26 September
2019

PLANET FORMATION, EXOPLANETS, & HABITABILITY

Homework #3 on WeBWorK due Monday at 7pm
Exam #1 on Tuesday in class

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)

Endor, seen (in Star Wars VI) from its Forest Moon (Wookiepedia)

Habitability

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

Exoplanet properties

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

Evolution of orbits within planetary systems

Tidal heating, tidal locking, and temperature of tidally-locked planets

Liquid water and the Habitable Zone

Earthlike planets and the Drake equation's n_e

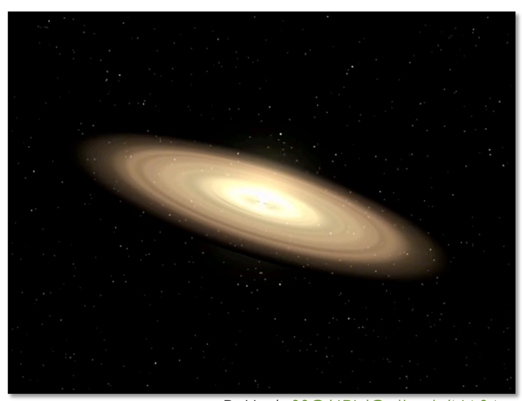
Habitability of tidally-heated moons

Transitional disks

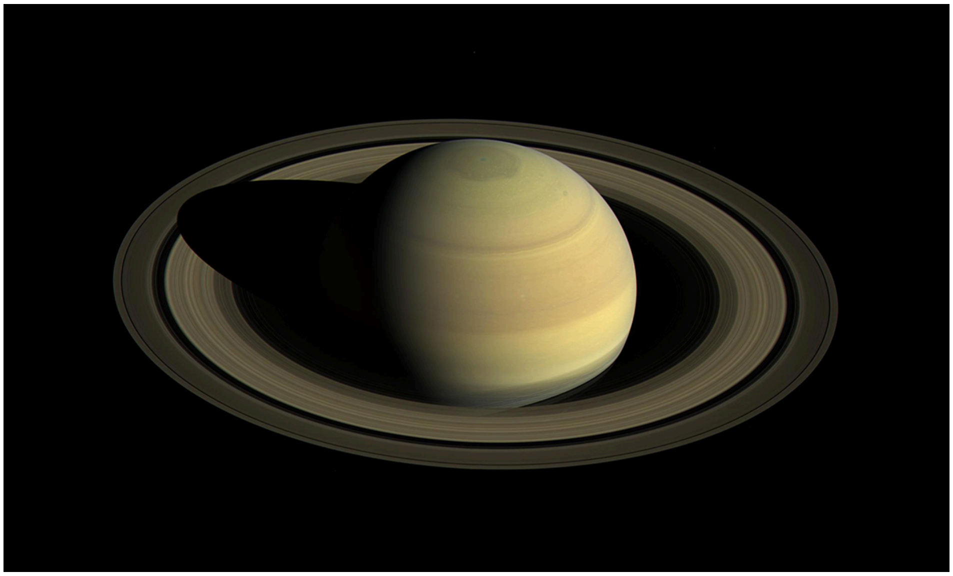
There are easier ways to detect planets recently formed within disks than to see the planet in an image: look for the planet's "wake."

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.

