Lecciones en Astroinformática Avanzada (Semester 1 2025)

Exoplanets - and how to detect them

Nina Hernitschek
Centro de Astronomía CITEVA
Universidad de Antofagasta

April 29, 2025

The Hunt for Exoplanets

Almost 5800 planet candidates have now been observed around other stars; among them, approx. 3200 count as "confirmed"*.

*source: `http://www.exoplanets.org/`

The Hunt for Exoplanets

How have they been detected?

What do they look like?

What do they tell us?

What does the future hold?

The Hunt for Exoplanets

How have they been detected?

What do they look like?

What do they tell us?

What does the future hold?

The planets we have detected to date are only a **sub-set of potential planets** out there.

Many of the new solar systems don't look at all like our own (example: Jupiter-mass planets within the orbit of our Mercury).

These new solar systems have raised big questions about how our own Solar System formed.

How to define *planet*?

Solid and gaseous bodies have several potential **energy sources**:

- graviational potential energy as they contract: $E_G \sim -GM_p^2/R_p$
- nuclear fusion (hydrogen, deuterium)
- radioactive decay

How to define *planet*?

Solid and gaseous bodies have several potential **energy sources**:

- graviational potential energy as they contract: $E_G \sim -GM_p^2/R_p$
- nuclear fusion (hydrogen, deuterium)
- radioactive decay

A planet is a body whose mass is low enough that it never derived a substantial fraction of its luminosity from (deuterium) fusion.
This gives an **upper mass limit** usually taken as $\sim 10 - 20\ M_{\rm jup}$.

How to define *planet*?

Solid and gaseous bodies have several potential **energy sources**:

- graviational potential energy as they contract: $E_G \sim -GM_p^2/R_p$
- nuclear fusion (hydrogen, deuterium)
- radioactive decay

A planet is a body whose mass is low enough that it never derived a substantial fraction of its luminosity from (deuterium) fusion.
This gives an **upper mass limit** usually taken as $\sim 10 - 20\ M_{\mathrm{jup}}$.

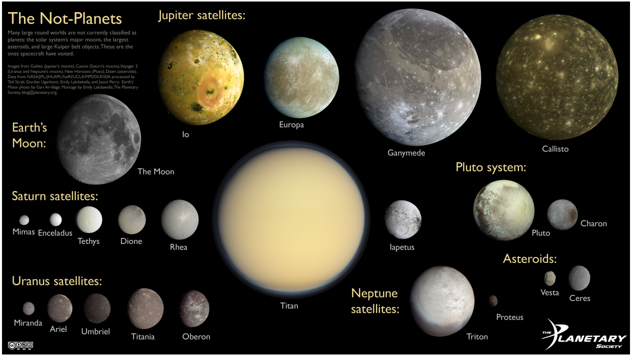
What about the **lower mass limit**?
"Geophysical" limit is a few hundred km, below this size bodies are irregular in shape and are not described as planets.

How to define *planet*?

Exoplanets

For Solar System bodies, the IAU makes a further distinction:

Planets are required to have largely cleared out their orbits of similarly-sized bodies.
Pluto is a **dwarf planet** by this definition. Pluto still has lots of asteroids along its orbit, rather than having absorbed most of them over time, like the larger planets have done.



How to define *planet*?

We usually distinguish:

Star:

- massive enough for nuclear fusion $H \rightarrow He$, $M > 0.1\ \mathrm{M}_\odot$
- Luminosity comes from heating by nuclear fusion.

Brown dwarf:

- mass too small for nuclear fusion, $M < 0.1\ \mathrm{M}_\odot (\sim 80\ M_{\mathrm{jup}})$
- Luminosity from slow contraction, release of gravitational energy.
- Probably form in similar manner as stars.

Planet:

- Upper limit usually taken as $\sim 10 - 20\ M_{\mathrm{jup}}$.
- Lower mass limit less important as of detection limit.
- Most of their luminosity is reflected light from their parent star, plus a smaller amount coming from their own thermal infrared radiation.
- We assume they all form from disks surrounding young stars.

How to define *planet*?

It has become traditional to classify extrasolar planets as what they **resemble most** in our own solar system.

Jupiters (or *gas giants*); Neptunes ($\sim$20 $M_{\rm Earth}$); and (more recently) Super-Earths ($\sim$5 $-$ 10 $M_{\rm Earth}$).

When we refer to extrasolar planets whose masses are similar to Earth, they are called *terrestrial-like* or *Earth-like* or *rocky* planets.

Finding Exoplanets

Why is it so hard to find planets around other stars?

Faint planet glimmer is lost in glare from parent star: Planets are small, close to their parent star, and shine by reflected starlight

Thought experiment:
Consider the case of Jupiter and the Sun:
As seen from the nearest star, Alpha Centauri, Jupiter would appear a billionth as bright as the Sun.
Jupiter would also be extremely close to the Sun, only 4 arcsec away.

Finding Exoplanets

Why is it so hard to find planets around other stars?

