Today in Astronomy 106: exoplanets

- Exoplanets and their diversity.
- Fraction of stars with planets: the Drake equation's f_p.
- How to find exoplanets.

Robert Hurt, SSC/JPL/Caltech/NASA.

Review. The innermost gap in HL Tau's disk lies r = 13.2 AU from the star, which has luminosity $L = 6.6L_\odot$. What is the temperature of dust grains there, if they have albedo A = 0.7?

A. 91.1 K

B. 113 K

C. 162 K

D. 288 K

E. 389 K

F. None of these

Exoplanets

Michel Mayor and
Didier Queloz

The first exoplanet known to humans and belonging to a normal star, 51 Pegasi b, was discovered in 1995, by Michel Mayor and Didier Queloz.

- Terminology: an **exoplanet** (= extrasolar planet) is a planet in orbit around star that is not the Sun. Similarly an **exomoon** is a moon belonging to an exoplanet.

- Mayor & Queloz shared half of the 2019 Nobel Prize in Physics for their discovery.

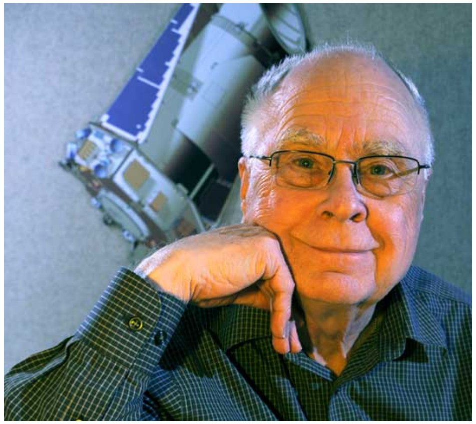
This discovery spawned intensive searches for more, which have revealed **4516 confirmed** exoplanets and **4511** additional good candidates. (No exomoons yet.)

- The number of confirmed exoplanets doubles about every 28 months.

Exoplanets (continued)

The NASA *Kepler* satellite has made the lion's share of the discoveries. Once *Kepler* had extended the exoplanet list to the thousands, their demographic statistics began to reveal

- that essentially all stars have planets, just as essentially all young stars have protoplanetary disks.
- wide and unexpected diversity among the planets and their host stars.
- both Earthlike planets lying in the **habitable zone** around their host star, *and* how frequently such situations are found.



Bill Borucki, leader of the *Kepler* team

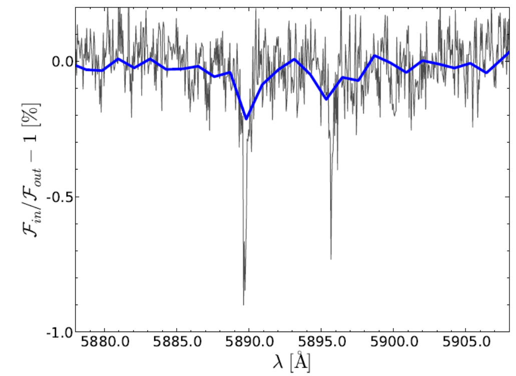
Exoplanets (continued)

State-of-the-art exoplanet observations now include studies of their atmospheres, both

- in transmission, as backlit by the host star,
- and in the planet's own emitted light.

Most of the exoplanet-atmosphere detections so far have been by the NASA Hubble Space Telescope (HST), but …

- … ground-based observatories are becoming capable, and adding many abilities not possessed by HST, and …
- … soon – 18 December – the NASA James Webb Space Telescope (JWST) will launch, and begin to spend about 25% of its time on exoplanets, their atmospheres, and protoplanetary disks.



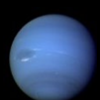
Sodium absorption in the atmosphere of HD 189733 b, seen with HST (blue) and from the ground (black); Wyttenbach et al 2015.

JWST, folded up in launch configuration.

Exoplanetary diversity

The five main types of exoplanets found in big surveys like *Kepler*:

- **Jupiters**: giant gaseous planets like our own Jupiter and Saturn. Large; mostly made of H_2 and He. Some would identify the largest examples of these as "super-Jupiters."



- **Neptunes**: medium-size planets with rocky cores and thick atmospheres mostly made of H_2 and He. Like our own Uranus and Neptune. Some would segregate the smaller ones into "mini-Neptunes."

- **Super-earths**: medium-size, rocky planets with little to no atmosphere. Our solar system has no super-earths.

- **Earths**: small rocky planets like ours. No exo-Earth has yet yielded an atmospheric detection; Earth wouldn't have, either.

- **Sub-earths**: Mars, Mercury, and such.

Exoplanetary diversity (continued)

Other dimensions of exoplanetary diversity:

- **Tidally-locked planets**: those whose day is precisely the same duration as their year, or, like Mercury, an integer-ratio multiple of their year. Most have permanent day- and night-sides; they are very common.
- **Hot Jupiters** and **hot Neptunes**: giant planets in orbits closer to their host stars than Mercury is to the Sun. They couldn't have formed in the orbits in which they are seen.
- **Tatooines**: planets in orbit around binary stars.
- **Superpuffs**: hot giant planets with especially extended atmospheres. For the atmospheres to last long enough for us to see them in this condition, is a challenge.
- **Waterworlds**: apparently covered with water. The only two we know about are hot and have atmospheres mostly made of steam.
- **Doomed worlds**: planets in orbit around brown dwarfs, white dwarfs, or giant/supergiant stars.

Exoplanetary demographics

How do we know there are all these different kinds? Because we can **measure** the orbits, masses, and radii of the exoplanets.

- The following pages contain graphs of the observed properties of exoplanets, and comparison to physical models, which demonstrate the distinctions between the planet types we currently distinguish.