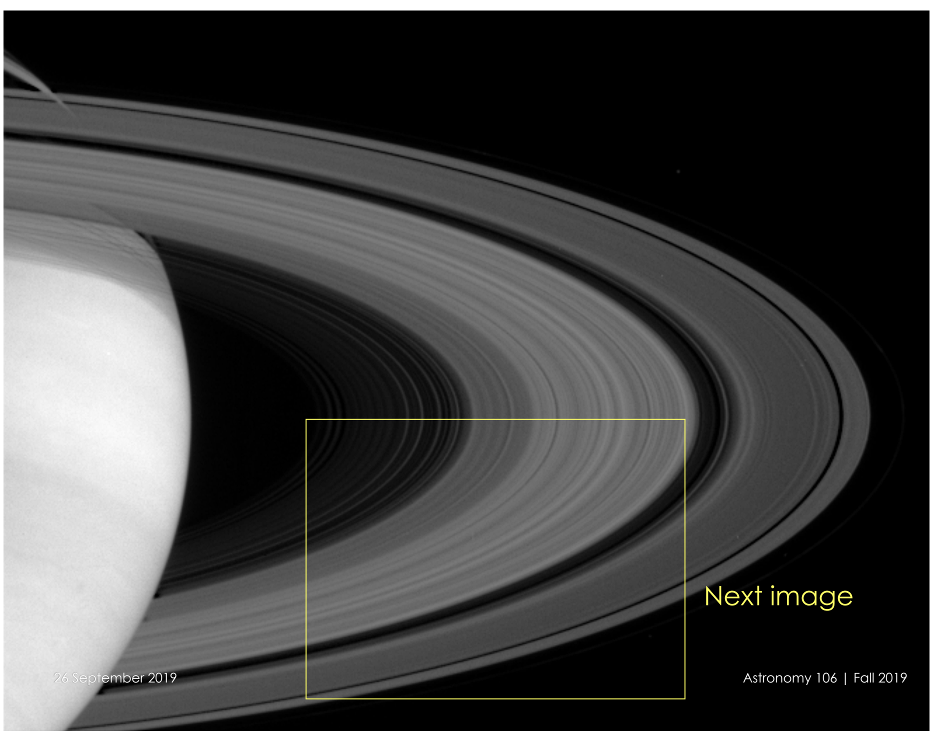


R. Hurt, SSC/JPL/Caltech/NASA



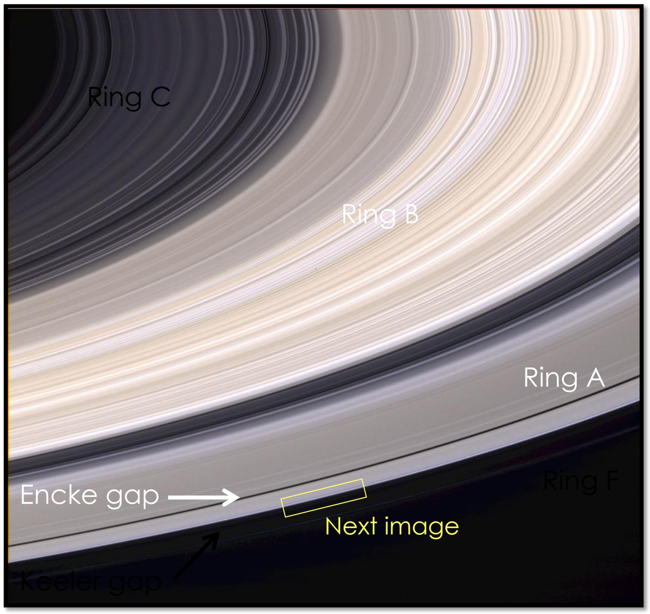
Saturn's rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)



Saturn's rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)



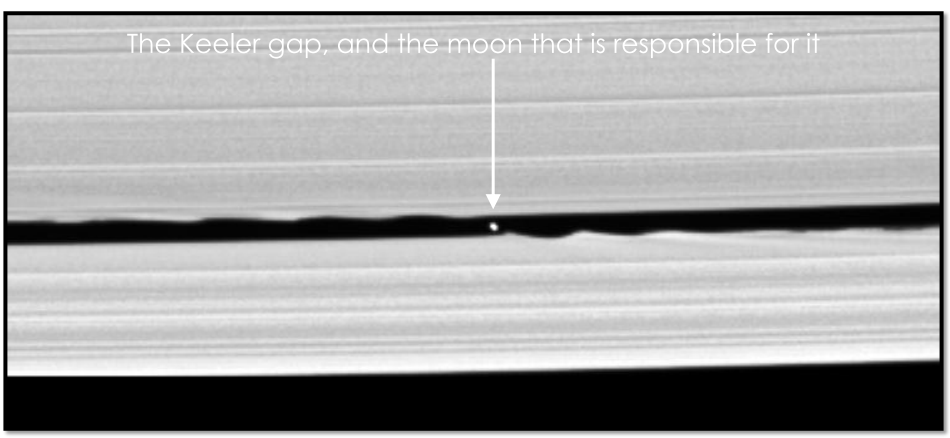
Saturn's rings: gaps and moonlets

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

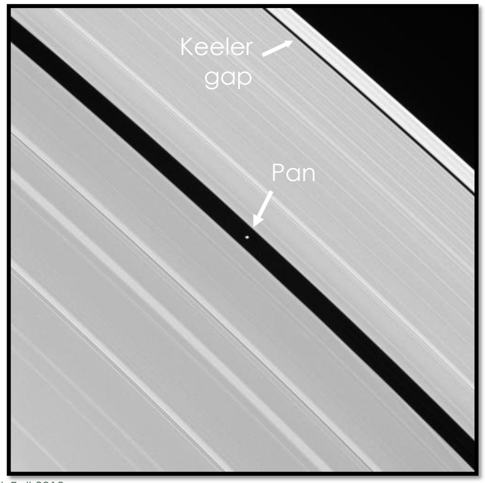
Image from the Cassini satellite (NASA/JPL)



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 both in images and 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)

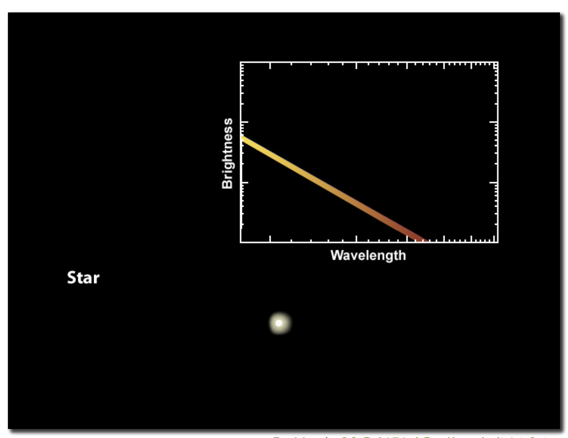
Transitional disks

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.



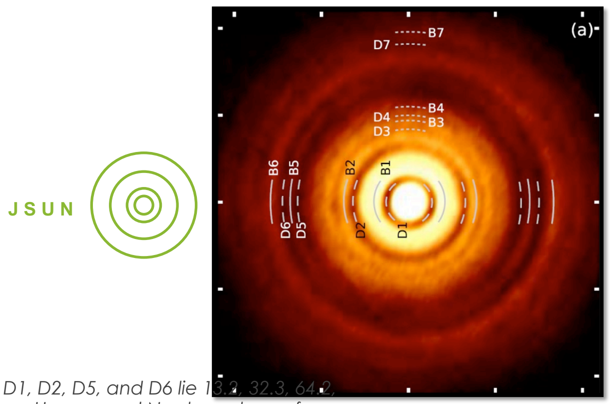
R. Hurt, SSC/JPL/Caltech/NASA

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**.

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

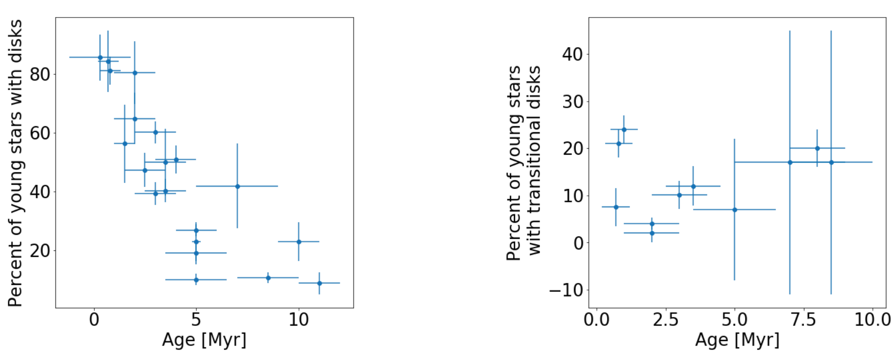
HL Tau is young enough that it is still embedded in its natural envelope, through which the disk is seen.