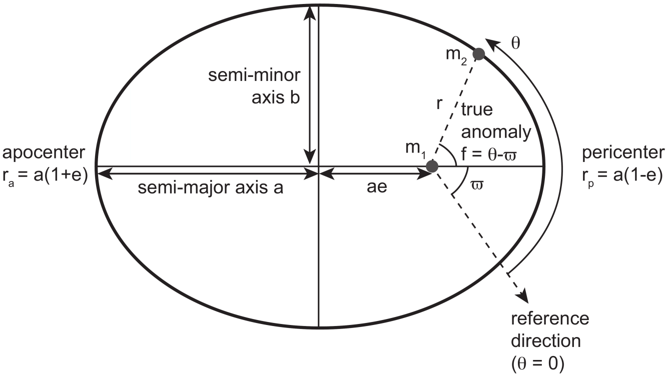
Faint planet glimmer is lost in glare from parent star: Planets are small, close to their parent star, and shine by reflected starlight

Thought experiment:
Consider the case of Jupiter and the Sun:
As seen from the nearest star, Alpha Centauri, Jupiter would appear a billionth as bright as the Sun.
Jupiter would also be extremely close to the Sun, only 4 arcsec away.

Since all other stars are farther than Alpha Centauri, Jupiter would be even harder to detect from other stars.

Finding Exoplanets

For most exoplanets, information is limited to the observables from either radial velocity or transit surveys.

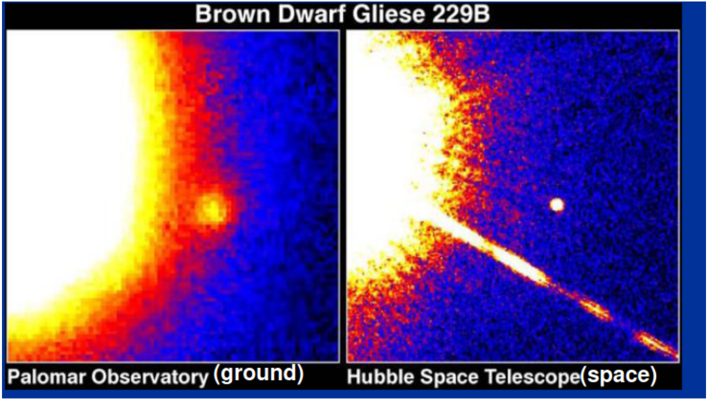


Finding Exoplanets

Planets are very hard to observe directly (by detecting their own light):

Planets shine by reflected light: Planets close to parent stars are brightest, but the light from the star makes them hardest to see.

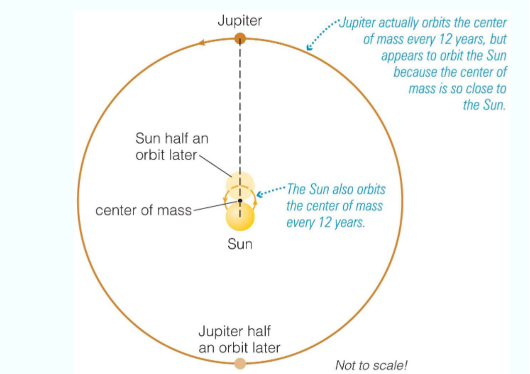
This brown dwarf star is barely visible, despite its star is faint:



Finding Exoplanets

Two objects orbit their center of mass, or **barycenter**. The barycenter is closer to the more massive object (star) than the less massive object (planet). A star is so much more massive than a planet that the barycenter is very close, or even inside, the star.

Example: Jupiter and the Sun



Planet Detection Methods

There are a variety of ways to (try to) detect exoplanets:

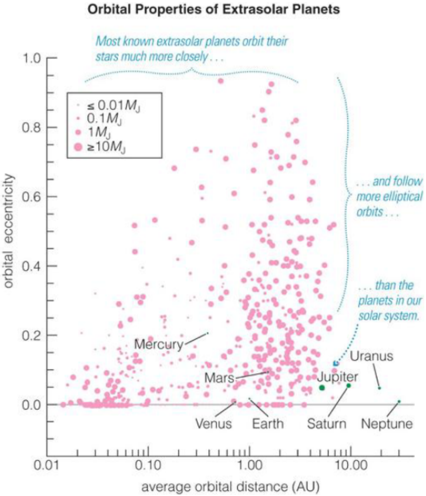
Indirect: measurements of stellar properties revealing the effects of orbiting planets. Stellar radial velocities, motions on the sky, dimming of star when planet passes in front. Most planets to date have been detected by indirect methods.

- Astrometric method (stellar wobble): uses image of star
- Radial velocity (Doppler): uses spectrum of star
- Transit photometry: uses light curve of star
- Gravitational lensing: uses light curve of star
- Pulsar timing: uses another photometric method and timing

Direct: pictures or spectra of the planets themselves
Recently starting to be used very successfully. Needs very large telescopes and interferometry.

Exoplanet Properties

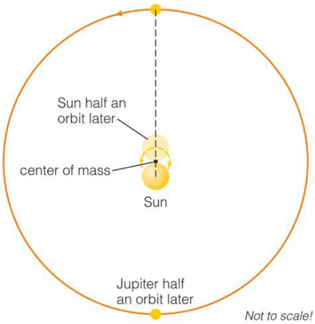
What properties of extrasolar planets can we measure?



Doppler Spectroscopy - The Radial Velocity Method

Principle of Doppler spectrosocopy: gravitational tugs on objects.

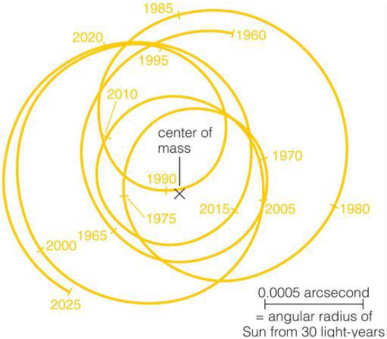
The Sun and Jupiter orbit around their common center of mass. This leads the Sun to wobble around that center of mass with same period as Jupiter.