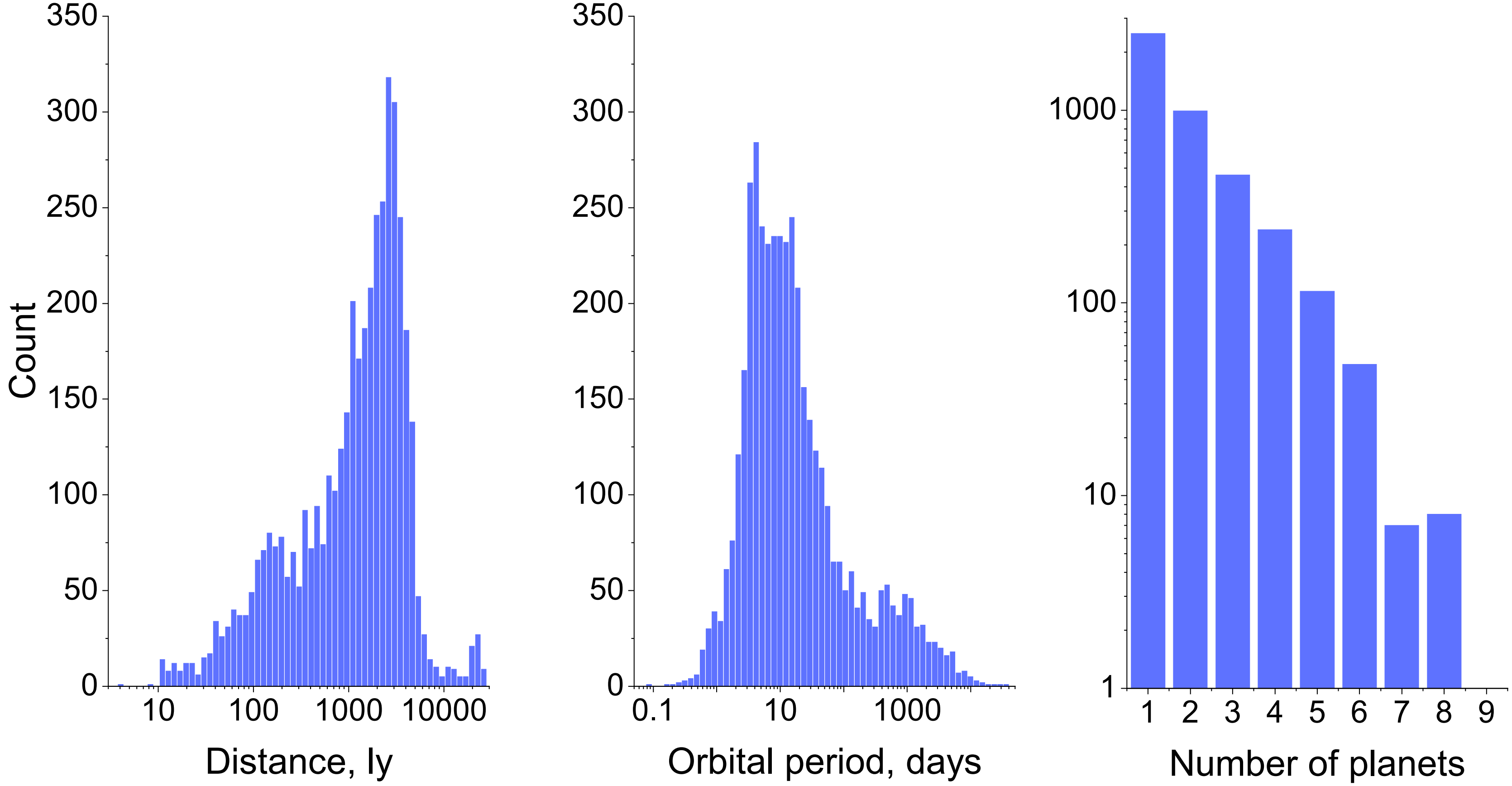
- They come from data, updated in real time, and contained in the **NASA Exoplanet Archive**, at

  https://exoplanetarchive.ipac.caltech.edu

  On the archive's plotting page, you can easily make your own graphs at any time, and easily download the data.

- For the following graphs I used the data as of 18 September 2021.

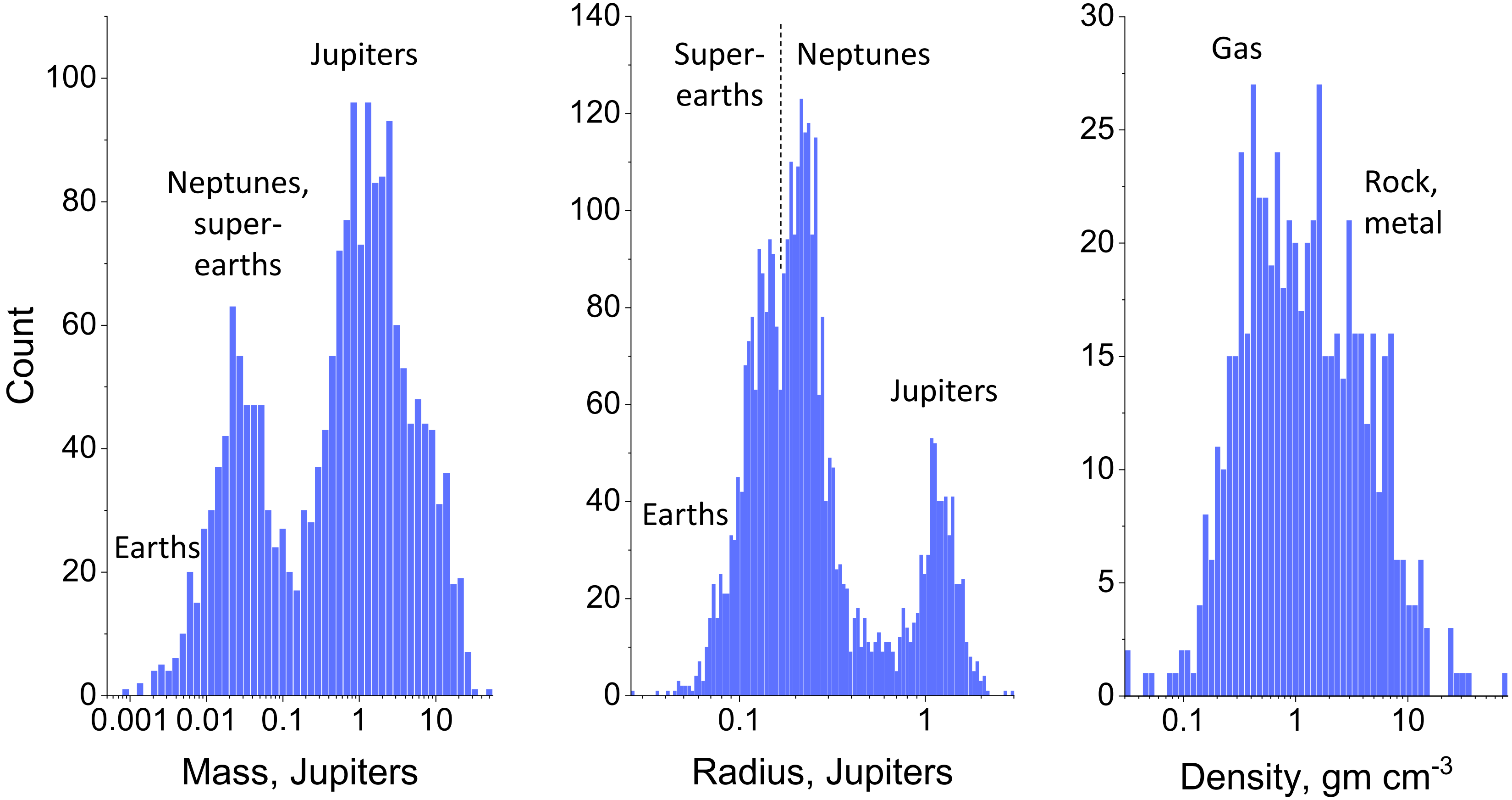
Exoplanet distances from Earth, orbital periods, and number of multiplanet systems



