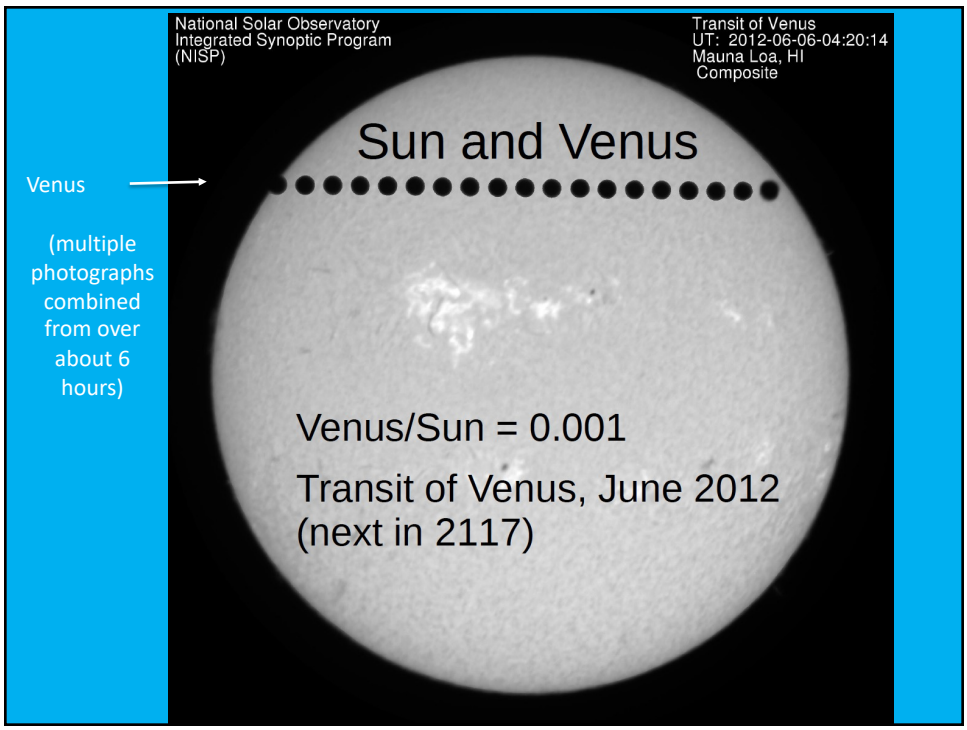
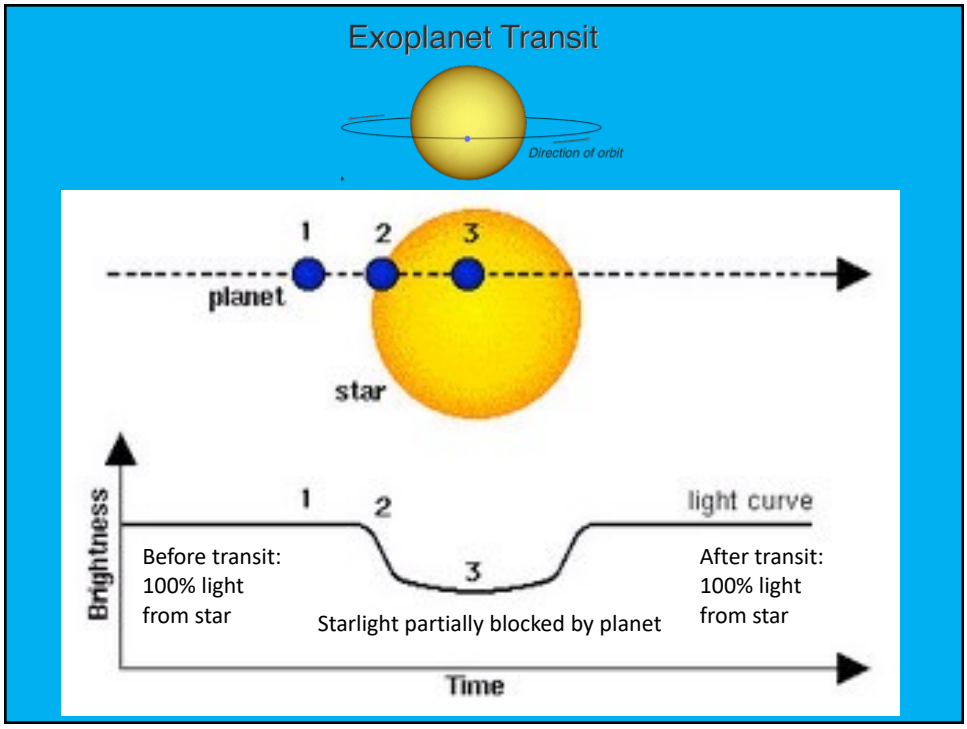