Doppler Spectroscopy - The Radial Velocity Method

The Sun' s motion around the solar system's center of mass depends on tugs from all the planets.

Astronomers around other stars that measured this motion could determine the masses and orbits of all of our planets.

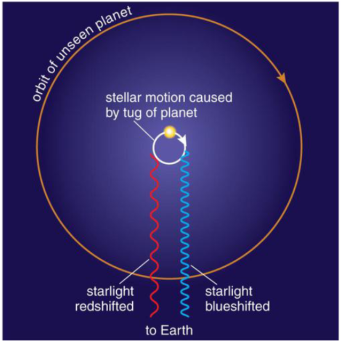


Doppler Spectroscopy - The Radial Velocity Method

We can detect planets by measuring the change in a star's position on sky (astrometry).

However, these tiny motions are very difficult to measure ($\sim$ 0.001 arcsec).

Instead: measure a star's Doppler shift which tells us its motion towards and away from us. Current techniques can measure motions as small as 1-2 m/s.



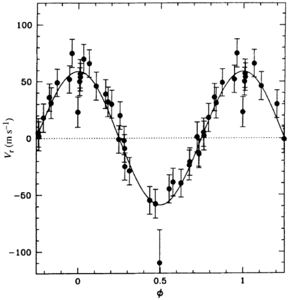
Doppler Spectroscopy - The Radial Velocity Method

First Extrasolar Planet: 51 Pegasi b

Big surprise in 1995: Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.

This was the first extrasolar planet to be discovered.

This short period means that the planet has a small orbital distance, well within orbit of Mercury. The planet has half the mass of Jupiter.



Radial radial velocity curve for 51 Peg b. Black points are data with error bars, and the continuous curve is the best fit to the data.
credit: *A Jupiter-mass companion to a solar-type star*, Michel Mayor & Didier Queloz, Nature volume 378, pages 355-359 (1995)

Doppler Spectroscopy - The Radial Velocity Method

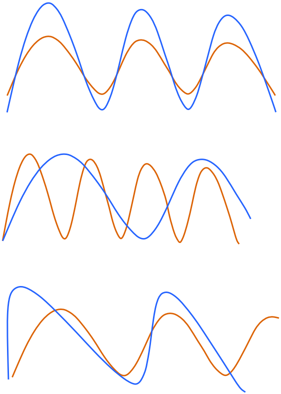
Other Extrasolar Planets found by the Radial Velocity Method, e.g.:

The most massive confirmed exoplanet is Iota Draconis b, which mass is 9.40 $M_{\rm Jupiter}$; the least massive confirmed planet is Gliese 581 e, which mass is 2.51 $M_{\rm Earth}$.

The longest period of any confirmed exoplanet is 55 Cancri d, which takes 5169 days or 14.15 years to make one trip around the star; the shortest period is Gliese 876 d, which takes just 1.938 days or 46.5 hours to orbit the star.

Doppler Spectroscopy - The Radial Velocity Method

Planetary signatures:
Radial velocity curves can tell us about a planet's mass and orbital eccentricity:



amplitude depends on mass of planet
low mass vs. high mass

period depends on orbital period of planet
short mass vs. long period

shape depends on eccentricity of orbit
circular vs. eccentric

Doppler Spectroscopy - The Radial Velocity Method

The Radial Velocity Method does not depend on the distance of the star from us.

However, a massive planet close to the star is necessary:
The closer the planet, the faster the orbital speed (of both planet and star).

Doppler Spectroscopy - The Radial Velocity Method

The Radial Velocity Method does not depend on the distance of the star from us.

However, a massive planet close to the star is necessary:
The closer the planet, the faster the orbital speed (of both planet and star).

A highly resolved spectrum is needed for this to measure Doppler shifts of $< 1\ \mathrm{ppm}$ (one part per million).

$\sim$ 90 % of the exoplanet detections to date are made with this method that once was incredibly hard but now has become standard

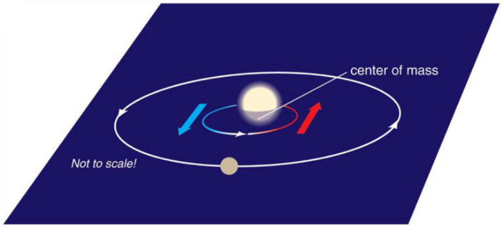
Doppler Spectroscopy - The Radial Velocity Method

As Doppler shift only detects velocity along line of sight, the radial velocity method is not able to give the complete orbital information.

e.g.: It can't distinguish a massive planet (or brown dwarf) in tilted orbit from a less massive planet in edge-on orbit as they both have the same line-of-sight velocity.

Doppler data thus can give us (only) **lower limits on masses**.

The only way to resolve this ambiguity is to observe using another method.



Doppler Spectroscopy - The Radial Velocity Method

Why the radial velocity method was not expected to be successful without several years of observations:

The Sun's motion about the solar system barycenter due to all the planets, and resulting radial velocity curve: Small (hard to measure) effect and should take years.

Doppler Spectroscopy - The Radial Velocity Method

Why the radial velocity method was not expected to be successful without several years of observations:

The Sun's motion about the solar system barycenter due to all the planets, and resulting radial velocity curve: Small (hard to measure) effect and should take years.

?

What was wrong about this assumption?