[NASA Exoplanet Archive, 18 September 2021]

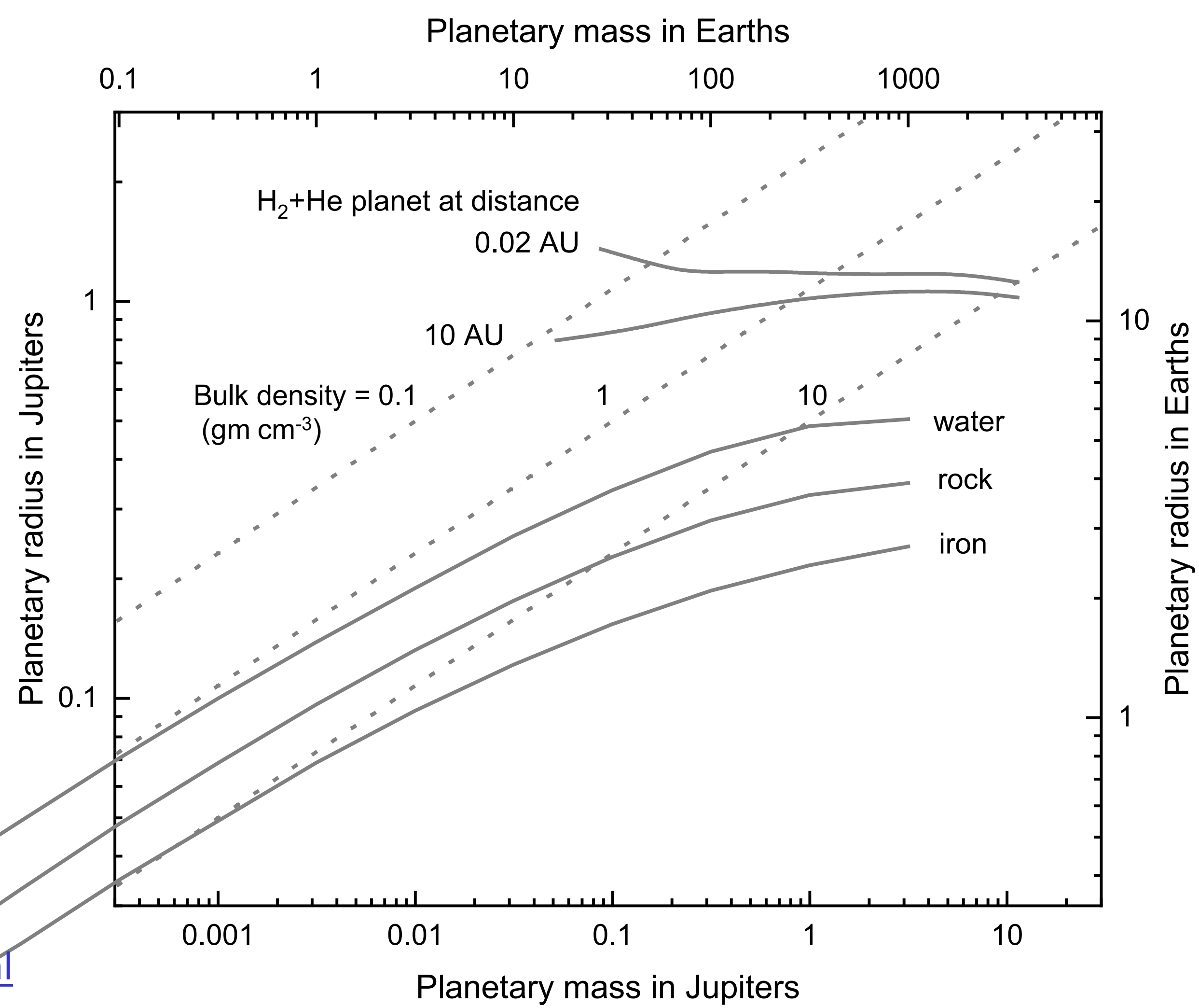
Exoplanet masses, radii, and bulk densities

Bulk density = planet's mass, divided by its volume.



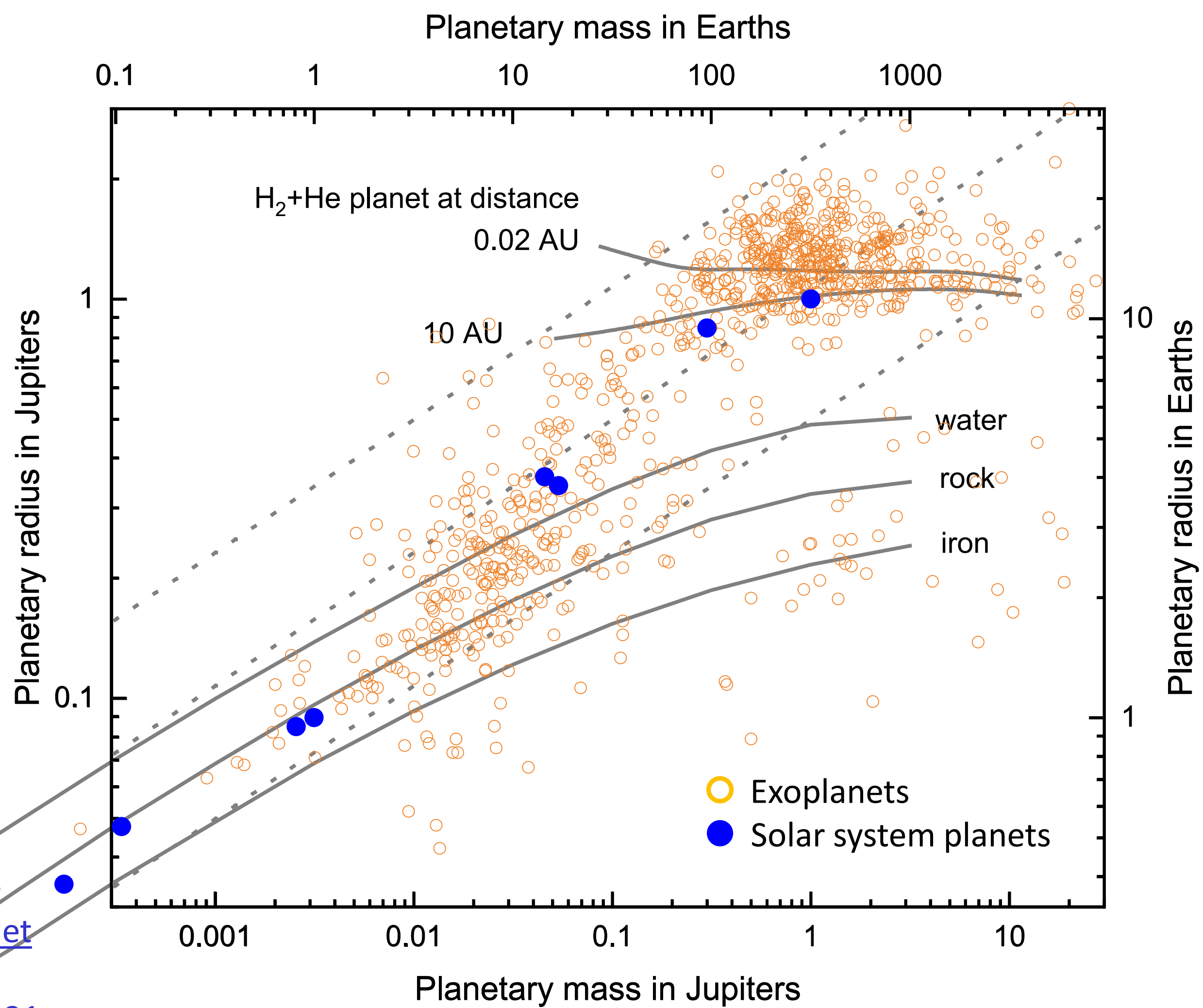
NASA Exoplanet Archive, 18 September 2021

