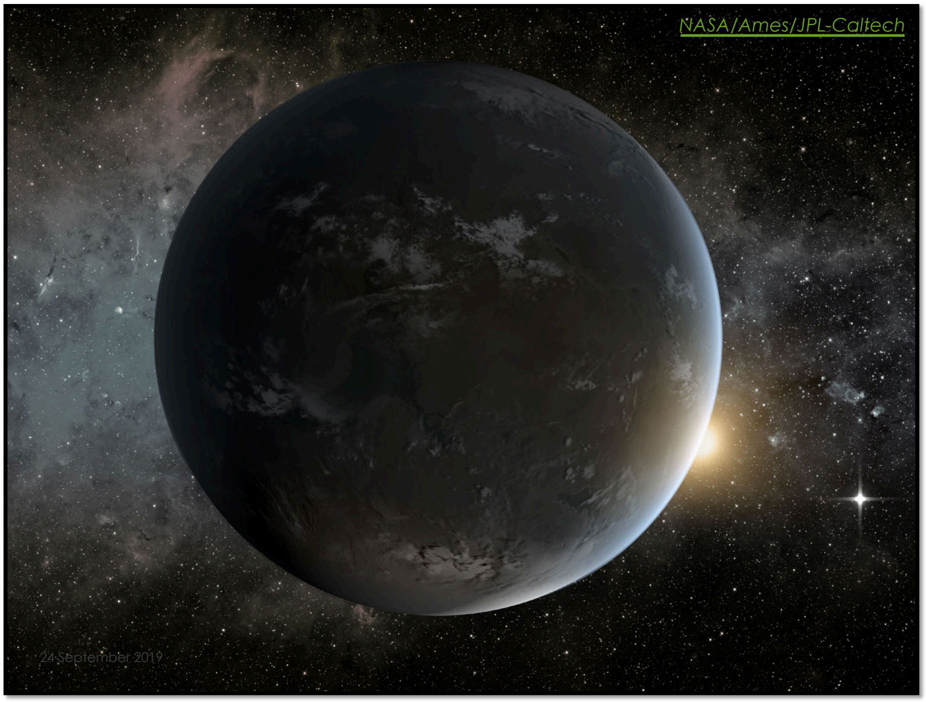
24 September
2019

PLANET FORMATION & EXOPLANETS

Homework #3 on WeBWorK due Monday at 7pm
Exam #1 next Tuesday, October 1st

Exam #1 – Tuesday, 10/1

- 1 hr 15 min in-class exam, open book and open notes
- Things you should DEFINITELY bring with you:
  - Writing utensil (pencil or pen – blue or black ink)
  - Calculator
- Things you should PROBABLY bring with you:
  - Lecture notes
  - Laptop or tablet (so that you can access the WeBWorK homework problems)
- REVIEW SESSION – Monday, Sept. 30th at 7pm (location TBD)



Planet Formation & Exoplanets

Star formation rate in the Milky Way: the Drake equation's R_*

Finding protoplanetary disks: infrared excess and the temperature of dust in disks

Protoplanetary disk evolution and planet formation

Three methods of the exoplanet search: imaging, radial velocity, and transit

The engines for detecting more exoplanets

Some properties of exoplanets

Fraction of stars with planets: the Drake equation's f_p

The star formation rate in the Milky Way (R_*)

We will estimate our first Drake Equation quantity, the star formation rate R_*, in three different ways using the most up-to-date observations.

One way of estimating this value is by making multiple measurements of the numbers and ages of very massive stars and extrapolating this to the total mass in stars. While rather complicated, this is the way astronomers attempt to measure star formation rates in galaxies outside the Milky Way. The result (Licquia & Newman, 2015) is

$$R_* = (1.65 \pm 0.19) M_\odot/\mathrm{yr}$$

The authors note that values larger by factors of at least 2-3 are usually obtained by counting all the stars, for cases in which that is possible.

The star formation rate in the Milky Way (R_*)

Current rate of star formation: based on counting very young stars still embedded in their placental molecular clouds, and dividing by their typical age

- Result for 20 nearby molecular clouds (Heiderman et al. 2010)
  - Star formation rate: $R = (8.2 \pm 3.8)\times 10^{-4} M_\odot/\mathrm{yr}$
  - Molecular cloud mass: $M = (8.7 \pm 3.5)\times 10^{4}\ M_\odot$
- It is only "easy" to count individual young stars in the nearest clouds. However, it is "easy" to measure the total mass of *dense* molecular clouds in the Galaxy by surveying molecular-line emission over the entire sky (e.g. Kennicut & Evans 2012):

$$M_{\mathrm{total}} = 8\times 10^{8}\ M_\odot$$

$$R_{*,\mathrm{now}} = R\frac{M_{\mathrm{total}}}{M} = (8 \pm 4)\ M_\odot/\mathrm{yr}$$

Star formation rate, R_*

Lifetime average rate of star formation. We know the mass of the stars in the Galaxy from observed extent and rotation speed of the Galaxy and Newton's Laws.

- Same way we know the mass of the Sun from the Earth's orbital extent and speed.
- Complicated, though, by presence of **dark matter** in the Galaxy, so we will skip to the answer (Licquia & Newman 2015):

$$M_* = (6.08 \pm 1.14)\times 10^{10}\ M_\odot$$

- We also know that stars more than 10 billion years old are rare, so the **average** rate of star formation has been something like

$$R_{*,\mathrm{average}} = \frac{M_*}{10\times 10^{9}\ \mathrm{yrs}} \approx 8\ M_\odot/\mathrm{yr}$$

Star formation rate, R_*

The Milky Way Galaxy's current star formation rate is within the (large!) uncertainties of the lifetime-average rate.

As the Galaxy's molecular-cloud supply is gradually used up in the form of very long-lived stars, we might expect the star formation rate to decrease with time over the course of tens of billions of years. Observations may someday show this.

We will adopt $8M_\odot/\mathrm{yr}$, and since the most common stars have mass $M = 0.5M_\odot$, we have

$$R_* = 8\ M_\odot/\ \mathrm{yr} \times \frac{\mathrm{star}}{0.5\ M_\odot} = \boxed{16\ \mathrm{stars/yr}}$$

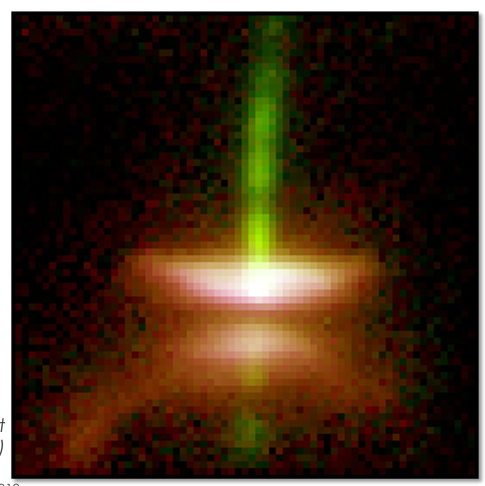
for our **Drake equation input**, noting that it is uncertain by something like a factor of two: the value may actually lie anywhere between 8 and 32 stars per year.

Young stars and protoplanetary disks

The youngest stars are found in close proximity to the molecular clouds from which they formed.

We can measure the age of a **cluster** of young stars by comparing the run of their **luminosities** (total power output in the form of light) and colors with those of older stars which do not belong to clusters.

Young stars are usually surrounded by disks.