Transit Method

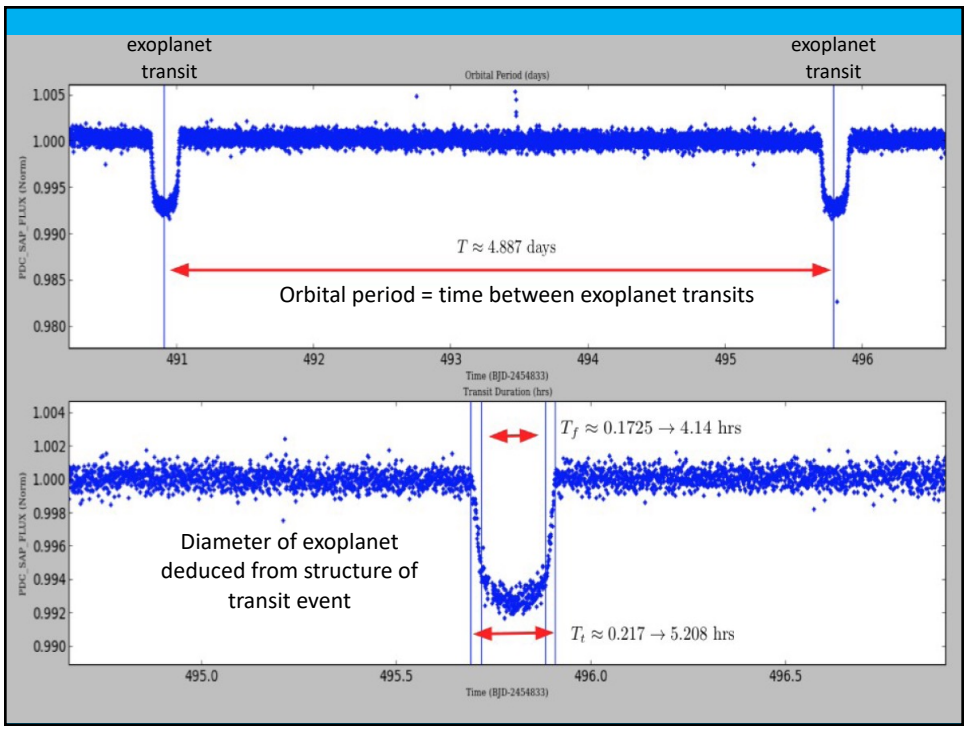
14


National Solar Observatory
Integrated Synoptic Program
(NISP)
Transit of Venus
UT: 2012-06-06-04:20:14
Mauna Loa, HI
Composite
Sun and Venus
Venus
(multiple photographs combined from over about 6 hours)
Venus/Sun = 0.001
Transit of Venus, June 2012
(next in 2117)