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.

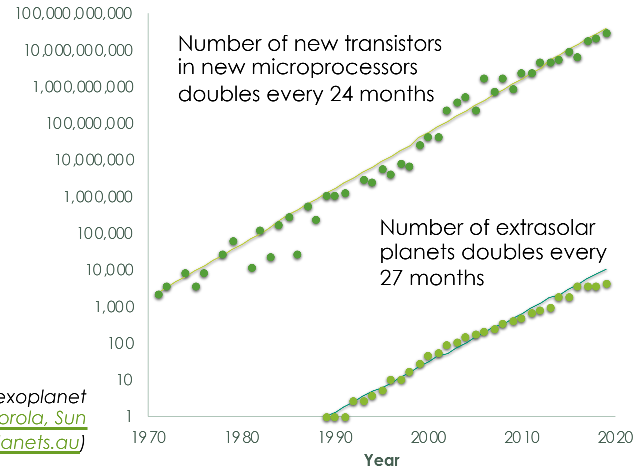
Kepler before launch (Ball Aerospace/NASA)

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



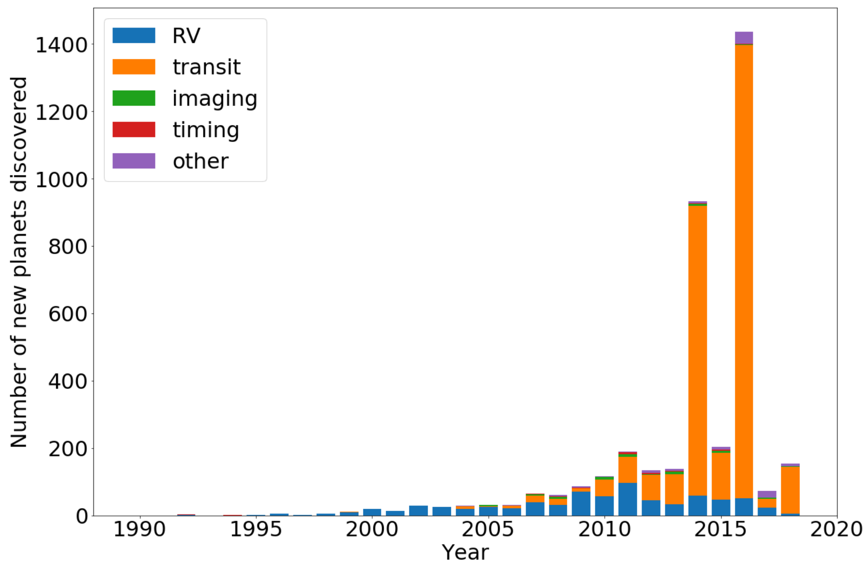
Exponential progress: Moore's law compared to exoplanet discovery. (Data from Intel, AMD, IBM, Zilog, Motorola, Sun Microsystems, Kepler, and exoplanets.au)

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:

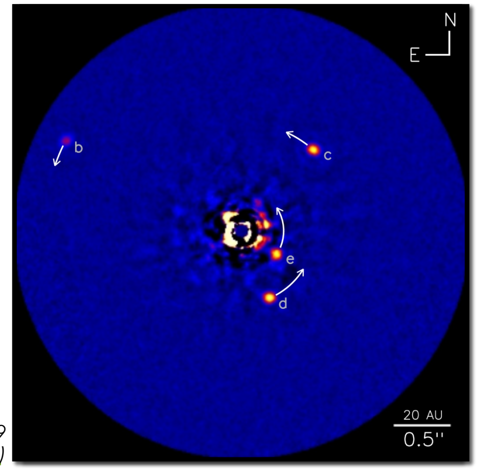
- 0.07 arcseconds on Hubble Space Telescope
- 0.04 arcseconds on Keck 10m telescopes with adaptive-optical (AO) atmospheric-blur correction
- > 0.5 arcseconds on telescopes on Earth without AO

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:

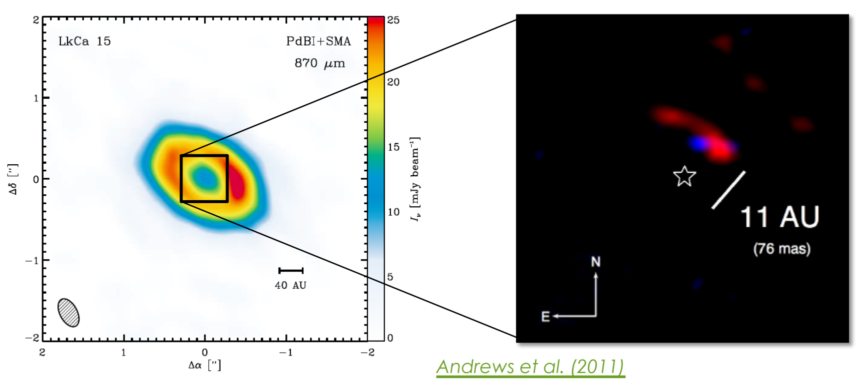
- The nearby star HR 8799, 129 ly away, has at least four giant planets in orbit in the gap between two asteroid belts.
- All 5-10 times Jupiter's size
- Apart from size, a striking resemblance to our four giant planets lying between two asteroid belts.



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.

Question

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

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.

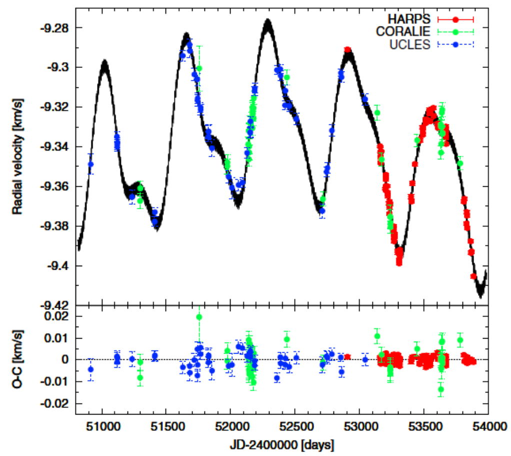
Demonstration

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%.