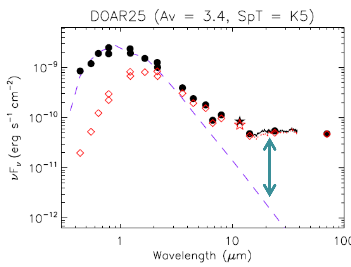


A protoplanetary disk viewed edge-on at visible wavelengths (HH30, STScI/NASA)

Detecting protoplanetary disks

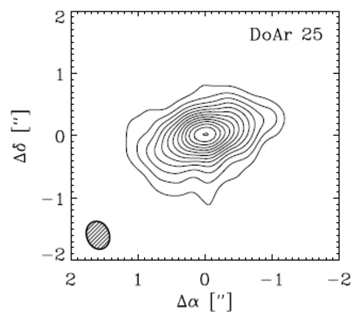
Most disks are too small on the sky, and most telescopes are too small, to easily take good pictures of them. We find them mostly by

- **Infrared excesses**: emission by dust in the disk in excess of the star's total power output. Thousands are known by this method.
- **Millimeter-wavelength interferometry**, in which signals from multiple telescopes are combined to replicate the functions of a very large telescope. Several dozen have been detected this way.



McClure et al. (2010)

Andrews et al. (2009)



Infrared excesses and the temperature of dust grains

The temperature of dust in protoplanetary disks is set by heating from the central star and cooling by the dust's **blackbody radiation**. The infrared excess is this radiation.

All opaque bodies emit radiation. You do not notice it because the light we emit comes out at infrared wavelengths, which our eyes are not sensitive to.

The total **flux** F (power per unit surface area) emitted by an opaque, perfectly light-absorbing body with temperature T turns out to be

$$F = \sigma T^4$$ Stefan's Law

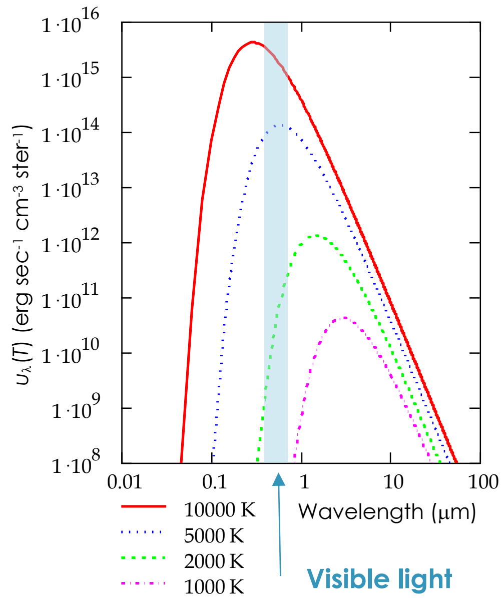
$$\text{where } \sigma = 5.67\times10^{-5}\ \text{erg s}^{-1}\ \text{cm}^{-2}\ \text{K}^{-4}$$ Stefan-Boltzmann constant

So what is the temperature (T) of a dust grain as a function of how far away it is from the star (r)?

Blackbodies

Blackbodies with different temperatures emit different total fluxes and have different spectra.

The wavelength at which a blackbody is brightest is inversely proportional to its temperature. This turns out to be a good way to measure the temperature of distant blackbodies.



Temperature of dust grains

Time for another derivation. You will be responsible for knowing the result and understanding the reasoning, but not for the algebra.

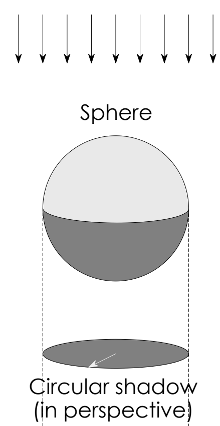
Consider a spherical, perfectly black dust grain with radius a (surface area $4\pi a^2$) which is located a distance r away from a star with luminosity (total light power per unit time) L.

- Starlight flux (power / unit area) at location of grain:

$$F_* = \frac{L}{4\pi r^2}$$

- Spheres cast circular shadows, so the total **power** (energy / unit time) absorbed, $P_{\rm abs}$, is

$$P_{\rm abs} = F_* \times (\text{shadow area}) = \frac{L}{4\pi r^2}\pi a^2$$



Temperature derivation

Suppose the dust grain is **uniform** in temperature (same T at all points on its surface). Then the power it emits in blackbody radiation is

$$P_{\text{emit}} = F_{\text{blackbody}} \times \text{surface area} = \sigma T^4 4\pi a^2$$

If its temperature is **constant** in time, then because **energy is conserved**, the grain emits exactly as much power as it absorbs:

$$P_{\text{abs}} = P_{\text{emit}}$$

$$\frac{L}{4\pi r^2}\pi a^2 = \sigma T^4 4\pi a^2$$

$$T = \left(\frac{L}{16\pi\sigma r^2}\right)^{1/4}$$

Dust grain temperature – units

Usually, it will be convenient to use units of solar luminosity, $L_\odot$, and Earth-Sun distance, AU, instead of erg/s and cm:

$$L_\odot = 3.83\times10^{33}\ \text{erg/s}$$

$$\text{AU} = 1.496\times10^{13}\ \text{cm}$$

In which case the equation for dust-grain temperature becomes

$$T = \left(\frac{L_\odot}{16\pi\sigma \text{AU}^2}\right)^{\frac{1}{4}} \left(\frac{L/L_\odot}{\left(r/\text{AU}\right)^2}\right)^{\frac{1}{4}} = 279\ \text{K}\times\left(\frac{L[L_\odot]}{(r[\text{AU}])^2}\right)^{\frac{1}{4}}$$

[x] means "in units of x"

Suppose the Earth were considered to be a large dust grain which acts as a perfect uniform-temperature blackbody. What would its temperature be, according to this procedure?

Question

A. 2790 K
B. 279 K
C. 27.9 K
D. 2.79 K

Albedo

Few grain, or planetary, surfaces are perfectly black. Most reflect some of the light.

We call the fraction of incident light that is reflected the **albedo**, usually give the symbol A.

This reduces the absorbed power by a factor of $1 - A$. That is the same as the star having a factor $1 - A$ lower luminosity, so our formula becomes

$$\boxed{T = \left(\frac{(1-A)L}{16\pi\sigma r^2}\right)^{\frac{1}{4}} = 279\ \mathrm{K} \times \left(\frac{(1-A)L[L_\odot]}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}}$$

You need to understand how to use this equation.

The snow line

If you know the temperature you want, you can also calculate the appropriate distance by solving for r instead of T:

$$\boxed{r[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{T}\right)^2 \sqrt{(1-A)L[L_\odot]}}$$

You also need to understand how to use this formula.

Example: the snow line. Ice makes dust grains shiny ($A{\sim}0.7$). In the vacuum of space, water ice sublimates at a temperature of 150 to 170 K depending upon what other ices it is mixed with. In a disk, how far away from a $1L_\odot$ star would ice be found?

$$r[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{150\text{ to }170\ \mathrm{K}}\right)^2 \sqrt{(0.3)(1)} = 1.9\text{ to }1.5\ \mathrm{AU}$$

Suppose the Earth were considered, again, to be a giant dust grain. Its numerous clouds endow it with an albedo of 0.37. What would its temperature be?