Doppler Spectroscopy - The Radial Velocity Method

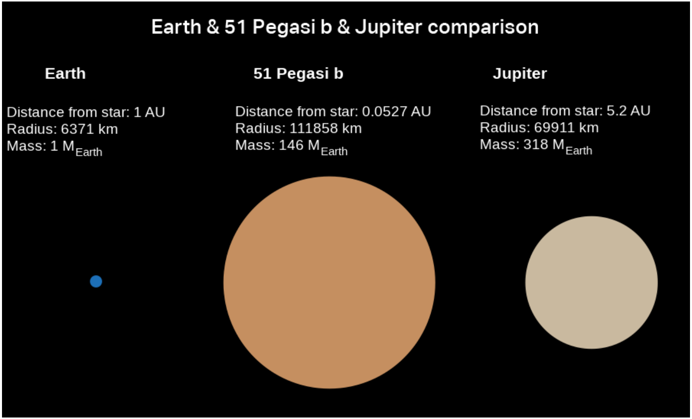
Why the radial velocity method was not expected to be successful without several years of observations:

The Sun's motion about the solar system barycenter due to all the planets, and resulting radial velocity curve: Small (hard to measure) effect and should take years.

? What was wrong about this assumption?

Doppler Spectroscopy - The Radial Velocity Method

Planetary systems don't need to look necessarily like ours!



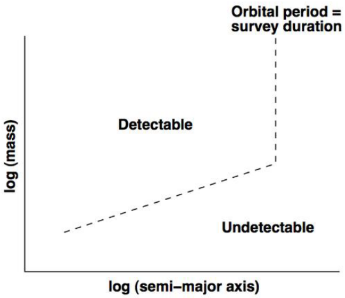
Doppler Spectroscopy - The Radial Velocity Method

Limitations of Doppler technique:

The closer to the star and the more massive the planet, the easier to detect.

Ground-based observatories can detect velocity shifts $> 1 - 2\mathrm{m/sec.}$

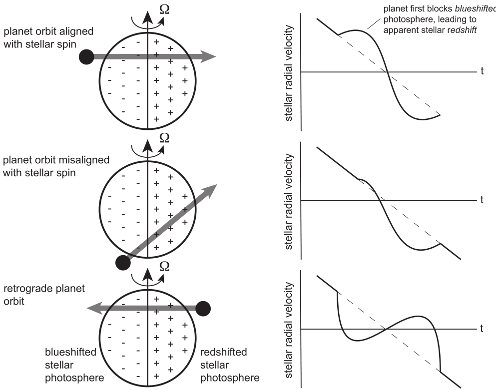
This corresponds to about 33 Earth masses at 1 AU for a solar mass star.



Doppler Spectroscopy - The Radial Velocity Method

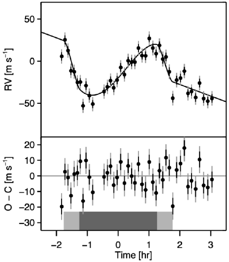
Rossiter-McLaughlin effect

Can measure whether the orbit is inclined relative to the stellar equator if we detect changes in the stellar radial velocity during a planetary transit.

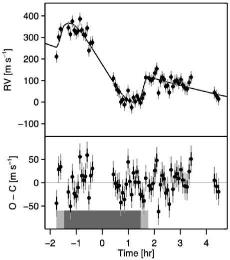


Doppler Spectroscopy - The Radial Velocity Method

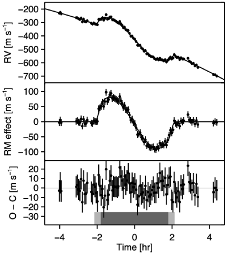
examples from Albrecht et al. (2018):



$(165 \pm 6)^\circ$



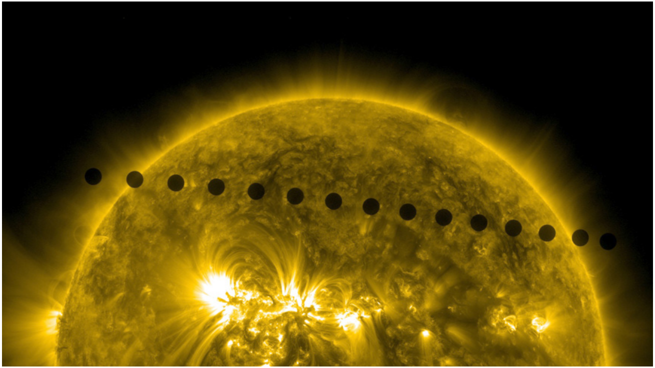
$(12 \pm 9)^\circ$



$(9 \pm 10)^\circ$

Transit Photometry and Spectra

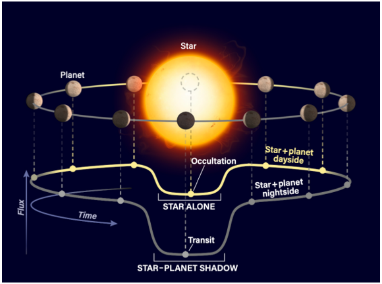
A **transit** is when a planet crosses in front of a star.



NASA's Solar Dynamics Observatory captured this sequence of the 2012 transit of Venus from space. (Image credit: NASA)

Transit Photometry and Spectra

Even when we cannot resolve the stellar disk, we can measure the change in stellar brightness as planet transits disk as seen from Earth.