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

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

$$1M_\odot = 1.989\times10^{33}\,\mathrm{g}$$
$$1M_J = 1.899\times10^{33}\,\mathrm{g}$$
$$1M_\oplus = 5.974\times10^{27}\,\mathrm{g}$$

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.

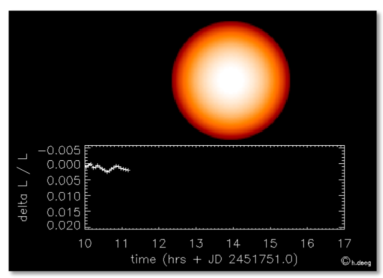
The orbit must be viewed close to edge-on to see a transit. Less than 2% of a randomly-oriented population is oriented this close to head-on.

Measuring the planet's size from a transit

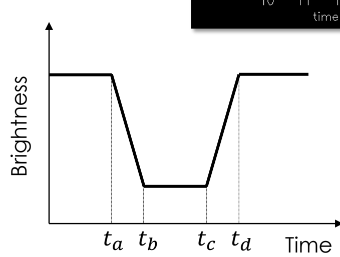
From a transit, we get a piece of information not found in the other methods: the size of the planet.

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)

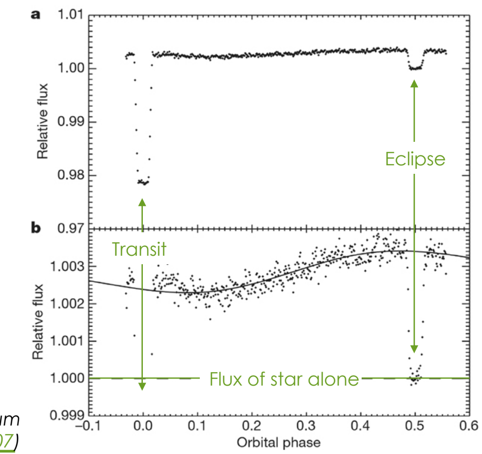


Probing a planet's flux from its transit

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.



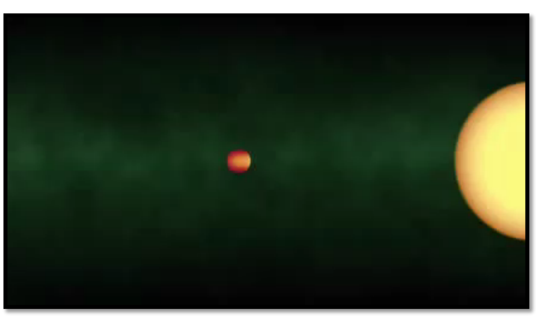
HD 189733 at λ = 8 μm (Knutson et al. 2007)

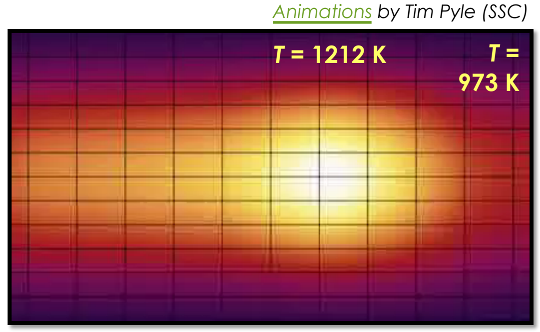
Measuring a planet's temperature from a transit

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.

Question

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

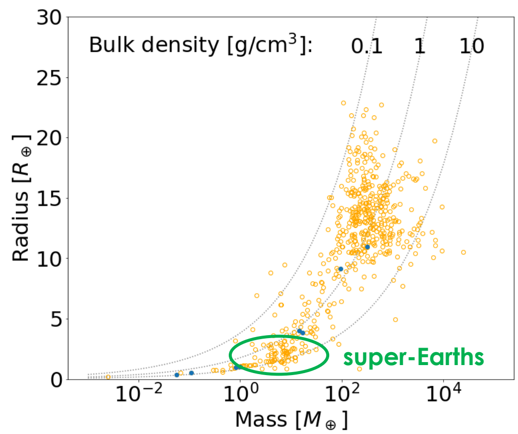
A. Radius
B. Mass (or $M \sin i$)
C. Orbital period
D. Orbital radius
E. Inclination of the orbital plane
F. Shape of orbit

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

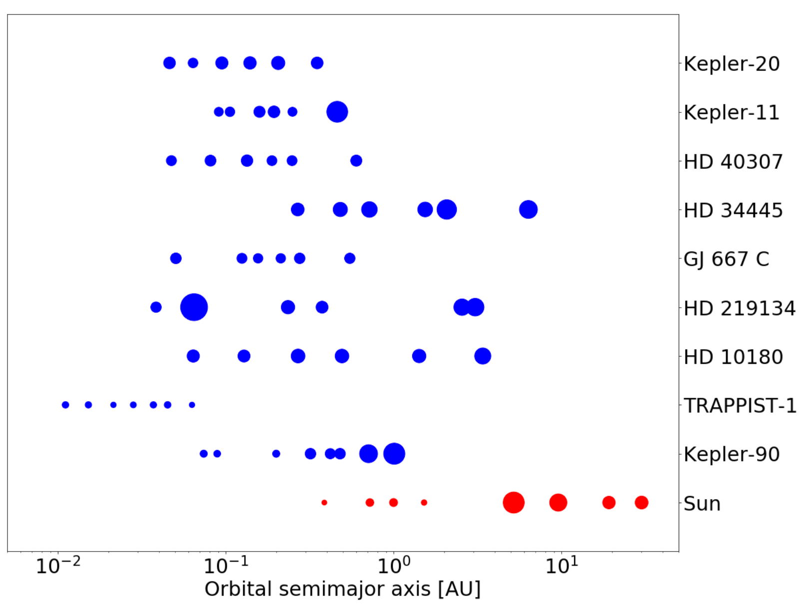
Today, there are 4112 objects listed as exoplanets.