Question

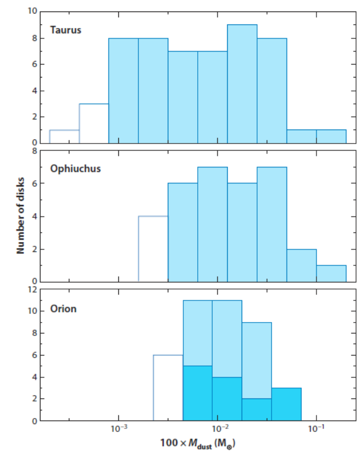
Protoplanetary disk mass

In the youngest stellar clusters, protoplanetary disks are found around essentially every star.

The masses of the disks can be measured by various means – notably via dust emission seen at millimeter wavelengths.

Disks turn out typically to have masses several percent of their central stars – plenty out of which to make planets.

- At least $0.03M_{\odot}$ of disk was necessary to make our planets.



Disk-mass census in three nearby young stellar clusters (Williams & Cieza 2011)

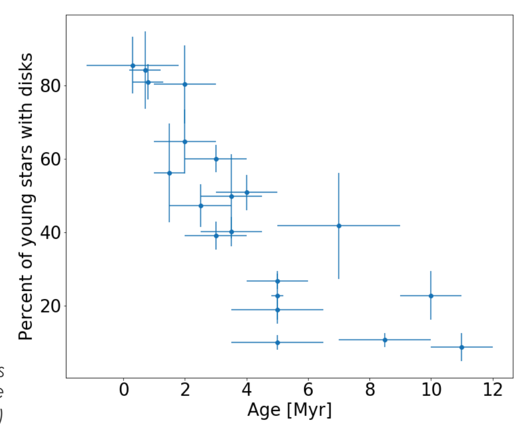
Protoplanetary disk evolution

Protoplanetary disks do not live very long – they vanish with a half-life of about 3 Myr.

Planet formation is only one of several processes that can eliminate the disk. Most others involve dispersal by the central star's light or magnetism.

If planets can form in 3 Myr or less, practically all stars will have planets – in Drake equation terms, $f_p = 1$

Sure enough, they do.



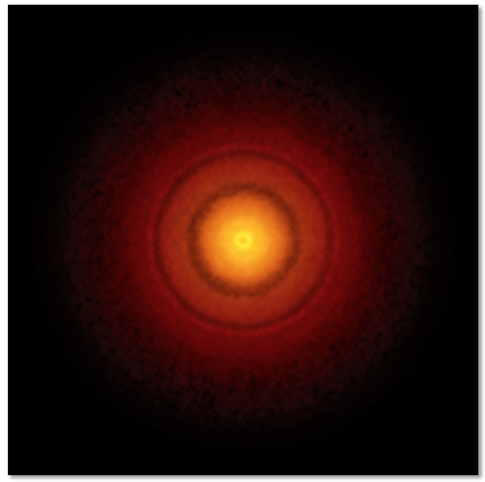
Disk census in young clusters within 1500 light years of the Sun (Kim et al. 2013)

How planets are thought to form

For a long time (Swedenborg 1734, Kant 1755, Laplace 1796), it had been though that the Solar System must have formed from a disk-shaped nebula.

When the youngest stars were found to always be surrounded by dusty disks in the 1970s, such disks were immediately identified as the birthplaces of planetary systems.

Unfortunately, these planets are very difficult to directly observe, since they are outshone by their stars and dust in the disks.



The disk around TW Hydrae (ALMA)

Planet formation by gravitational instability

Two of the three mechanisms people have thought up for planetary formation from disks are similar to the collapse of molecular clumps into protostars:

- Rapid growth of gravitational instabilities in the gas (Kuiper 1951, Cameron 1962, Boss 2001). This would be a good way to make gas-giant planets directly and rapidly.
- Rapid growth of gravitational instabilities in the dust (Goldreich & Ward 1973). This would be a good way to make terrestrial planets or rocky cores for giant planets.

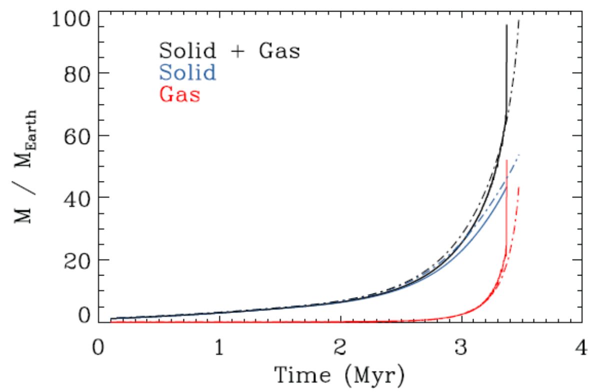
Instability growth in a gas disk (NASA, A. Field (STScI))

Planet formation by core-accretion

The third is **core-accretion**: two-body collisions combine small solid bodies (starting with dust grains) into larger ones, eventually resulting in planet or planet-core size bodies.

This is much slower than the other methods, but it is faster than it sounds because the rate of accretion of the largest bodies increases rapidly with the size of these bodies.

These days, it looks like **most planets form by core-accretion**, though some very massive ones far from their stars may give a good argument for gravitational-instabilities.



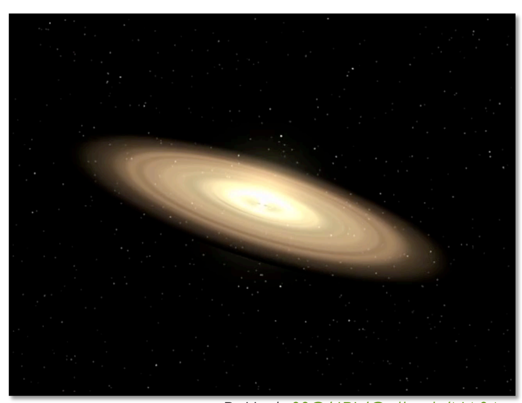
Core-accretion model for the formation of Saturn (Dodson-Robinson et al. 2008)

Transitional disks

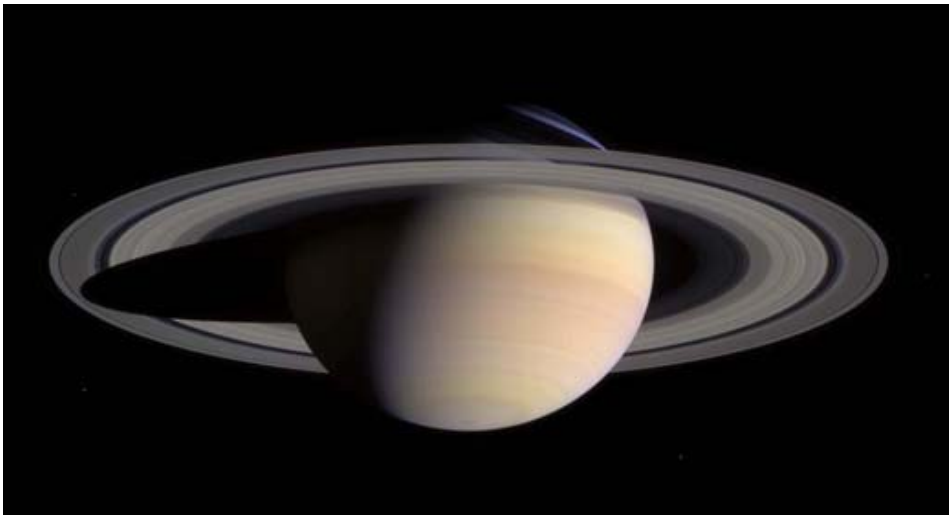
There are easier ways to detect planets recently formed within disks than to see the planet in an image: look for the planet's "wake."