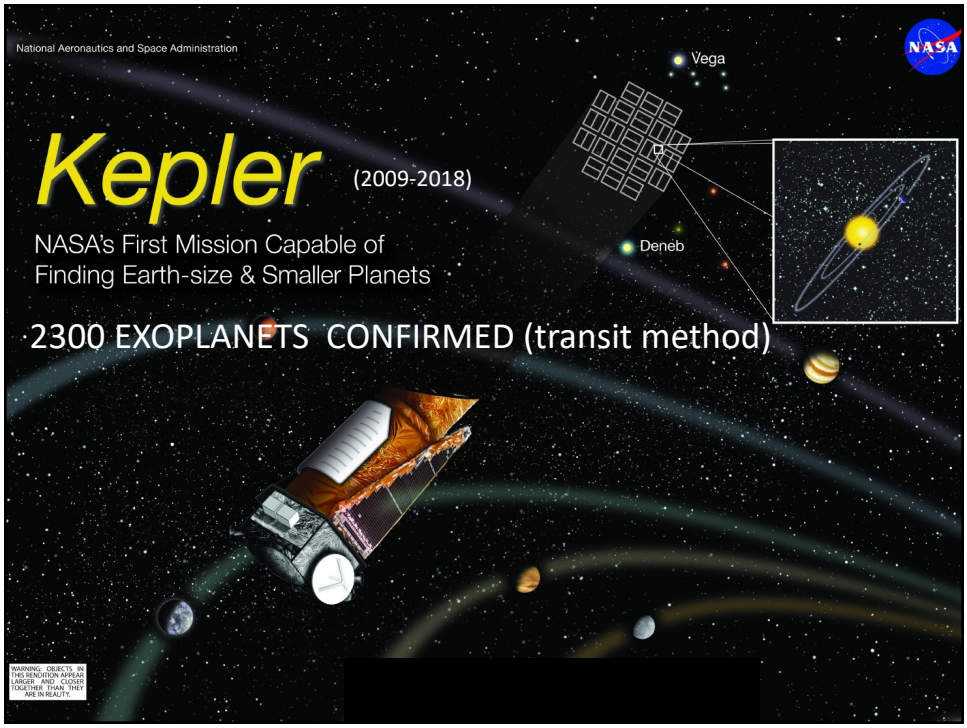
15


Exoplanet Transit
Direction of orbit
1
2
3
planet
star
Brightness
light curve
Before transit:
100% light
from star
Starlight partially blocked by planet
After transit:
100% light
from star
Time

16


exoplanet transit
exoplanet transit
Orbital Period (days)
PDC_SAP_FLUX (Norm)
1.005
1.000
0.995
0.990
0.985
0.980
$T \approx 4.887$ days
Orbital period = time between exoplanet transits
491
492
493
494
495
496
Time (BJD-2454833)
Transit Duration (hrs)
1.004
1.002
1.000
0.998
0.996
0.994
0.992
0.990
$T_f \approx 0.1725 \rightarrow 4.14$ hrs
Diameter of exoplanet deduced from structure of transit event
$T_t \approx 0.217 \rightarrow 5.208$ hrs
495.0
495.5
496.0
496.5
Time (BJD-2454833)

17

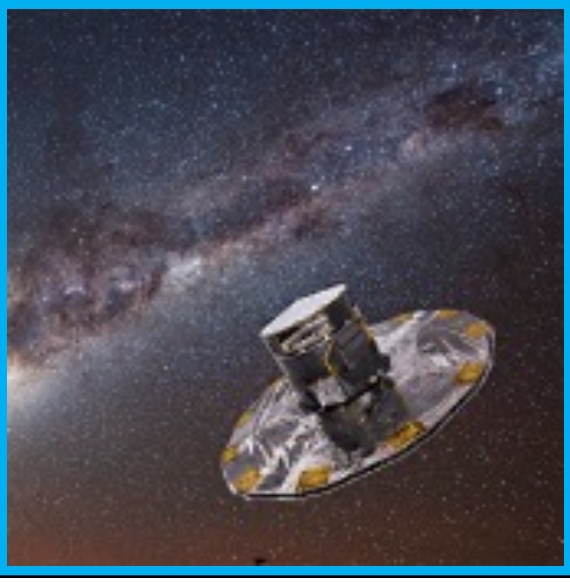

National Aeronautics and Space Administration
NASA
Vega
Deneb
Kepler
(2009-2018)
NASA's First Mission Capable of Finding Earth-size & Smaller Planets
2300 EXOPLANETS CONFIRMED (transit method)
WARNING: OBJECTS IN THIS RENDITION APPEAR LARGER AND CLOSER TOGETHER THAN THEY ARE IN REALITY.