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)



Typical multi-planet systems

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*.

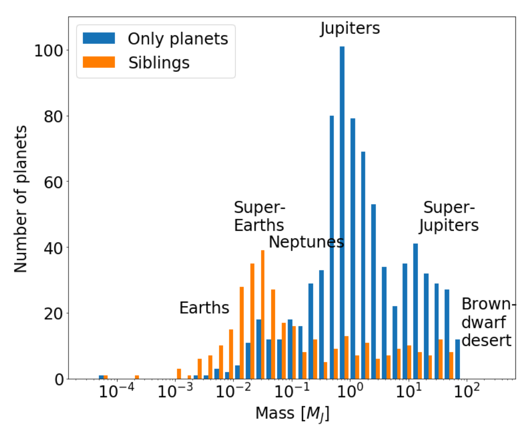
NASA's new travel-agency sideline features trips to exotic destinations.

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.



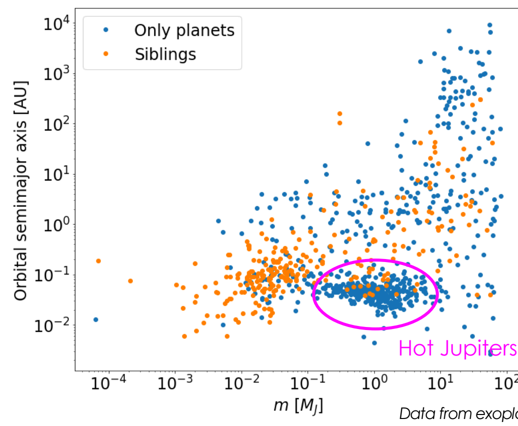
Data from exoplanet.au

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.



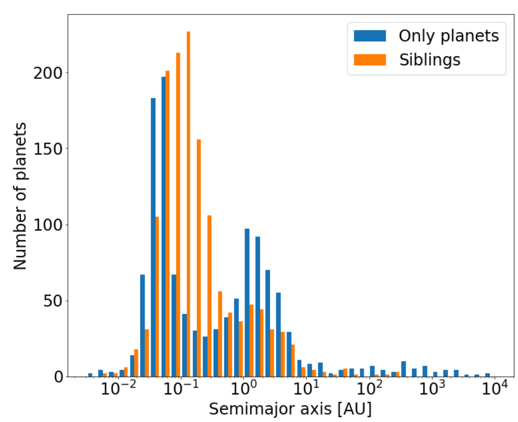
Data from exoplanet.au

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.

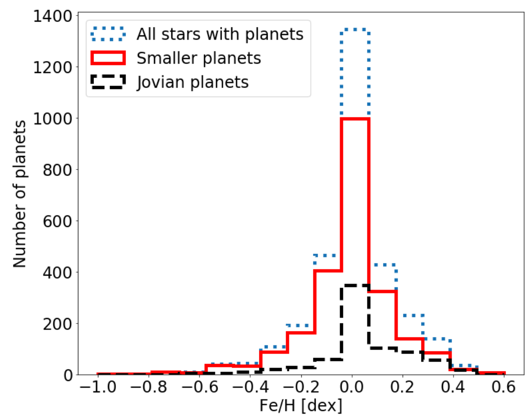


Data from exoplanet.au. Includes many planets not appearing in the previous graphs, for which Kepler has measured orbit sizes but for which there are not yet RV observations.

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.



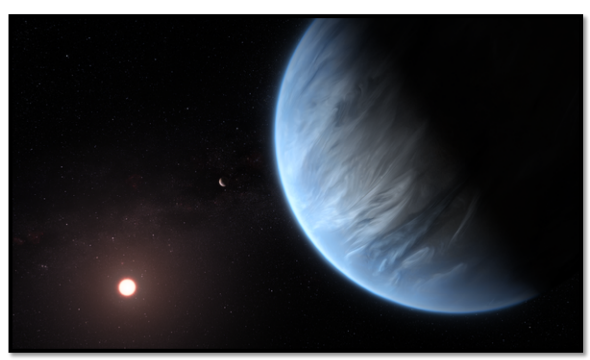
Iron-abundance census (based on Fig. 16 in Mayor et al. 2012)

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 (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**.

Planets move around each other

After planets form, they begin (with the gravitational forces they exert) to perturb the orbits and rotation of smaller Solar System bodies and each other. This results in

- Orbital **migration**: the large-scale changing of planetary orbits
- Capture into, or ejection from, **resonant orbits**
- Systematic **ejection** of small planetesimals, sometimes *en masse*
- **Tidal locking**: the slowing of rotation of a body due to tidal forces by another orbiting body

These effects influence the habitability of given planets and the existence of habitable planets in a planetary system.

Planets are constantly under the influence of the gravity of each other as well as that of the central star.

Gravitational influence on orbits

These effects are largest when they are closest together in their orbits because the gravitational force is steeply dependent upon distance.

You can think of each body suffering an impulsive "tug"– technical term **perturbation** – at closest approach.

If the closest approach happens in the same place in each orbit – a situation in which the orbits are called **resonant** – the perturbations can build up over time to large differences instead of averaging out.

If the orbital periods of two bodies have a ratio very close to the ratio of integers (whole numbers), they are resonant.

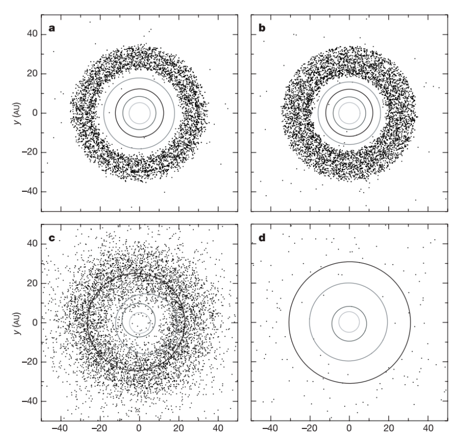
Planets, especially giant ones, can force each other to drastically change orbits.