A giant planet like Jupiter would cause the formation of a radial gap or a central clearing in the dusty disk in which it formed by gravitational influence on orbiting disk material.

…just as in the case of the moonlets and gaps in Saturn's rings.



R. Hurt, SSC/JPL/Caltech/NASA



Saturn's rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)

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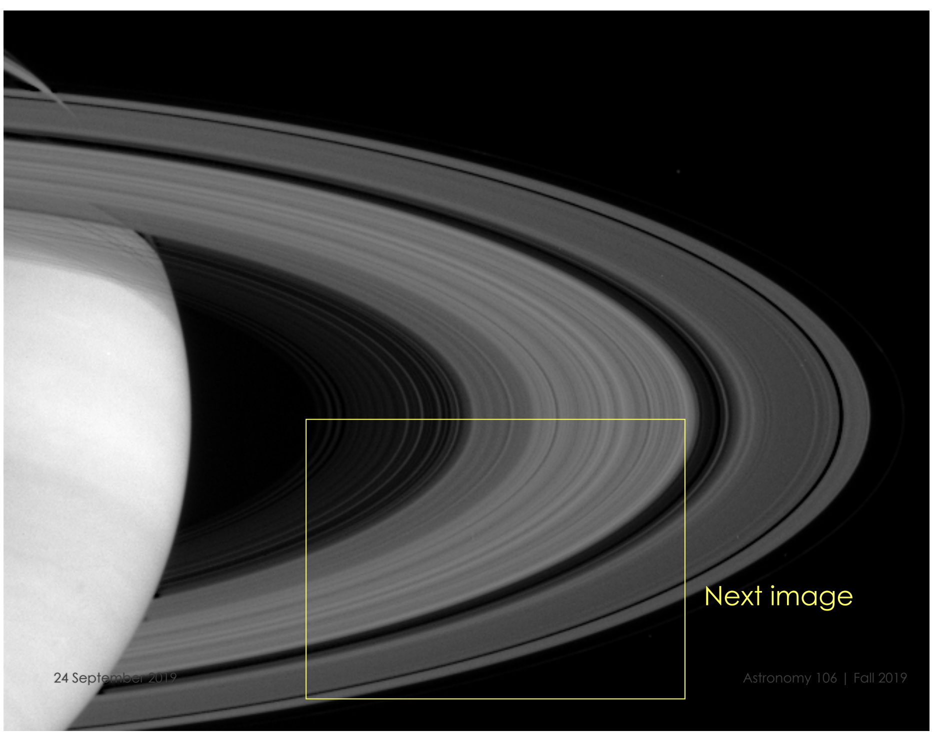

Saturn's rings: gaps and moonlets

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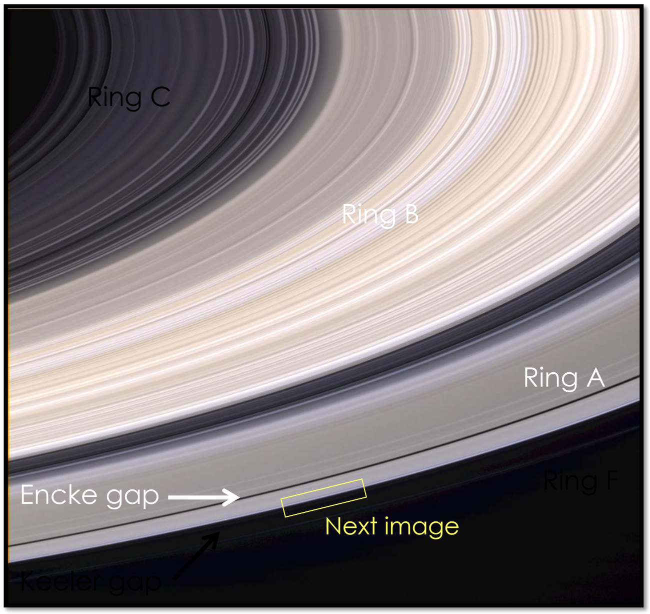


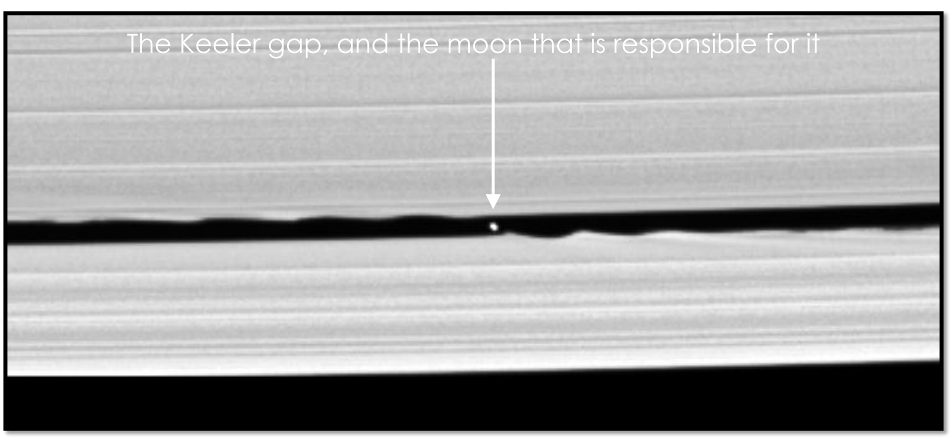
Saturn's rings: gaps and moonlets

Cassini division caused by the moon Mimas, which lies slightly outside the rings.

Image from the Cassini satellite (NASA/JPL)

Saturn's rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)

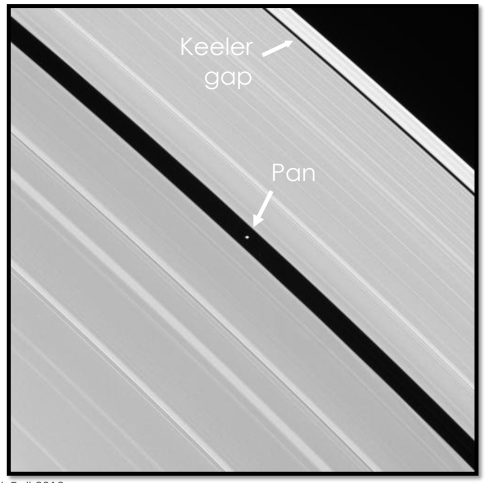


Saturn's rings: gaps and moonlets

Notice how much easier it is to see the gap than the moonlet that made it?

Gaps can be seen in images, but…

…in principle, also seen as "gaps" in the blackbody emission of dust within the disks.



The Encke gap and the moonlet Pan. Image from the Cassini satellite (NASA/JPL)

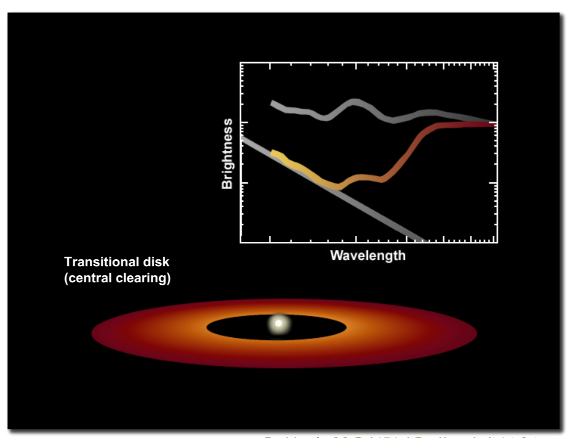
Transitional disks

In some protoplanetary disks, gaps appear as deficits in the infrared excess over a range of wavelengths compared to the spectra of ordinary disks.