Requires near-edge-on inclination of orbit. Because stars and planets are oriented randomly in space, not all planets have orbits that carry them in front of their stars from our point of view.
Credit: Astronomy: Roen Kelly

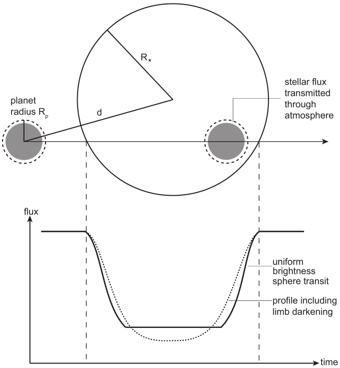
Assuming a circular orbit, where R_* is the stellar radius, R_p the planet's radius, and a the planet's semi-major axis, the probability for a transit is:

$$p_{\mathrm{transit}} = \frac{R_* + R_p}{a}$$

(approximation by Borucki & Summers (1984))

Transit Photometry and Spectra

Transit Depth:



The depth of the transit (the relative difference in flux inside and outside the transit) is approximately related to the ratio of planetary and stellar area by:

$$f = \left(\frac{R_p}{R_*}\right)^2$$
$$= 8.4 \times 10^{-5} \left(\frac{M_p}{M_{\mathrm{Earth}}}\right)^{2/3}$$

assuming constant mean density equal to the Earth.

Transit duration:

$$t_{\mathrm{transit}} \approx \frac{2R_*}{v_K}$$

which is ∼13 hours for the Earth

Transit Photometry and Spectra

observable quantities:

- transit depth $\Rightarrow$ Planet radius if we know the stellar radius
- orbital period $\Rightarrow$ Planet semi-major axis if we know the stellar mass

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

Inclination is measured (necessarily close to edge-on)

Orbital eccentricity is not easily measured

Mass is not measured at all without additional data

Transit Photometry and Spectra

As the transit happens, we know there is **only minimal orbital tilt**: With this information, accurate measurement of planet mass from other methods is possible.

The mass of a detected transiting planet has to be determined by for example the radial velocity method where the knowledge about the edge-on orbit allows for the calculation of the **true mass**.

The combination of radius and true mass provides the mean density of the planet, which, in combination with models of planetary interiors, allows us to constrain the **planetary inner structures**.

Transit Photometry and Spectra

Sources of noise:

- Atmospheric fluctuations
- Shot noise
- Stellar brightness fluctuations (star spots, etc)
- Confusion or blending

Transit Photometry and Spectra

Sources of noise:

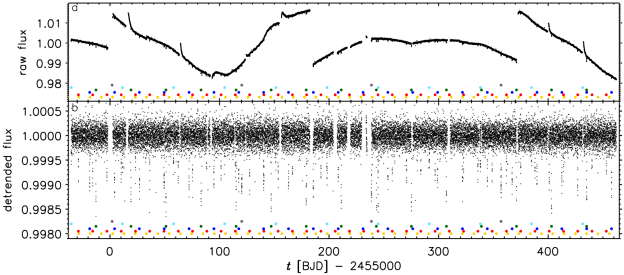
- Atmospheric fluctuations
- Shot noise
- Stellar brightness fluctuations (star spots, etc)
- Confusion or blending

example:

Eclipsing binary star with an unrelated 3rd star in the foreground or background.
Deep eclipse is diluted by light from 3rd star, so we see a shallow eclipse and mistakenly infer a planet.

Transit Photometry and Spectra

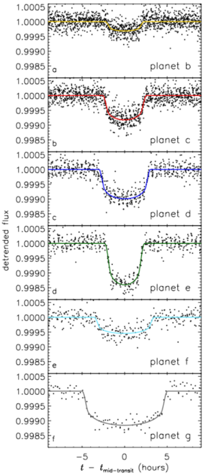
Substantial processing is needed to identify transit signals even in space-based data.



Lightcurves of the Kepler-11 system, raw and detrended.
Kepler-11 is a G dwarf star with Kepler magnitude $K_p = 13.7$, visual magnitude $V = 14.2\,\mathrm{mag}$.
The six sets of periodic transits are indicated with dots of differing colors.
Credit: Lissauer et al. (2011)

Transit Photometry and Spectra

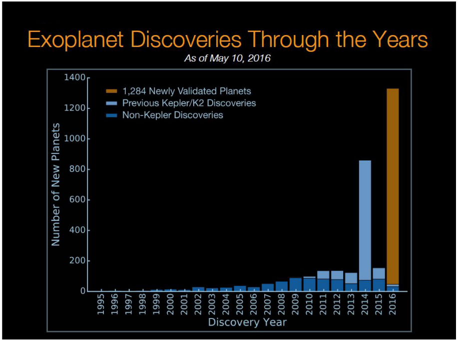
Substantial processing is needed to identify transit signals even in space-based data.

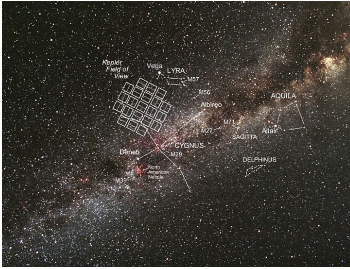


Detrended data of previous figure shown phased at the period of each transit signal and zoomed to an 18-hour region around mid-transit.
Credit: Lissauer et al. (2011)

Transit Photometry and Spectra

Huge number of new exoplanets due to **Kepler** transit mission:



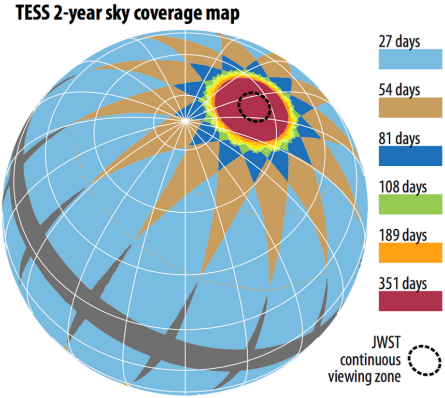


Kepler field. Credit: NASA

Kepler has so far discovered 2774 planets (as of May 2024).