Orbital readjustments

This can have huge effects on smaller bodies. If a giant planet migrates by a substantial amount, small bodies in between are subject to ejection or consumption.

Example: the early history of our Solar System according to the Nice Model

Main events: perturbation of Jupiter and Saturn by each other migrate these planets outward, eventually resonantly perturbing Neptune and Uranus, swapping their orbits and ejecting 99% of the smaller bodies.



Rotation-rate changes and tidal locking

Though planets (or moons) are many diameters away from their stars (or planets), their diameters are not negligible.

- As a planet and star orbit each other, they tug on each other's near side significantly harder than the far side.
- This results in the left and right sides getting pulled closer together.
- These force differences are known as **tides**.
- When two bodies pass each other, they stretch and compress in response to tidal forces, and relax back to their previous shapes after the perturbation is over.

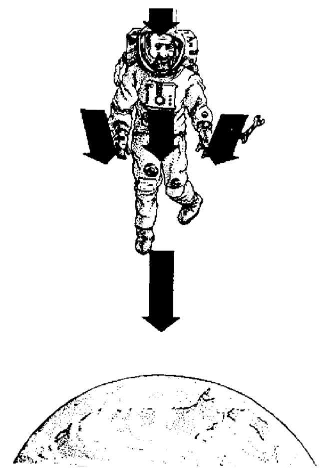
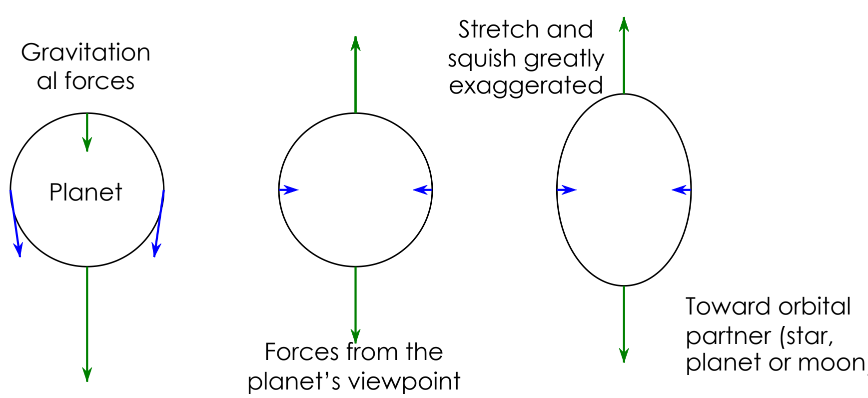


Figure from Thorne, Black Holes and Time Warps

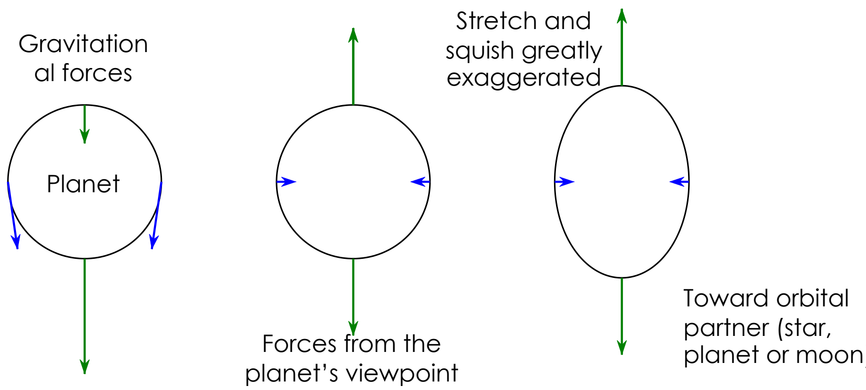
Tidal forces and tidal stretching

The force of gravity decreases with distance, and a spherical mass exerts the force as if all of its mass lies at its center.



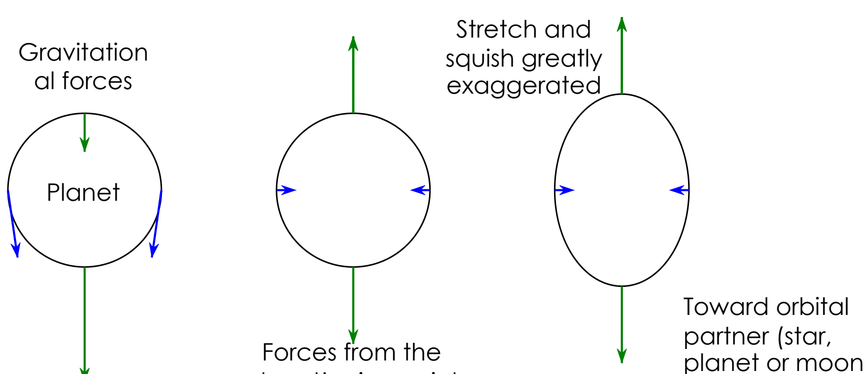
Tidal forces and tidal stretching

The planet is **stretched in the direction toward the other body, as the near side gets tugged harder than the far side**.



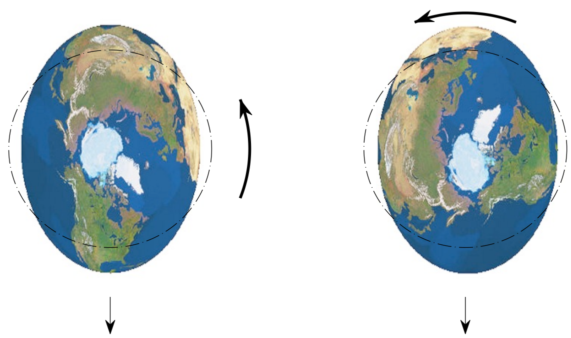
Tidal forces and tidal stretching

And is **squished in the perpendicular direction by the convergence of the forces at the other body's center**.