Such disks are called **transitional disks**.

By this means, we know of some 200 protoplanetary disks within 1500 ly of the Sun which have a few-AU to few-10s-of-AU gaps.

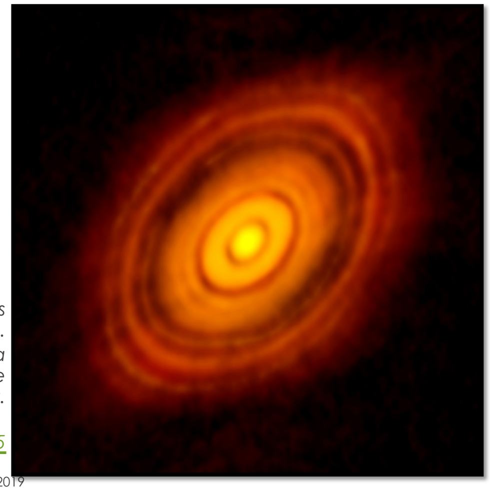
The vast majority of these gaps must be cleared by objects of giant planetary mass.



R. Hurt, SSC/JPL/Caltech/NASA

Smaller gaps in a younger disk

Recent observations at wavelength 1 mm by the new Atacama Large Millimeter Array (ALMA) of a 0.5 Myr-old young star called HL Tauri revealed a concentric nest of gaps, **each probably harboring a giant planet**.



HL Tau, as observed. The system lies 457 light-years from the Solar System. Gaps do not appear circular when a tilt of 46.72° is inferred between the rotation axis and our line of sight.

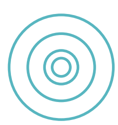
ALMA partnership 2015

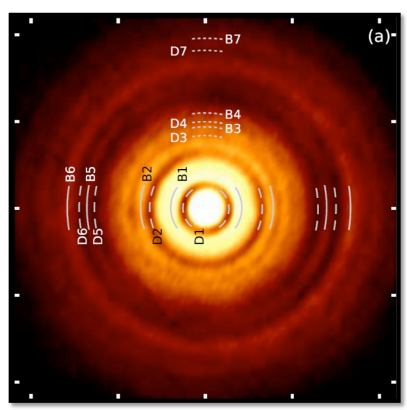
Smaller gaps in a younger disk

Observed emission is predominantly from mm-size dust grains in the disk; star and planets not seen in image.

HL Tau is young enough that it is still embedded in its natural envelope, through which the disk is seen.

JSUN





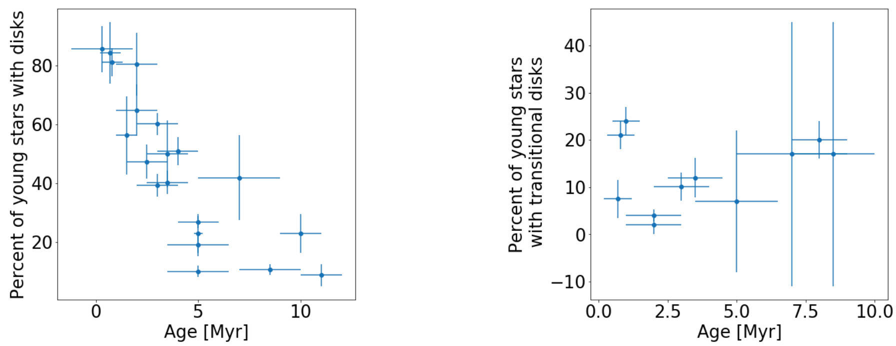
Digitally de-tilted. Tick marks 50 AU apart; gaps D1, D2, D5, and D6 lie 13.2, 32.3, 64.2, and 73.7 AU from the star.

Orbits of Jupiter, Saturn, Uranus, and Neptune shown for comparison.

ALMA partnership 2015

Transitional disks

Though disks themselves disappear with a half-life of 3 Myr, the fraction of transitional disks among them can be as large among the youngest as the oldest (5-20%). Giant planets are quite common among even the young stars we see.



Kim et al. 2013

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

Question

Exoplanets: the newest frontier of astronomy

The observational study of extrasolar planets only started in 1995 with the discovery that the star 51 Pegasi has a companion (51 Peg b) with a mass about half of Jupiter's and an orbital period of 4.2 days (Mayor & Queloz, 1995; Marcy & Butler, 1995).

The enterprise was already going very well when the NASA Kepler satellite was launched (2009), which added more than two thousand new planets and thousands of additional candidates.

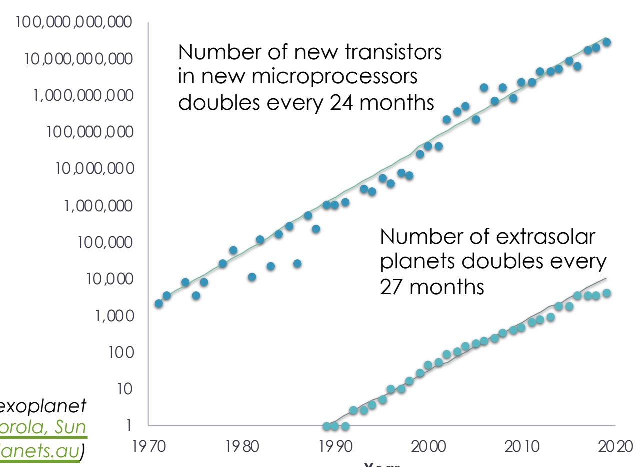
Kepler before launch (Ball Aerospace/NASA)

Exoplanets: the hottest frontier of astronomy

Today, there are 4112 confirmed extrasolar planets and thousands of other good candidates.

Their diversity is also growing. There are several types not found in the Solar System, including

- Hot Jupiters
- Super-Earths
- Tatooines



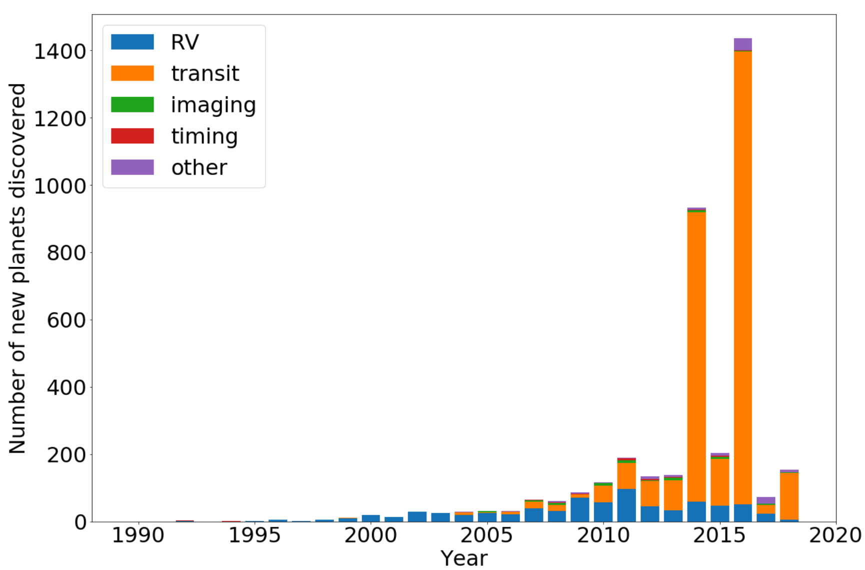
Exponential progress: Moore's law compared to exoplanet discovery. (Data from Intel, AMD, IBM, Zilog, Motorola, Sun Microsystems, Kepler, and exoplanets.au)

Observing 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 had to be more clever and employ the motion of the orbiting planet. They mostly use:

- **Imaging**: take pictures over a period of time, watch the planet orbit the star.
- **Radial velocity (RV)**: measure tiny, periodic wobble in star's motion along the line of sight by Doppler shift.
- **Transits**: periodic eclipsing of star by planet, or vice versa.