18

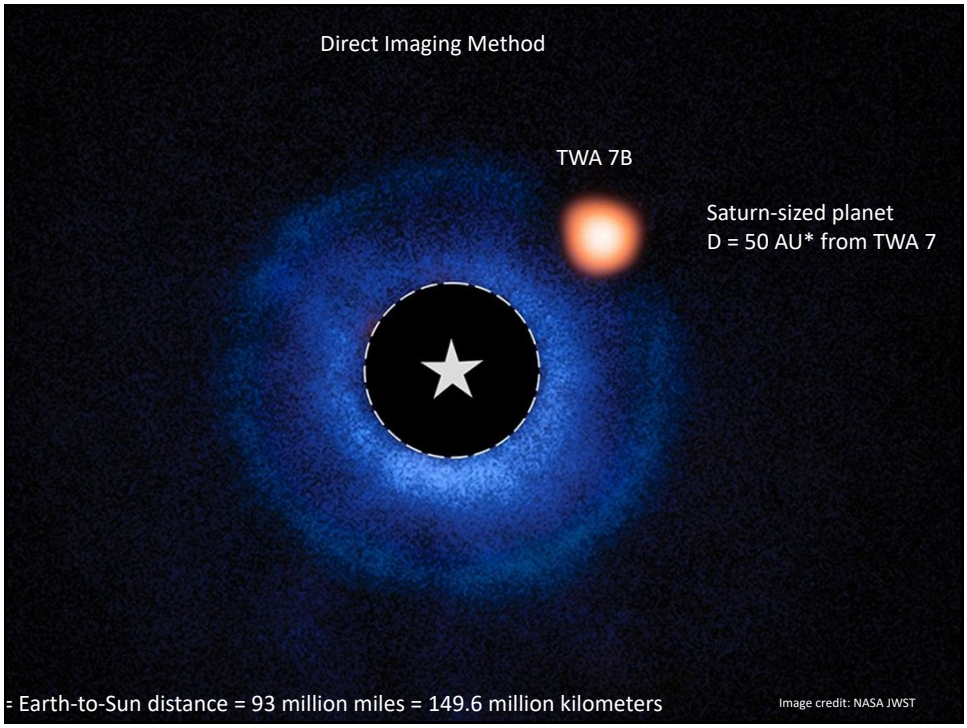
TESS Mission (launched 2018, still active) (transit method):
638 exoplanets found;
7,000+ exoplanet candidates (under study)

19

Gaia Mission (astrometry method):
Launched by European Space Agency (ESA) in 2013:
2 exoplanets found: 6000+ exoplanet candidates (under study)



20


Direct Imaging Method
TWA 7B
Saturn-sized planet
D = 50 AU* from TWA 7
= Earth-to-Sun distance = 93 million miles = 149.6 million kilometers
Image credit: NASA JWST