Exoplanet internal structure



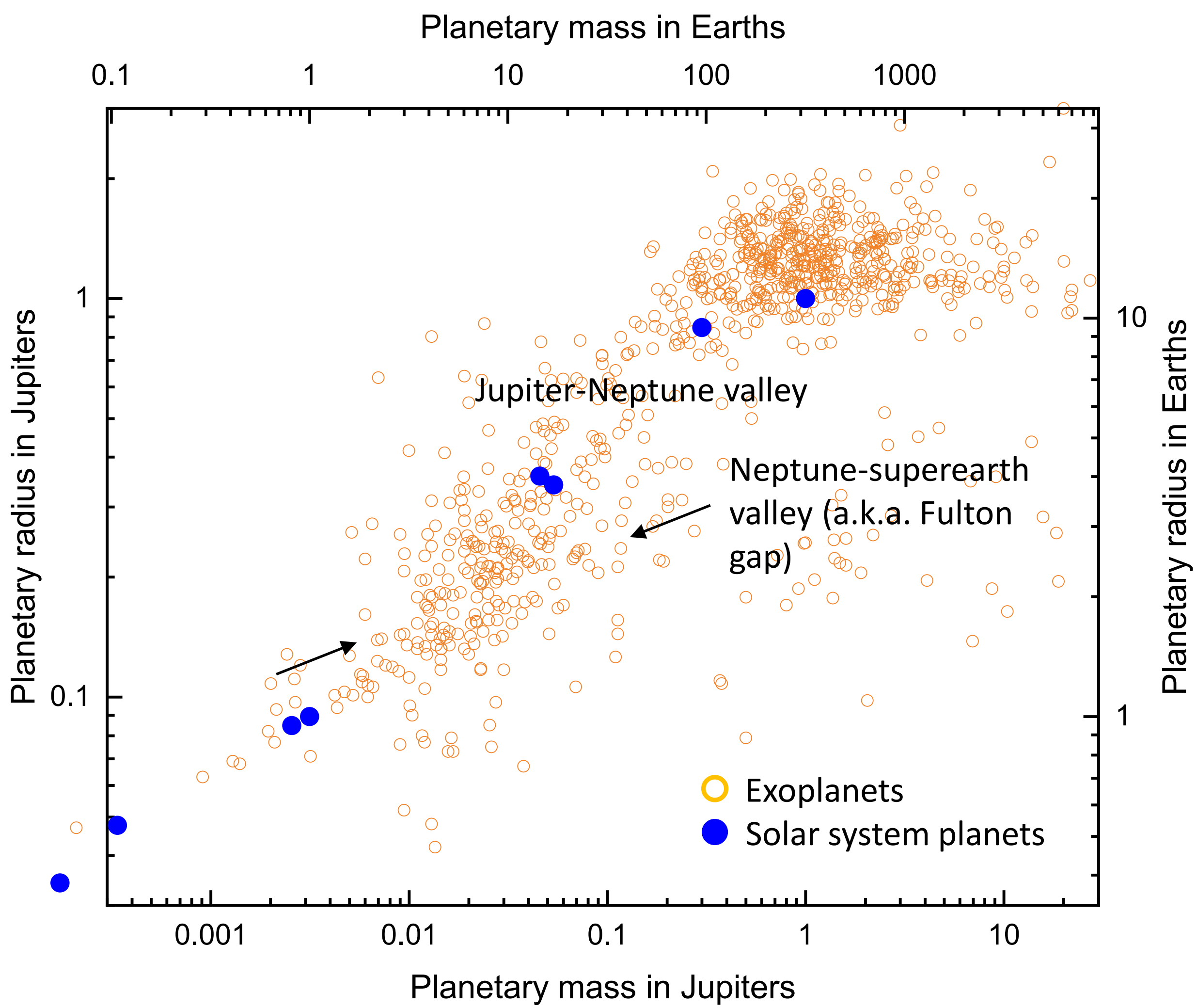
From planetary models by [Fortney et al (2007)]

Exoplanet internal structure (continued)