Of today's exoplanets, 72% have been detected by transits, 21% by RV, and 3% by imaging. The remaining 4% were identified by a variety of lesser-used means.



Discovered exoplanets

Thanks to Kepler, most of the exoplanets discovered to date were found using the transiting technique.

Open Exoplanet Catalog

Taking images of exoplanets

This is much more difficult than it sounds.

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 ($4.5\times10^{-5\circ}$). Compare to blur:

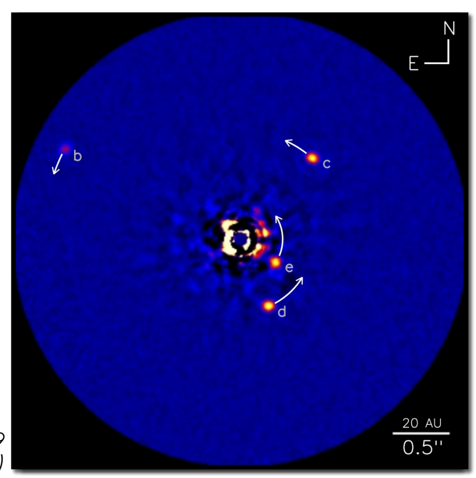
- 0.07 arcseconds on Hubble Space Telescope
- 0.04 arcseconds on Keck 10m telescopes with adaptive-optical (AO) atmospheric-blur correction
- > 0.5 arcseconds on telescopes on Earth without AO

The blur would have to be <<<<<<< 0.17 arcseconds to see the faint planet so close to the star.

Imaging exoplanets

Nevertheless, technical progress in high-contrast AO imaging has recently enabled the imaging of a few exoplanet systems. Good examples:

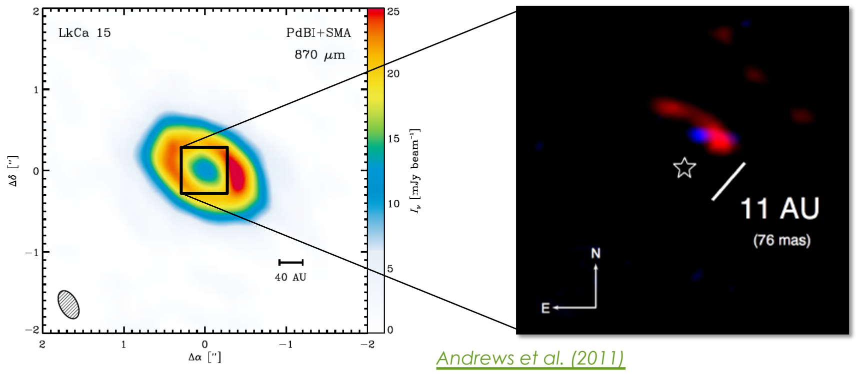
- The nearby star HR 8799, 129 ly away, has at least four giant planets in orbit in the gap between two asteroid belts.
- All 5-10 times Jupiter's size
- Apart from size, a striking resemblance to our four giant planets lying between two asteroid belts.



Infrared image of the HR 8799 system (Marois et al. 2010)

Imaging exoplanets

The transitional disk around LkCa 15 has become the first known to have a Jupiter-like giant planet orbiting in the disk's gap.



Andrews et al. (2011)

Imaging exoplanets

Upsides of direct imaging

From the track of the planet over an orbital period, an accurate measurement of planet mass and orbital radius and shape can be made.

In principle, this would permit the spectrum of the planet to be measured separately from the star, and thus its atmosphere to be unambiguously studied.

Downsides of direct imaging

Not very many planetary systems (maybe 80?) will be "imageable" by existing telescopes (< 10m diameter)

Larger telescopes (30m diameter), currently in the planning stages, will cost at least $1G each.

Which of the following planetary properties can be determined from direct imaging?

Question

A. Radius
B. Mass (or $M \sin i$)
C. Orbital period
D. Orbital radius
E. Inclination of the orbital plane
F. Shape of orbit

Radial velocity (RV) detection of planets

Also not easy, but easier than imaging.

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

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

- Consider Jupiter and the Sun, which orbit each other with an 11.9-year period.
- Jupiter's circular orbit: $r = 5.2$ AU, $v = 13$ km/s
- Sun's circular orbit: $r = 0.0049$ AU, $v = 0.012$ km/s

Know star's mass and orbital v ←→ know planet's mass and velocity

The best planet-search instruments can measure stellar velocities as small as 0.0002 km/s = 20 cm/s

RV detectors

RV detectors work by measuring the Doppler velocity of a star.

Similar to the way the police radar measures the speed of your car, but no radar gun is needed, since 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 Doppler velocity.

If the Doppler velocity varies periodically up and down, then the maximum gives the orbital velocity and the time between the maxima is the orbital period.

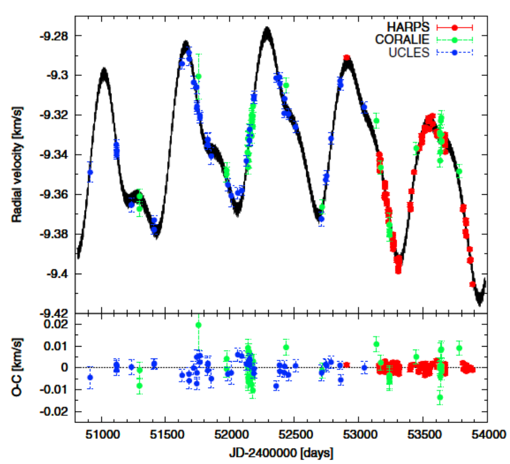
Demonstration

Advantages of RV planet detection

From Doppler velocity observed over an orbital period, get planet mass and orbit shape and radius

No need for high image contrast or resolved 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)

Disadvantages of RV planet detection

Since it does not involve detecting light from the planet, we cannot learn about the planet's surface, atmosphere, density, etc. from RV

We do not know the orbit inclination *a priori*, so the "mass" that we measure 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 $\sin i < 0.1$ is only 0.5%.

Question

Which of the following planetary properties can be determined from radial velocity detection?

A. Radius
B. Mass (or $M \sin i$)
C. Orbital period
D. Orbital radius
E. Inclination of the orbital plane
F. Shape of orbit

Natural planetary-mass units

Object	Mass [$M_\odot$]	Mass [M_J]	Mass [$M_\oplus$]
Sun	1	1048	332900
Typical disk	0.1	105	33290
Jupiter	0.00095	1	318
Earth	0.000003	0.0031	1

$$1M_\odot = 1.989\times10^{33}\text{g}$$

$$1M_J = 1.899\times10^{33}\text{g}$$

$$1M_\oplus = 5.974\times10^{27}\text{g}$$

Transit detection of exoplanets

This involves detecting the decrease in total brightness when the planet passes in front of a star (**transit**) or vice versa (**eclipse**), and it is also not easy.