Tidal forces and tidal stretching

The **stretch and squish stay fixed in the direction toward the other body**, so if the planet rotates faster than it revolves, every point on the surface will be pushed up multiple times a day from the stretch, and down multiple times a day from the squish.



Stretch and squish greatly exaggerated

Tidal locking

It takes work to stretch/compress the planet, and not all the energy springs back when the forces decrease.

- Friction and viscosity within the planet dissipate some of the energy as heat, which is then radiated away (via blackbody radiation).

Because the tidal heating depends upon the state of rotation of the body as well as its orbit, radiation of the tidal heat drains the rotational and orbital energy.

The planet (or moon) rotates more slowly and **drifts to a larger orbital distance**.

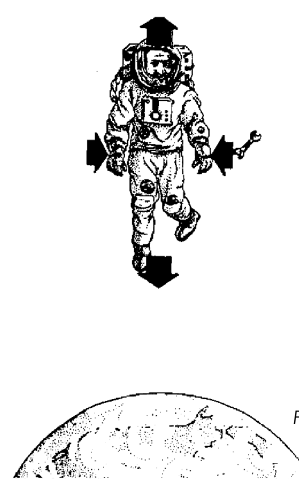


Figure from Thorne, Black Holes and Time Warps

Tidal locking

Eventually (in 1-100 Myr), this results in a special relation (such as equality) between the orbital and rotation period, corresponding to the minimum of tidal heating. This is called tidal **locking**.

Tidal locking happens in both star-planet and planet-moon systems.

- The Moon is tidally locked: it rotates once per revolution.
- Pluto and its largest moon Charon are mutually tidally locked: each rotates once every 6.4-day revolution.
- All the large moons of Jupiter and Saturn are tidally locked.
- **Planets in orbits very close to their stars will tend to be tidally locked.** (Mercury, for example.)
- This changes their heating situations.

Temperatures for fast and slow rotators

Implications for the temperature of a revolving body that is mainly heated by starlight:

- If a body rotates faster than it can cool off, its surface will have a fairly uniform temperature, given by the formula for dust grains. This is the case for the Earth and Mars, for example.
- If not, it will have hot and cold sides.
  - If it is tidally locked in circular orbit around its star, it will have **permanently** hot and cold sides.

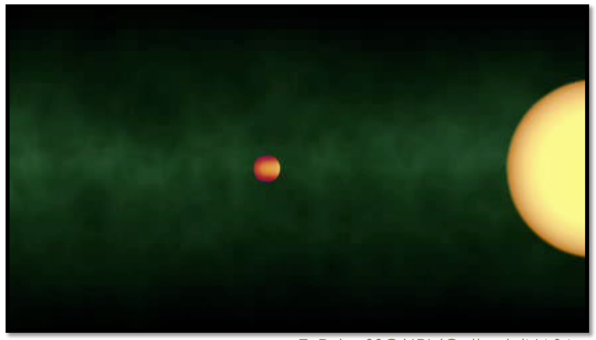
Temperature of slow rotators

For a slow rotator, the maximum temperature, which is generally reached at the substellar ("noon") point, is

$$T = \left(\frac{(1-A)L}{4\pi\sigma r^2}\right)^{\frac{1}{4}} = 394\ \mathrm{K}\times\left(\frac{(1-A)L[L_\odot]}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}$$

You need to understand how to use this formula.

Fortunately, it is the same as the last one, just with 394 K replacing 279 K.



T. Pyle, SSC/JPL/Caltech/NASA

The habitable zone

Since the interstellar medium already provides infant solar systems with the basic, and some processed, ingredients for life, the next basic requirement for habitability is for the ingredients to have the correct temperature.

What is the correct temperature? Clues from Earth:

- Simple organisms are not killed by prolonged exposure to temperatures *slightly* below the freezing point of water, or *slightly* above the boiling point. (These beasts are called **extremophiles**.)
- Complex organisms are most abundantly found in habitats between freezing and boiling.

Earth suggests that **liquid water** promotes habitability by organic chemical/water based life.

Is this geocentrism, to presume that life requires water?

Does life require water?

As we will discuss after the first exam, **chemistry in liquids is by far the fastest way for life to evolve**.

Usually, this means having a solvent: a liquid for other molecules to dissolve in, that can facilitate their reactions.

Water is by far the most abundant solvent molecule in protoplanetary disks, and it is a great solvent chemically.

The temperature range within which water is liquid overlaps that of many other solvent candidates like methanol and ammonia.

While it is possible that life requires water, we do need to be wary of this Earth-centric bias.

Habitability

The most common definition of habitability in a planetary system is that water exists permanently in liquid form on a suitable planet.

- That is, $T = 273 - 373$ K under normal pressure conditions on Earth, and this range is often used.
- The water need not be exposed on the surface; if it is, the planet better have an atmosphere.

Such planets are found this far from their stars:

$$r[AU] = \left(\frac{T_0}{T}\right)^2 \sqrt{(1-A)L[L_\odot]}$$

Where $T_0 = 279$ K for fast rotators and 394 K for slow ones, and T runs from 273 to 373 K if the planets are just "large dust grains."

Question

By this token, the habitable zone for Earthlike planets ($A = 0.37$) in the Solar System lies between 0.44 and 0.82 AU from the Sun. Which planets lie in the Solar System's habitable zone?

(Feel free to use the internet to look up distances!)

The greenhouse effect

Planets are not large dust grains: they have atmospheres.

Recall that the reasoning above gives only $T = 294$ K for the Earth. This is the temperature of the cloud tops; it is (definitely) warmer down below. Why?

Because the atmosphere is transparent at shorter wavelengths (visible, ultraviolet,…) at which stars emit much of their light.