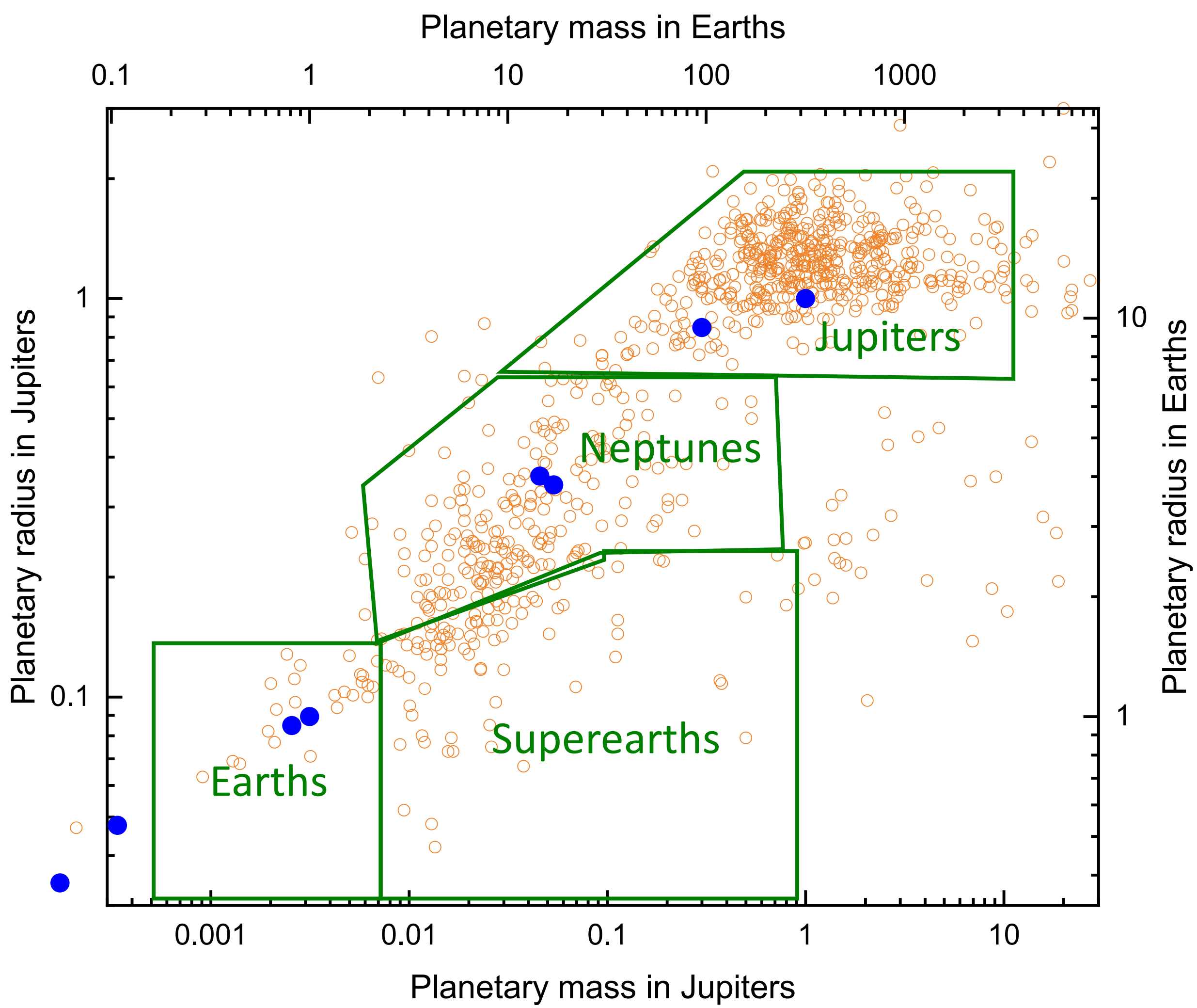


Data from the [NASA Exoplanet Archive, 18 September 2021]

Exoplanet internal structure (continued)



Exoplanet internal structure (continued)



Demographics and the Drake equation: f_p

- Essentially 100% of stars are born with enough material around them to make multiple planets of all sorts.

- We have made surveys, of nearby stars for planets, that are unbiased over certain ranges of masses and orbital periods.

- The resulting score at present (Mayor et al. 2012), for stars with mass 0.6-1.5$M_\odot$:

  - 14%$\pm$2% host a gas-giant planet with $P \leq$ 10 years.

  - 75% $\pm$2% host a planet of any currently-detectable mass with $P \leq$ 10 years.

- And we aren't even very good yet at detecting Earths and sub-Earths, or planets with long orbital periods, so **f_p must be very close to 1.**

Mid-lecture Break.

- Homework #2 is due Monday, 7:00 PM.
- **Quiz #1 is next Tuesday, in lecture, on WeBWorK. Bring your laptop to class to take the quiz.**

For reference:

$$1M_\odot = 1.989 \times 10^{33} \text{ gm}$$

$$1M_J = 1.899 \times 10^{30} \text{ gm}$$

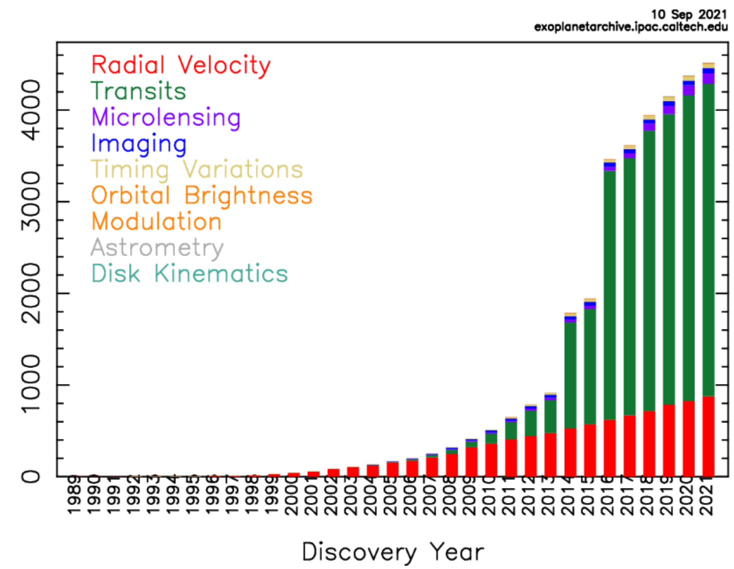
$$1M_\oplus = 5.974 \times 10^{27} \text{ gm}$$

What	Solar masses ($M_\odot$)	Jupiter masses (M_J)	Earth masses ($M_\oplus$)
Sun	1	1048	332900
Typical disk	0.1	105	33290
Jupiter	0.00095	1	318
Earth	0.000003	0.0031	1

Measuring the properties of exoplanets

Stars are vastly brighter and more massive than planets, and most stars are far enough away that the planets are lost in the glare.

So astronomers have had to be more clever, and employ the **motion** of the orbiting planet. They **mostly** use:



- **Transits**: periodic eclipsing of star by planet, or *vice versa*.
- **Radial velocity (RV)**: measure tiny, periodic wobble in star's motion along the line of sight by Doppler shift.

And when they can, they use

- **Imaging**: take pictures over a period of time, watch the planet orbit the star.

Summary of exoplanet detection by imaging, radial velocity, and transits

For purposes of discovery and classification of large numbers of exoplanets, rather than, say, studying the atmospheres of a few:

	Measure planetary mass?	Measure stellar mass?	Measure tilt of orbit from line of sight?	Measure planetary size?	Measure stellar size?	Detect planet close to star?	Detect planet far from star?	Detect planet orbiting very distant star?
Images	No	Yes	Yes	No	No	No	Yes	No
Radial velocity	Yes	Yes	No	No	No	Yes	Yes, if monitored	With large existing telescopes
Transits	Not easily	Not easily	Yes	Yes	Yes	Yes	Yes, if monitored	Yes

- The combination of transits and RV gives a Yes in every column.
- So the main discovery technique has become transits, with RV used to measure the masses of the exoplanets discovered thereby.