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 top of its clouds, 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 top of its clouds.

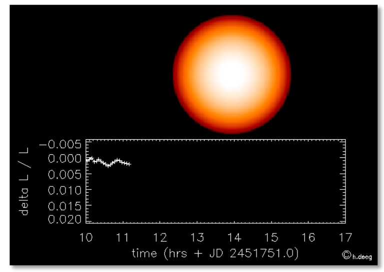
The orbit must be viewed close to edge-on to see a transit. Less than 2% of a randomly-oriented population is oriented this close to head-on.

Measuring the planet's size from a transit

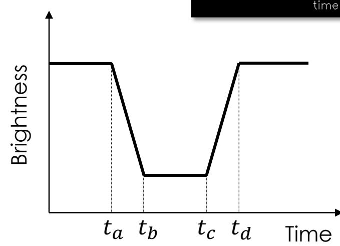
From a transit, we get a piece of information not found in the other methods: the size of the planet.

The duration of the transit enables a measurement of the diameter of the star and/or the precise orbit inclination.

The depth of the flux "dip" and the time it takes the planet to turn off or on offers a measurement of the diameter of the planet.



Deeg & Garrido (2000)

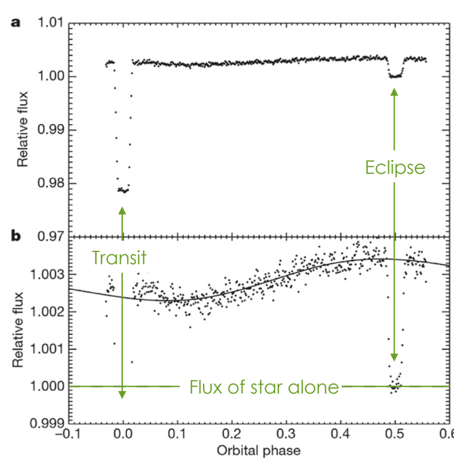


Probing a planet's flux from its transit

At mid-infrared wavelengths, the difference between transit, eclipse, and points in between enable us to isolate the flux from a hot planet and to "map" the emission from the planet's surface.

Example: HD 189733b is brightest near, but not exactly at, eclipse

This is the planet's blackbody emission at mid-infrared wavelengths.



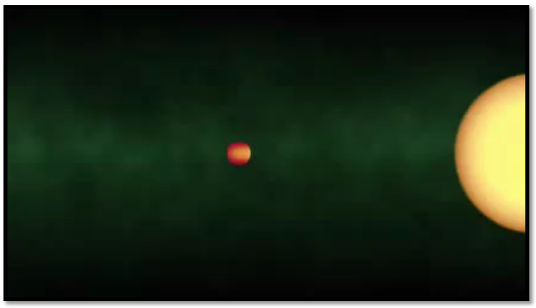
HD 189733 at λ = 8 μm
(Knutson et al. 2007)

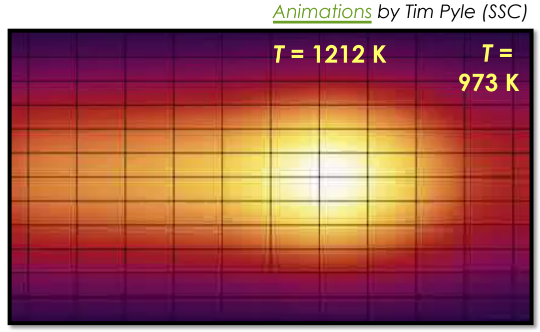
Measuring a planet's temperature from a transit

The temperature over the planet's surface can be worked out from the planet's brightness through the orbit.

Example: in HD 189733b, the warmest spot is offset from "noon" in the direction of the planet's rotation.

Animations by Tim Pyle (SSC)





Transit detection of exoplanets

Advantages

Gives radius of planet and star, which are very difficult to get otherwise.

- In fact, *Kepler* measurements of stellar radii has had a profound effect on the physics of stars, as they tend to be very slightly larger than expected.

While not easy, it is at least easier than the other two methods and can be carried out with small telescopes.

Disadvantages

Only a small fraction of exoplanets transit: the ones viewed close to edge-on

- We do not think that there is anything systematically different about these compared to the others.

Which of the following planetary properties can be determined from transit detection?

Question

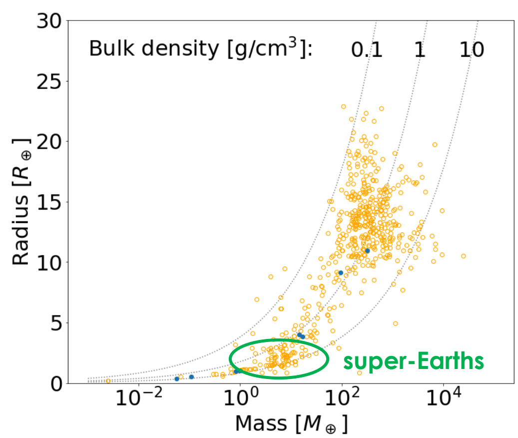
A. Radius
B. Mass (or $M \sin i$)
C. Orbital period
D. Orbital radius
E. Inclination of the orbital plane
F. Shape of orbit

The engines of exoplanet discovery: measuring exoplanet masses and sizes

Note that if an exoplanet has RV and transit observations, then we know its mass (not just $M \sin i$) and its radius.

And therefore we also know its bulk density: mass divided by volume.

Its bulk density can be used to tell rocky planets like Earth from gas-giant planets like Jupiter and Saturn.



Based on Fig. 11 of Fortney & Nettelmann (2010)

Observing transits with *Kepler* and *TESS*

The common way to proceed is to seek both RV and transits.

First do transits, which is what *Kepler*/K2, and *TESS* are designed to do.

Kepler is succeeded in its transit work by the NASA Transiting Exoplanet Survey Satellite (TESS), which launched in April 2018. At the end of its 2-year mission, it will have imaged 85% of the sky (400x that observed by Kepler), and is expected to find more than 20,000 exoplanets.

TESS (MIT/GSFC/NASA)

Today's exoplanets

Today, there are 4112 objects listed as exoplanets.

These planets live in 3059 planetary systems: there are 669 multiple-planet RV or RV+T systems so far.

- 447 have two; 142 have three, 56 have four, 17 have five, 7 have six, 1 has seven, and 1 has eight. Seen so far, that is.
- With eight confirmed planets, the most populous system so far is Kepler-90.

Smallest planets found around normal stars.