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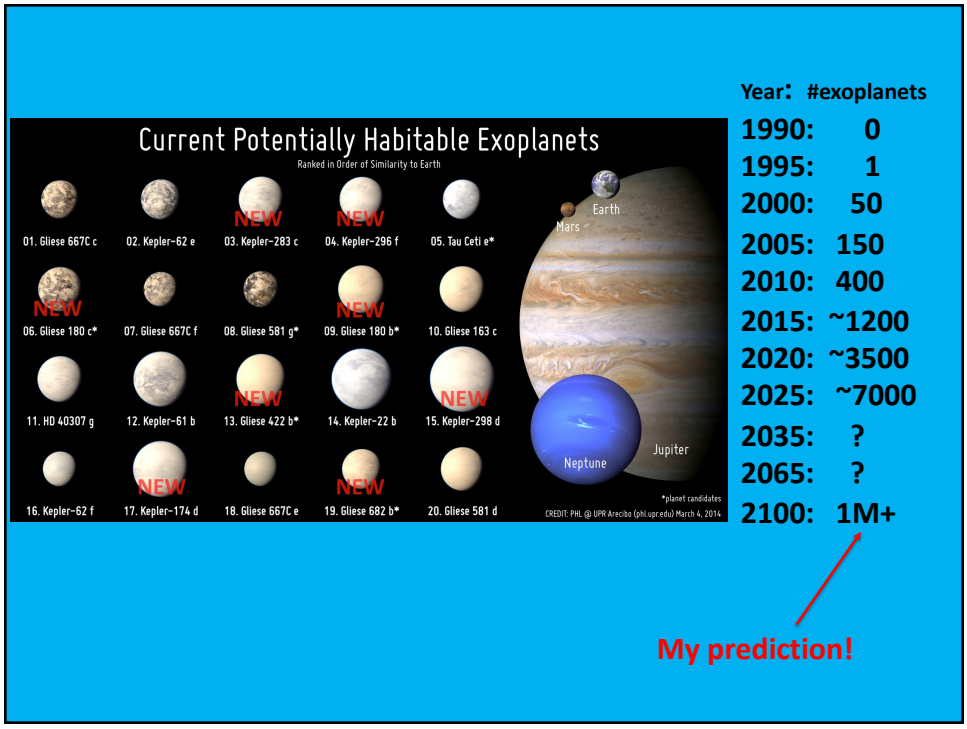
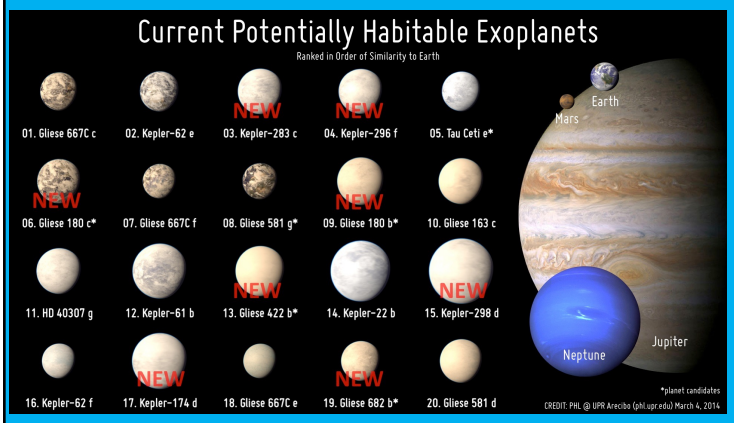

Current Potentially Habitable Exoplanets
Ranked in Order of Similarity to Earth
01. Gliese 667C c
02. Kepler-62 e
NEW
03. Kepler-283 c
NEW
04. Kepler-296 f
05. Tau Ceti e*
NEW
06. Gliese 180 c*
07. Gliese 667C f
08. Gliese 581 g*
NEW
09. Gliese 180 b*
10. Gliese 163 c
11. HD 40307 g
12. Kepler-61 b
NEW
13. Gliese 422 b*
14. Kepler-22 b
NEW
15. Kepler-298 d
16. Kepler-62 f
NEW
17. Kepler-174 d
18. Gliese 667C e
NEW
19. Gliese 682 b*
20. Gliese 581 d
Earth
Mars
Jupiter
Neptune
*planet candidates
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) March 4, 2014
Year: #exoplanets
1990: 0
1995: 1
2000: 50
2005: 150
2010: 400
2015: ~1200
2020: ~3500
2025: ~7000
2035: ?
2065: ?
2100: 1M+
My prediction!