Transit Photometry and Spectra

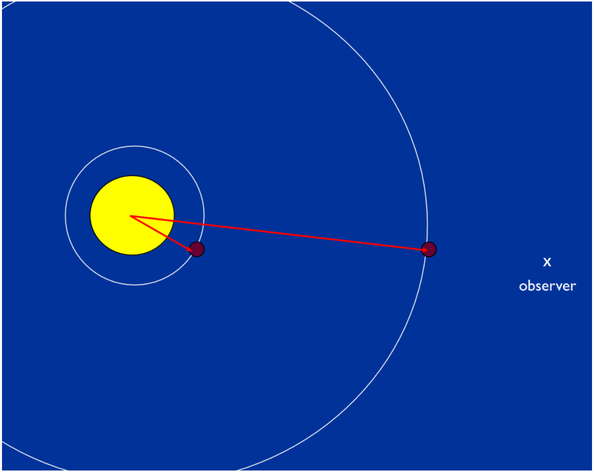
TESS (Transiting Exoplanet Survey Satellite) has discovered 450 confirmed exoplanets so far (and 7147 candidates) during its initial and extended mission (as of May 2024).



Credit: TESS

Transit Photometry and Spectra

A transit is more likely observed when the planet is close to its star. This technique is best for close-in, large planets.



Transit Photometry and Spectra

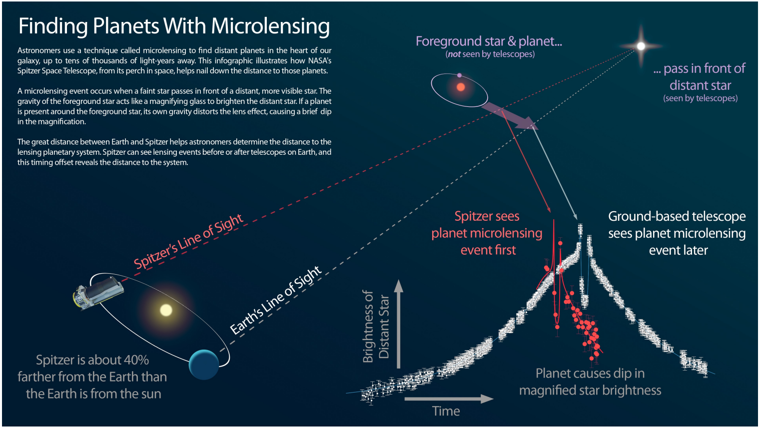
In addition to measure an exoplanet's size, mass and orbit parameters, its temperature and spectra can be measured.
We can test the **atmospheric models** that have been developed for planets in our Solar system.

example: HD 209458b

On 23 June 2010, astronomers announced they have measured a superstorm (with windspeeds of up to 7,000 km/h) for the first time in the atmosphere of HD 209458 b. The very high-precision observations done by ESO's Very Large Telescope and its powerful CRIRES spectrograph of carbon monoxide gas show that it is streaming at enormous speed from the extremely hot day side to the cooler night side of the planet. The observations also allow another exciting "first": measuring the orbital speed of the exoplanet itself, providing a direct determination of its mass.

Microlensing

Microlensing around a star (or black hole)



Credit: Spitzer Caltech

Microlensing

Microlensing can detect planets at large distances from us, even farther away than transit method can and much farther than radial velocity or astrometry can do.

Microlensing needs almost perfect **alignment** between source and lens. This method can detect very low mass planets, but they are one-time events one cannot follow up.

OGLE 2005-BLG-235Lb, announced 1/25/06

Mass of second lens only $8 \times 10 - 5$ as massive as star. Most likely mass of this planet is 5.5 M_{Earth} and separation from star is 2.6 AU, around a star that is most likely low-mass (0.22 $M_{\odot}$).
If correct, this is one of lowest-mass planets yet detected.

Astrometry

The idea behind Astrometry:

Same principle as for Doppler spectroscopy (the radial velocity method), but now look for motion of the star on the plane of the sky due to orbiting planet (with respect to other stars).

Need to measure angles (motion on sky) of $< 10^{-4}$ arcsec.

Definition of center of mass: $M_p a = M_* a_*$
observe at distance d, angular size of a face-on orbit:

$$\theta = \left(\frac{M_p}{M_*}\right) \frac{a}{d} \ [radians]$$

Unlike radial velocity, signal size favors wide orbits signal is inversely proportional to distance.

Astrometry

ESA Gaia mission

The Gaia Data Processing and Analysis Consortium (DPAC) will extract exoplanet detections from the Gaia observations using three different methods:

- Astrometrically, by observing the wobble of the host star's position on the sky caused by the exoplanet
- Photometrically, by observing the photometric transit of the exoplanet in front of its host star
- Spectroscopically, by observing the variation in the radial velocity of the host star caused by the exoplanet

ESA Gaia mission

The Gaia Data Processing and Analysis Consortium (DPAC) will extract exoplanet detections from the Gaia observations using three different methods:

- Astrometrically, by observing the wobble of the host star's position on the sky caused by the exoplanet
- Photometrically, by observing the photometric transit of the exoplanet in front of its host star
- Spectroscopically, by observing the variation in the radial velocity of the host star caused by the exoplanet

According to the recent data release, there are ∼300 exoplanet candidates discovered by Gaia.