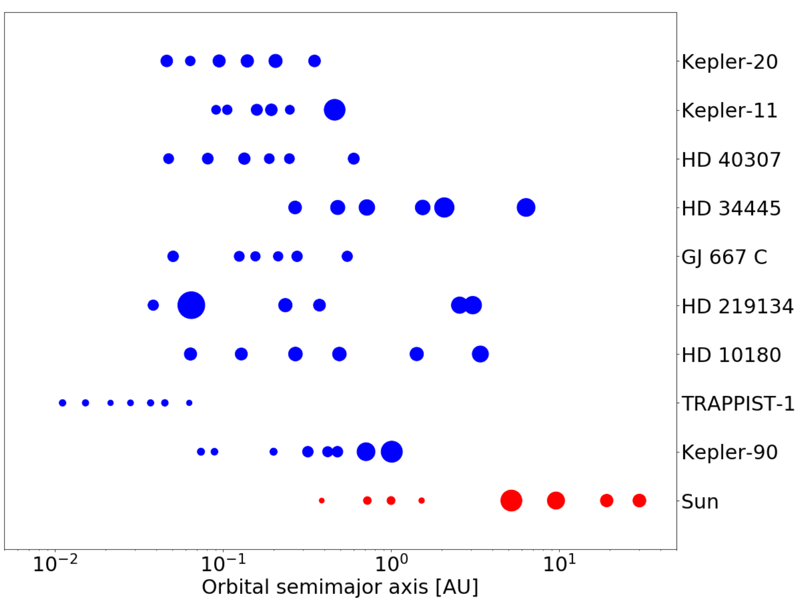
- Kepler-37 b: $M = 2.78M_{\oplus}$, $R = 0.32R_{\oplus}$ (smallest radius)
- Kepler-1520 b: $M = 0.0200M_{\oplus}$, $R = 0.832R_{\oplus}$ (smallest mass)

Today's exoplanets – multi-star systems

34 planets have been found in multiple-star systems, starting with Kepler-16AB in 2011.

These planets orbit the center of mass of the pair of stars at a distance much greater than the separation of the stars. They are called Tatooines, after the planet on which Luke Skywalker grew up in *Star Wars*.

NASA's new travel-agency sideline features trips to exotic destinations.



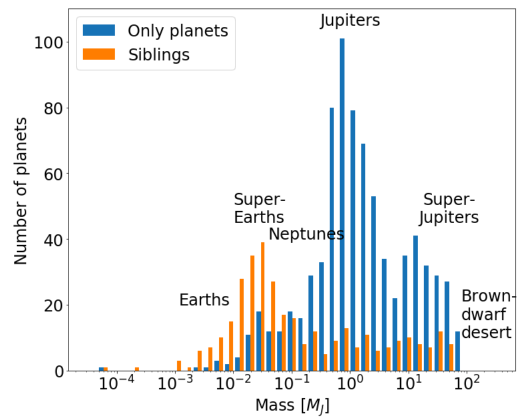
Typical multi-planet systems

Exoplanet masses

Numbers of Jupiters and Super-Jupiters in < few AU orbits are accurately represented, as is the **brown-dwarf desert**: the absence of "planets" with $m > 30M_J$.

The gap around $0.1M_J$ is also real (Mayor et al. 2012).

The smaller population of Neptunes and Earths, though, is a bias: planets this small are still much more difficult to detect than Jupiters.



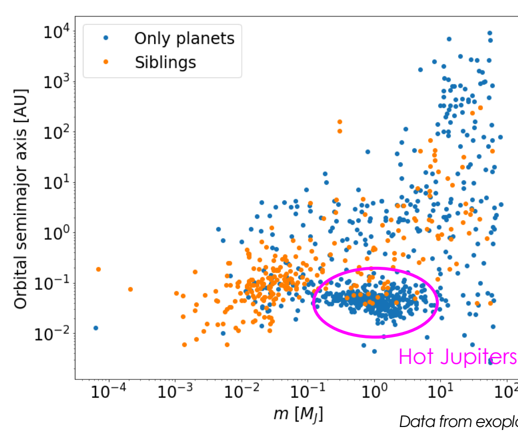
Data from exoplanet.au

Exoplanet orbit sizes

There is a sharp peak in the distribution of orbit radii for Jupiter-like masses around 0.06 AU.

These are the **hot Jupiters**. They do not comprise a large fraction of planets, but they are the easiest to detect.

There was not enough material in their locations in their protoplanetary disks for such massive planets to have formed where they are seen; they must have **migrated** from elsewhere in the disk.



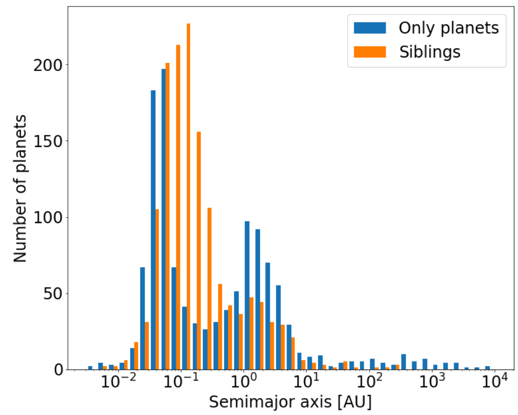
Data from exoplanet.au

Exoplanet orbit sizes

Orbit sizes are dominated by two peaks just past 0.1 AU and 1 AU.

The decline at 6 AU is, again, a bias against long-orbital periods: we have not watched such planets move far through their orbits.

It is widely suggested that the 1 AU rise reflects an onset of increased planet formation efficiency, as the snow line is usually around there.

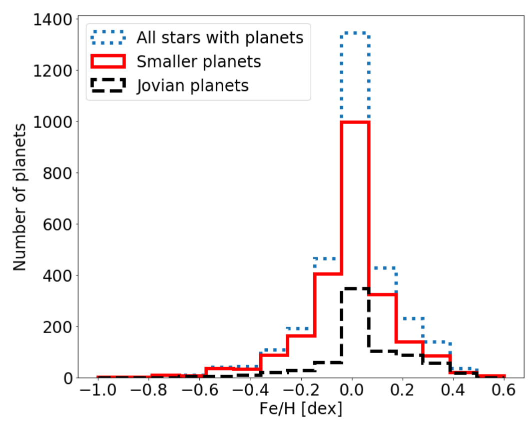


Data from exoplanet.au. Includes many planets not appearing in the previous graphs, for which Kepler has measured orbit sizes but for which there are not yet RV observations.

Composition of exo-solar systems

We are only starting to be able to measure planet composition, but we can measure heavy element abundances in their host stars, and the result is interesting:

- Jupiter-size exoplanets have a tendency to occur around stars richer in heavy elements than usual.
- There is less of a tendency for Neptunes and super-Earths to be associated with heavy-element-enriched stars.



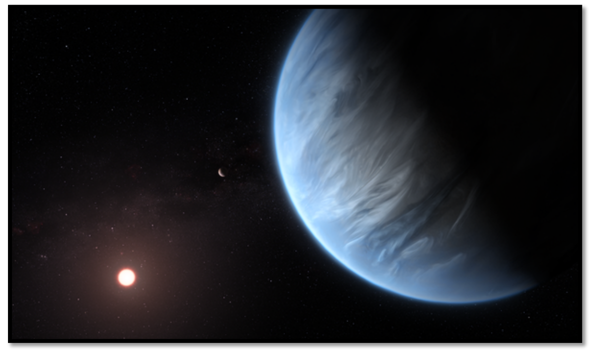
Iron-abundance census (based on Fig. 16 in Mayor et al. 2012)

Composition of exoplanet atmospheres

The light from a star as it passes through an exoplanet's atmosphere allows us to measure different elements and molecules present in the exoplanet's atmosphere.

Recently, water (H_2O) molecules have been identified in the atmosphere of K2-18b, an exoplanet about twice the size of Earth, nine times as massive, and has a 33-day year.

- It is in the habitable zone of its star!



Artist's impression of K2-18b orbiting its red dwarf star (ESA/Hubble, M. Kornmesser)

Back to 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 $0.6 - 1.5M_{\odot}$

- About 0.9% host a hot Jupiter
- 14% ±2% host a gas-giant planet with $P < 10$ years
- 75% ±2% host a planet of any currently-detectable mass with $P < 10$ years

And we are not even good at detecting Earthlike planets, so it seems clear that **f_p is very close to 1**.