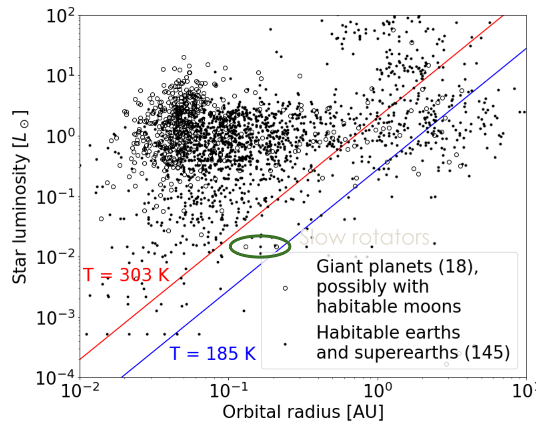
- This light directly heats the planet's surface.
- The extra energy cannot escape quickly. It is trapped: the surface radiates at the same infrared wavelengths at which the atmosphere is opaque.
- Therefore, the surface is warmer than the cloud tops.

This is called the **greenhouse effect**. We will go into more detail about it at the end of the semester.

The habitable zone (w/ greenhouse)

A simple estimate of the magnitude of the greenhouse effect, popularized by the *Kepler* team, is to use $A = 0.3$ and to take the temperature bounds to be **$T =$ 185 K and 303 K**, which in typical atmosphere models would correspond to surface temperatures of 273 K and 373 K.

- By this token, at least 145 of our current known Earth-sized planets (less than twice the size of Earth) lie in the habitable zone.
- There are giant planets which also exist in the habitable zone. Any moons with atmospheres around these giant planets would be habitable.



Data: exoplanet.eu

The Drake equation: n_e

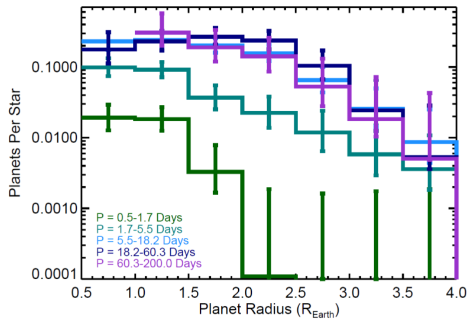
This is what the NASA *Kepler* mission was designed to measure, and it has succeeded.

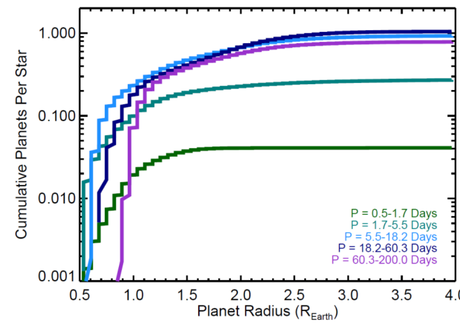
Originally, the n_e factor was supposed to count Earth-like planets, meaning habitable ones. Now, with such unexpected things as super-Earths, abundant tidally-locked planets, and the trickiness of the greenhouse effect, there is more context required around the numbers.

- Around Sun-like stars, there appear to be more planets of radius $2 - 2.8R_\oplus$ – super-Earth size – than planets larger or smaller (Silburt et al. 2015).
- Earths and super-Earths are more abundant around low-mass, cool stars ("M") than around Sun-like stars (G-K):
  - G-K: 46% ±3% of stars have E or SE (Silburt et al. 2015)
  - M: 56% ±6% of stars have E, 46% ±7% have SE (Dressing & Charbonneau 2015)
- Within the habitable zone as modeled by Kopparapu et al. (2013), the fraction of stars possessing planets is
  - G-K stars: 6% Earths, 17% SE (Silbert et al. 2015)
  - M stars: 16% E, 12% SE (Dressing & Charbonneau 2015)

The Drake equation: n_e

Splitting the difference in percents and ignoring the difference in E/SE, we will adopt $\boxed{n_e = 0.25}$ (25%)





Dressing & Charbonneau (2015)

Question

Ignoring habitable moons of giant planets, about how many stars would we have to visit to find one habitable planet (on average)?

Habitability outside the habitable zone

We chose starlight as the energy source above because it is generally provided at a steady rate for billions of years while other heat sources are not. All but one, anyway:

- Tidal heating of suitably-placed moons and planets can be significant sources of energy for as long as they rotate rapidly and/or do not have circular orbits.
- On the other hand, as the moon or planet radiates the energy away, the rotation slows and the orbit circularizes over time, reducing the tidal heating to zero. But on the other…
- …If something can force a suitably-placed planet or moon to rotate or follow an elliptical orbit permanently, the tidal heating would be permanent.
- And something can: perturbations of moons and planets on each other's orbit can result in orbits being locked into orbital resonance.
- Since there is an attractive impulse at closest approach, and since for resonant orbits this happens in the same spot in the orbit every time, these **resonantly-locked** orbits cannot be precisely circular.
- Thus, tidal heating can be permanent and substantial.

Habitability on tidally-locked bodies

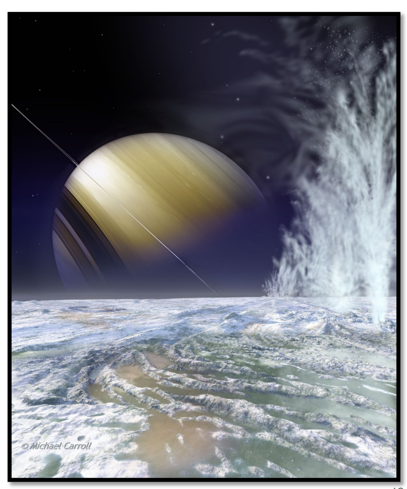
This is the case for the large moons of Jupiter and Saturn, particularly **Io, Europa, and Ganymede** (orbital periods in ratio 1:2:4).

- Permanent liquid water further away from the star than the habitable zone!

We will discuss this further when our talk turns to the search for life elsewhere within the Solar System.

Questions to ponder:

- In what important ways would life be different on such a habitable world outside the habitable zone?
- Do you think that microbial life could develop in such a place? Complex organisms?
- Do you think life could survive in such a place if implanted from elsewhere?



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APOD