Taking images of exoplanets

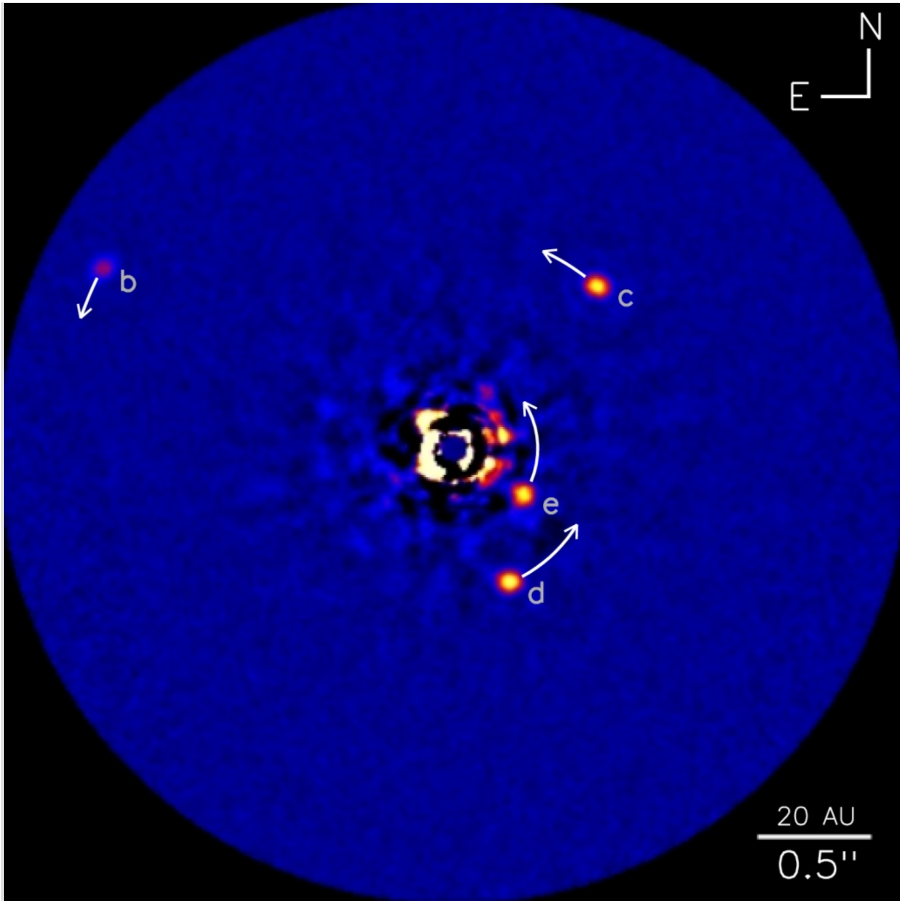
This is a lot harder than it sounds. Consider:

- Seen from a great distance, the Sun would appear to be two **billion** times brighter than Jupiter.
- Seen from a distance of 100 light years, Jupiter and the Sun would be separated by an angle no more than 0.17 arcseconds (4.5×10^{-5} degrees). Compare to blur:
  - 0.07 arcseconds on HST;
  - 0.04 arcseconds on Keck 10 m telescopes with adaptive-optical (AO) atmospheric-blur correction;
  - >0.5 arcseconds on telescopes on Earth without AO.
- The blur would have to be <<<<< 0.17 arcsec to see the faint planet so close to the bright star.

Taking images of exoplanets (continued)

Nevertheless, technical progress in high-contrast imaging has enabled the imaging of several exoplanet systems. Good examples:

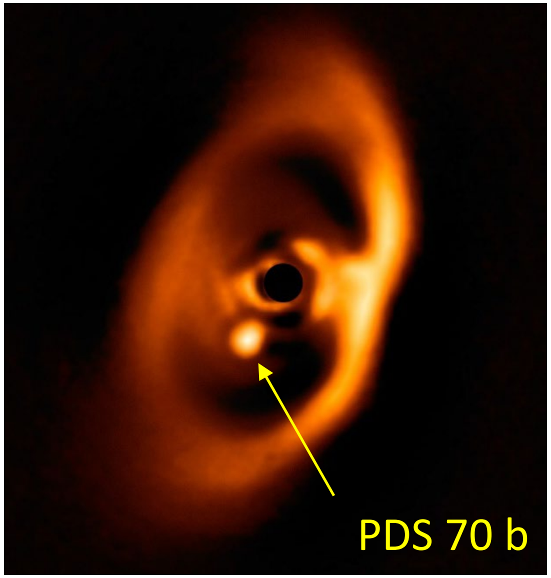
- The nearby star HR 8799, 129 ly away, has at least four giant planets in orbit, in the gap between two asteroid belts.
- All 5-10 times Jupiter's size.
- Apart from size, a striking resemblance to our four giant planets lying between two asteroid belts.



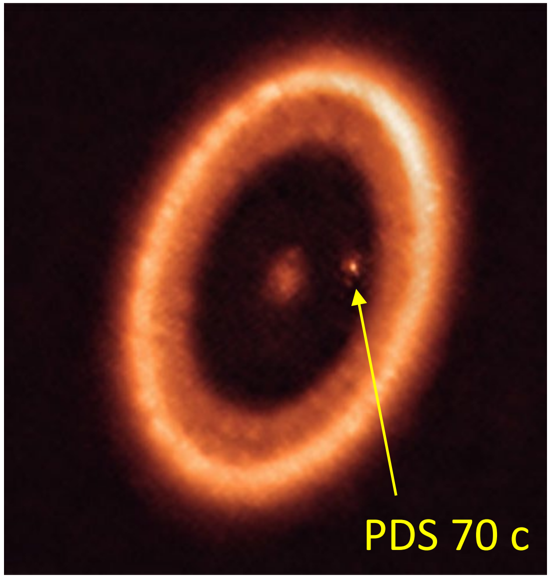
Infrared image of the HR8799 system (Marois et al. 2010)

Taking images of exoplanets (continued)

- The transitional disk around the young star PDS 70 – 370 light years away – has two Jupiter-like planets orbiting in the gap. One, PDS 70 c, looks to be surrounded by a proto-lunar disk.



VLT/SPHERE: [Keppler et al 2018]



ALMA: [Benisty et al 2021]

Radial velocity (RV) detection of planets

The method used by Mayor & Queloz for the 51 Peg b discovery.
Also not easy, but easier than imaging. Here's how it works.

- Stars and their planets are *both* in orbit, around their common center of mass.

- The orbital radius and velocity of each object is larger, the smaller its mass. Thus the star moves slowly in a tiny orbit.