22



Year:	#exoplanets
1990:	0
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2035:	?
2065:	?
2100:	1M+

My prediction!

WHY SEARCH FOR EXOPLANETS?

23

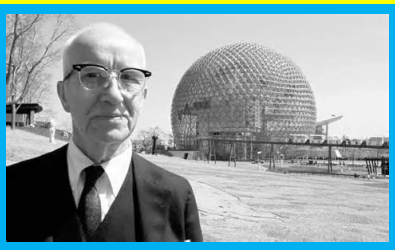
Carl Sagan,
The Cosmic Connection, 1979

"The idea of extraterrestrial life is an idea whose time has come."

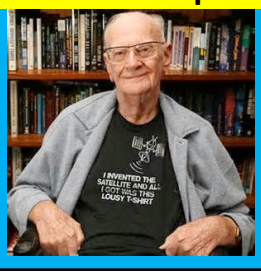
50 YEARS LATER, HE IS RIGHT!

24

"Sometimes I think we're alone. Sometimes I think we're not. In either case, the thought is staggering."
--- Buckminster Fuller
architect, inventor, futurist



"Two possibilities exist: either we are alone in the universe, or we are not. Both are equally terrifying."
--- Arthur C. Clarke
science fiction writer, futurist



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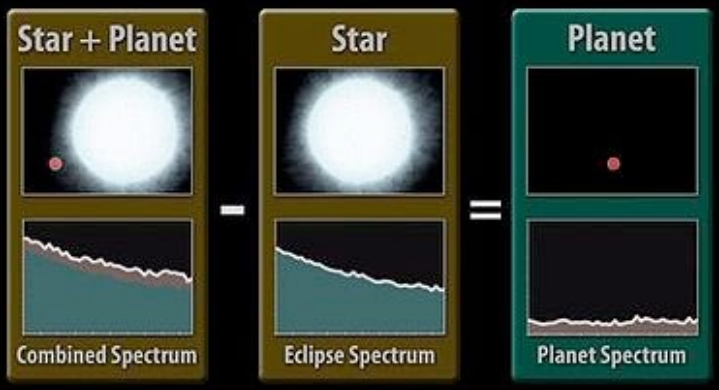
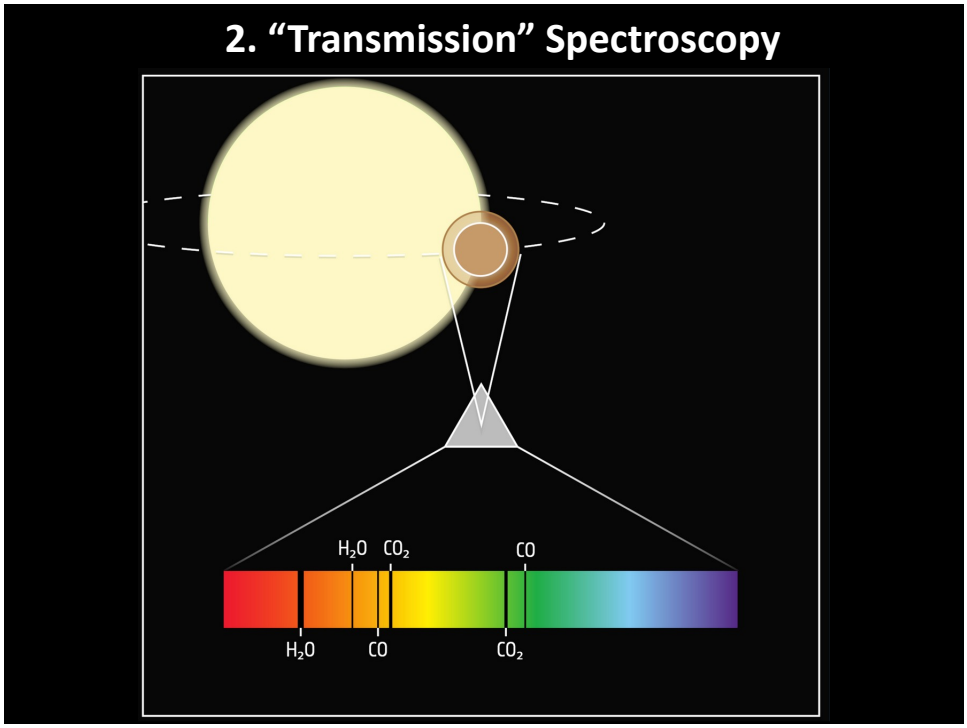
How will we learn about the possibility of extraterrestrial life?
By studying the atmospheres of exoplanets