Direct Imaging

The idea behind direct imaging: Take an image of an exoplanet.

The full **orbit** can be reconstructed from multiple images.
In addition, **spectra** from the planet itself can be taken to better understand physical conditions, atmosphere, maybe even presence of life.

Resolve the planet as a spatially distinct source from the host star:

- Faintness: reflected light or thermal emission
- Contrast: angular separation

Direct Imaging

Reflected starlight: planet radius R_p, orbital radius a, albedo A. Fraction f of the incident starlight that is reflected:

$$f = \frac{\pi R_p^2}{4\pi a^2} A = 1.4 \times 10^{-10} \left(\frac{A}{0.3}\right) \left(\frac{R_p}{R_{\mathrm{earth}}}\right)^2 \left(\frac{a}{1\ \mathrm{AU}}\right)$$

Earth is about 24-25 magnitudes fainter than the Sun to a distant observer.

Direct Imaging

example: the Earth

Thermal emission: suppose the star and planet both emit thermal emission at temperatures T_* and T respectively. Planck function:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/k_B T) - 1}$$

with frequency ν, Planck's constant h, Boltzmann constant k_B

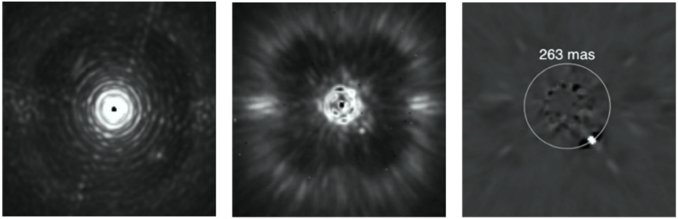
Consider a wavelength near where the Earth's thermal emission peaks:
$T = 290\ \mathrm{K}$, $\lambda = 20\ \mu\mathrm{m}$
Fraction f of the incidend starlight that is reflected:

$$f = \left(\frac{R_p}{R_*}\right)^2 \frac{\exp(h\nu/k_B T_*) - 1}{\exp(h\nu/k_B T) - 1} \sim 10^{-6}$$

Also need to resolve the planet as a distinct source:
For a telescope of diameter D, observing at wavelength λ, classical criterion is the Rayleigh limit:
$\theta \sim 1.22\frac{\lambda}{D}$; with $1\,\mathrm{AU}$ at $d = 10\,\mathrm{pc} \Rightarrow \theta = 0.1\ \mathrm{arcsec}$

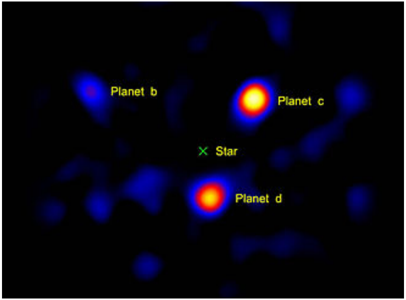
Direct Imaging

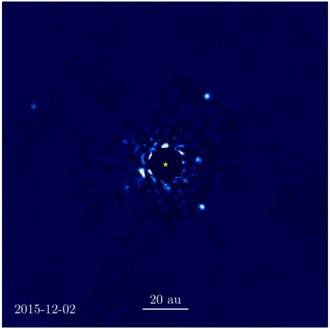
Current state-of-the-art: SPHERE on VLT and GPI on Gemini



adaptive optics + coronograph + angular differential imaging

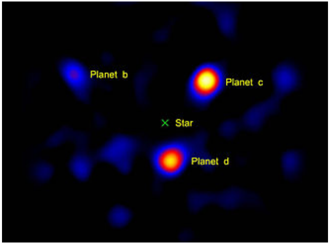
First Images of Exoplanets: HR 8799 Solar System

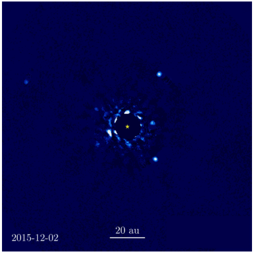




Left: Direct image of exoplanets around the star HR 8799 using a vortex coronagraph on a 1.5 m portion of the Hale Telescope
Right: Direct image from HR 8799 (center) with HR 8799 e (right), HR 8799 d (lower right), HR 8799 c (upper right), HR 8799 b (upper left) from W. M. Keck Observatory

First Images of Exoplanets: HR 8799 Solar System

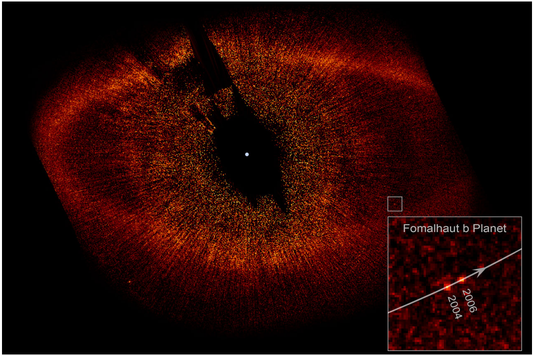




Initially 3 orbiting planets around HR 8799 were observed - the first imaged planetary system. Nowadays we know the system contains at least four massive planets and a debris disk.
Advanced observing techniques were used to block the star's light.
Adaptive Optics was used to sharpen images.
Observations were repeated over years, confirming planetary motion.
The planets are young and hot, and therefore glow more brightly than by reflected starlight alone.