  - Consider Jupiter and the Sun, which orbit each other with an 11.9-year period:

$$\text{Jupiter's circular orbit: } r = 5.2\text{ AU},\ V = 13\text{ km sec}^{-1};$$

$$\text{Sun's circular orbit: } r = 0.0049\text{ AU},\ V = 0.012\text{ km sec}^{-1}.$$

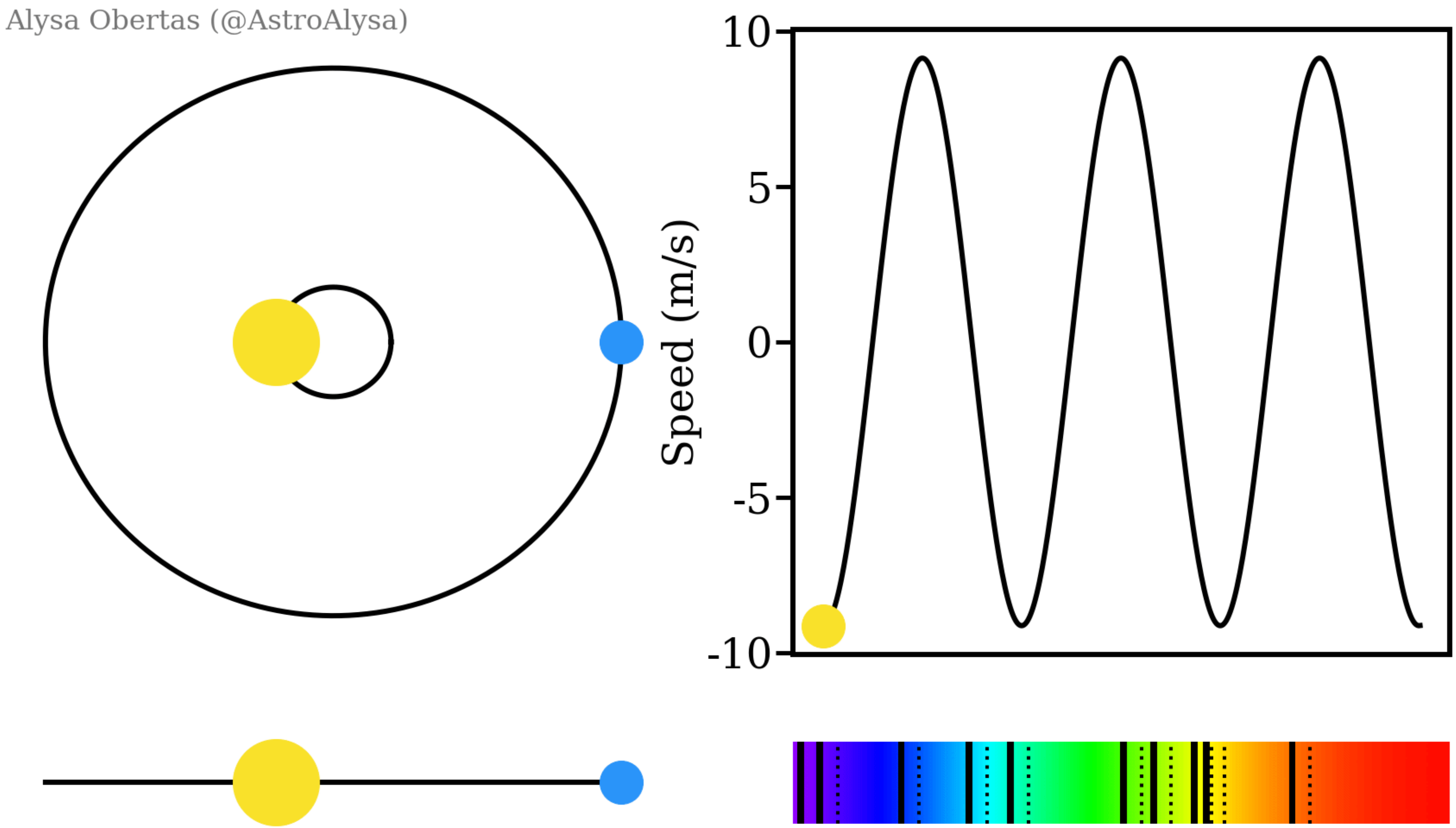
  - **Know star's mass and orbital *V* ⇔ know planet's mass and orbital *V*.**

  - The best planet-search instruments can measure stellar velocities as small as $0.0002\text{ km sec}^{-1} = 20\text{ cm sec}^{-1}$.

RV detection of planets (continued)

- RV detectors work by measuring the radial (Doppler) velocity of the star.
    - **Terminology**: the "radial" part of radial velocity means "along the line of sight."
- Similar to the way the police radar measures the speed of your car, but no radar gun is needed, as …
- … spectral lines in the star provide the signal.
- Spectral lines are shifted in wavelength: the fraction of the wavelength by which a line shifts is the same as the fraction of the speed of light represented by the star's radial velocity.
- If the radial velocity varies up and down periodically, then the maximum gives the orbital velocity component along the line of sight, and time between maxima is the orbital period.

Radial velocity (RV) detection of planets

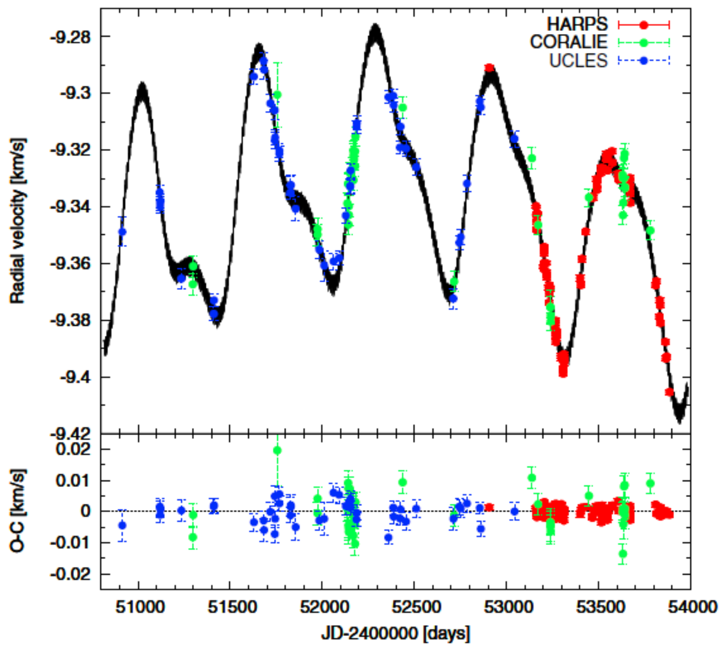


[Wikimedia Commons/Alysa Obertas]

RV detection of planets (continued)

Upsides of exoplanet detection with radial velocity:

- From radial velocity observed over an orbital period, get planet mass, plus shape and radius of orbit.
- No need for high image contrast or high-resolution images.
- Can detect many thousands with existing instruments and telescopes.



RV measurements on μ Arae, over some eight years, showing the presence of four planets. (Pepe et al. 2007)

RV detection of planets (continued)

Downsides:

- Since it doesn't involve detecting light from the planet, one can't learn about the planet's surface, atmosphere, density, *etc*. from RV.
- One doesn't know the **orbit inclination** *a priori*, so the "mass" that one measures is mass times sin *i,* where *i* is the angle between the line of sight and the rotation axis.
    - This makes less difference than you might think:
        - the average value of sin *i* for a large population of randomly-oriented exoplanet orbits is 0.785.
        - the probability that sin $i \leq 0.1$ is only 0.5%.