1. "Eclipse" spectroscopy

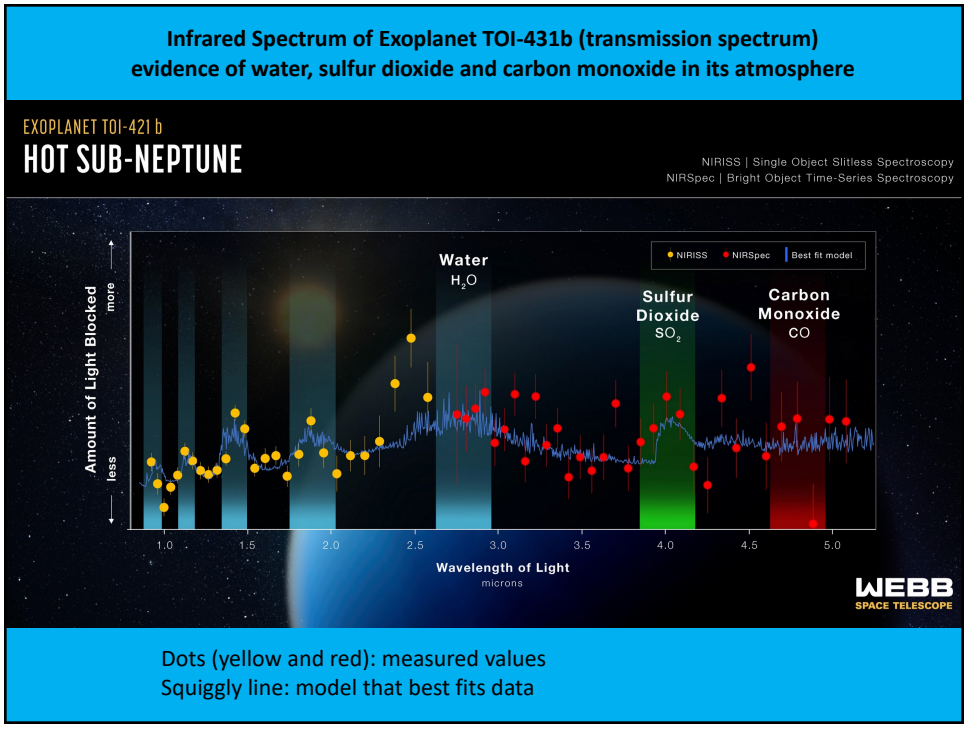


Oxygen?
Ozone?
Nitrous oxide?
Methyl chloride?
Other biomarkers?

26


2. “Transmission” Spectroscopy
H_2O CO_2
CO
H_2O
CO
CO_2

27


Infrared Spectrum of Exoplanet TOI-431b (transmission spectrum)
evidence of water, sulfur dioxide and carbon monoxide in its atmosphere
EXOPLANET TOI-421 b
HOT SUB-NEPTUNE
NIRISS | Single Object Slitless Spectroscopy
NIRSpec | Bright Object Time-Series Spectroscopy
NIRISS
NIRSpec
Best fit model
Water
H_2O
Sulfur Dioxide
SO_2
Carbon Monoxide
CO
Amount of Light Blocked
more
less
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Wavelength of Light
microns
WEBB
SPACE TELESCOPE
Dots (yellow and red): measured values
Squiggly line: model that best fits data

28

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