Transit detection of exoplanets

The method employed by the *Kepler* satellite, and **by you, in ASTR 106**.

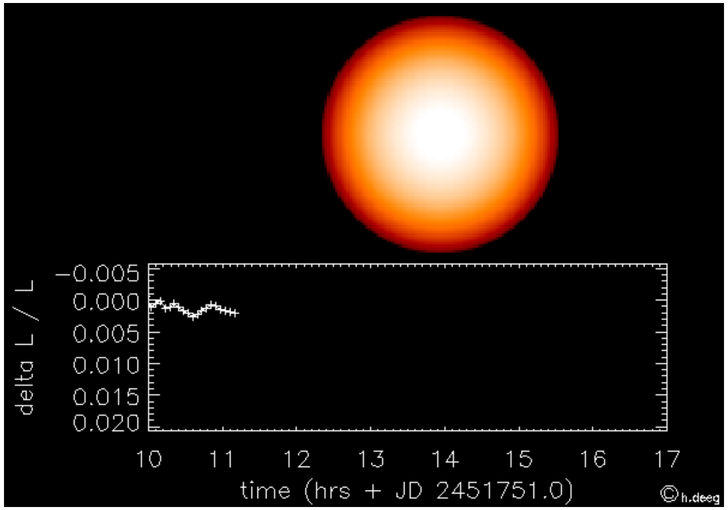
This involves detecting the decrease in starlight flux received when planet passes in front of star (**transit**) or vice versa (**eclipse**), and is also not easy. Consider:

- Seen from a great distance, the Sun is about 9.8 times the diameter of Jupiter, so Jupiter would block only 1.1% of the Sun's visible light if it were to transit the Sun.
- Even if Jupiter were T = 1000 K at the cloudtops, the total infrared-light brightness of the Sun-Jupiter pair would decrease by only 0.1% if the Sun were to eclipse Jupiter.
    - And Jupiter is only T = 112 K at the cloudtops.
- **Also**: the orbit must be viewed close to edge on to see a transit. Less than 2% of a randomly-oriented population is oriented this close to edge-on.

Transit detection of exoplanets (continued)

Method: one measures the brightness of the host star, periodically, during a time span containing a transit, and plots the brightness as a function of time. The resulting graph is called a **transit light curve**.

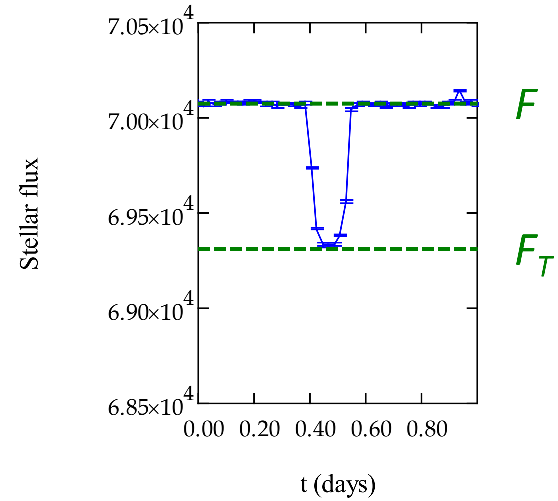
- The main idea is to take light curves for several transits of the planet, and work out the orbital period from when these transits take place.
- Bonus! We get a piece of information not found in any other method: the size of the planet and the star.
- From the duration of the transit one can measure the diameter of the star and/or the precise orbit inclination.



Stars are too far away for us to see the transit in an image (upper), but we can still measure the light curve (lower). Animation by [Deeg and Garrido 2000](#).

Transit detection of exoplanets (continued)

- And from the depth of transit we can measure the radius of the planet. In simplified terms this works as follows:



- Measure the host star's flux F before or after transit.

- In the same units, measure the star's flux F_T during transit.

- With the planet's radius as R_P and the star's as R_*,

$$F_T = F - \frac{\pi R_P^2}{\pi R_*^2} F$$

, or, with a little bit of algebra,

$$\boxed{R_P = R_* \sqrt{1 - \frac{F_T}{F}} \quad .}$$

You need to understand how to use this equation.

Transit detection of exoplanets (continued)

Upsides of exoplanet detection by transit:

- Gives radius of planet *and* star, which are very hard to get otherwise.
  - *Kepler* measurements of stellar radii is having a profound effect on the physics of stars, as they tend to be very slightly larger than expected.
- While not easy, is at least easier than the other two methods, and can be carried out with small telescopes.

Downsides:

- Only a small fraction of exoplanets transit: the ones viewed close to edge-on.
- That’s not an important drawback: we don’t think there’s anything systematically different about these, compared to the others.

From orbital period to orbital radius

- In the late 1500s, Johannes Kepler – analyzing Tycho Brahe's large collection of observations of the planets out to Saturn, noticed that a pattern emerges between their orbital periods *P* and orbital radii* *a*:

$$a^3 = P^2$$

r in AU,

P in years

Kepler's third law

- A few decades later, Isaac Newton, armed with his new theory of gravity, demonstrated that any planet in orbit around a star with mass *M* would obey

$$a^3 = \frac{GM}{4\pi^2}P^2 \quad \Rightarrow \quad a[\mathrm{AU}]^3 = M[M_\odot]P[\mathrm{year}]^2$$

  which is Kepler's third law, again, when *M* is the mass of the Sun.

  - This was the first huge experimental validation of Newton's theory of gravitation.

* *a* is really the semimajor axis length of the planets' slightly elliptical orbits, but we will ignore the small difference between radius and *a*.

Orbital period to orbital radius (continued)

- We can (and will) measure the orbital period *P* of an exoplanet this semester, using our own observations of the planet's transits across its host star.
- We will also measure the color of the host star, from which we can use the leverage of many decades of observations to determine the star's mass *M.*
- From these observations we will determine the exoplanet's orbital radius, from Newton's version of Kepler's third law:

$$\boxed{a[\mathrm{AU}] = \left(M\left[M_\odot\right]P[\mathrm{year}]^2\right)^{1/3}}$$

You need to understand how to use this equation.

- And, since we will also know the star's luminosity *L* (from its mass), we can calculate the cloud-top temperature of the planet – the first step in telling whether or not it might be habitable.

An exoplanet is found in orbit around a 0.5 solar mass star, with orbital period 36.525 days. What is its orbital radius, in AU?

A. 0.17 AU

B. 0.79 AU

C. 3.7 AU

D. 4.6 AU

E. None of these

The luminosity of the 0.5 solar-mass star is 0.063 solar luminosities. What is the temperature of the cloudtops or surface of this exoplanet, if its albedo is earthlike *(A* = 0.37)?

A. 279 K

B. 301 K

C. 325 K

D. 383 K

E. None of these