Direct Imaging

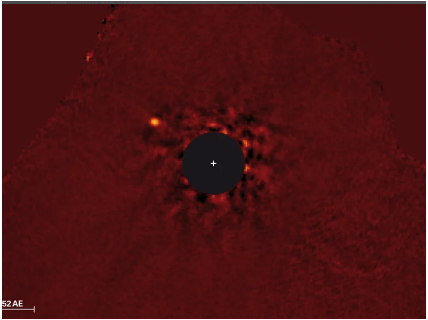
First Images of Exoplanets: Fomalhaut b



Hubble Space Telescope image shows Fomalhaut b, orbiting its parent star, Fomalhaut. Inset: Images taken ∼2 years apart show a planet moving around the star. Fomalhaut b has carved a path along the inner edge of a vast, dusty debris ring (similar to the Kuiper belt). Fomalhaut b completes an orbit around its star every 872 years.

Direct Imaging

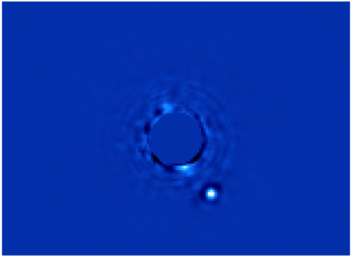
Directly imaged planet around the star Kappa Andromedae



NIR image of the Kappa Andromedae system, taken in June 2012 with the Subaru telescope. Most of the light from the parent star was filtered out by image processing. The spots around the disk are residual effects of the starlight removed in processing. The super-Jupiter Kappa Andromedae is clearly visible at the top left. Its distance from its star corresponds to 1.8 times the distance between Neptune and the Sun. Credit: NAOJ

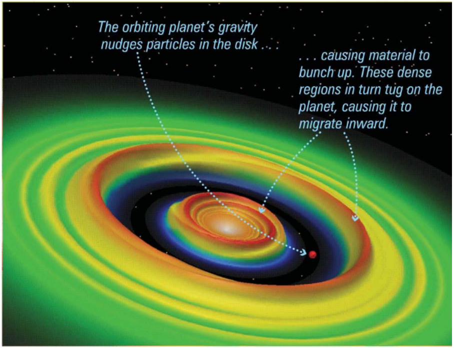
Direct Imaging

Directly imaged planet around the star Beta Pictoris



Adaptive optics image of the planet Beta Pictoris b, taken with the Gemini Planet Imager at the Gemini South Telescope, Chile.
The star is blocked by a mask. In addition to the image, GPI obtains a spectrum for every pixel, allowing to study the planet in great detail.
Beta Pictoris b is a giant planet, several times larger than Jupiter, and is approximately ten million years old. These NIR images (1.5-1.8 microns) show the planet glowing in IR light from the heat released in its formation.
Image credit: Processing by Christian Marois, NRC Canada.

Planetary Formation



artistic illustration

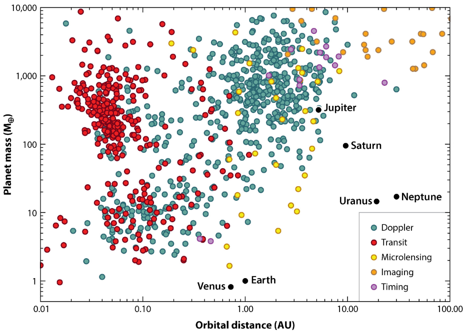
Millimeter/submillimeter-wave observations (such as from ALMA) are capable of detecting extrasolar planets under formation: **protoplanets**. Multi-antenna millimeter/submillimeter-wave telescope such as ALMA can provide much higher resolving power, or ability to see fine detail, than current optical or infrared telescopes. Moreover, these observations would not be degraded by interference from the zodiacal light reflected by interplanetary dust, either in the extrasolar system or our Solar System.

Planetary Formation

Planets can be much closer to their star than Mercury:

Hot Jupiters are massive planets with $a < 0.1\ \mathrm{AU}$

Most of the Solar System's planets would not yet be detectable around another star



credit: Winn & Fabrycky Annual Review

Planetary Formation

Many of these close-in *hot Jupiters* were subsequently discovered: this is just the kind of system that the radial velocity method works best for. But how could a Jupiter-like planet be formed so near to its parent star? (It can't.)

Planetary Formation

Many of these close-in *hot Jupiters* were subsequently discovered: this is just the kind of system that the radial velocity method works best for. But how could a Jupiter-like planet be formed so near to its parent star? (It can't.)

$\Rightarrow$ direct evidence for **planetary migration**

Planetary Formation

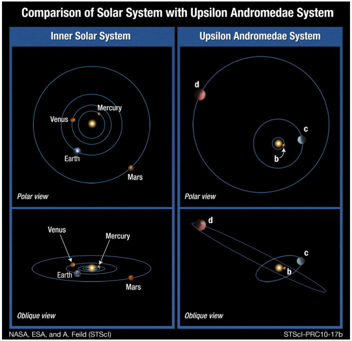
Many of these close-in *hot Jupiters* were subsequently discovered: this is just the kind of system that the radial velocity method works best for.
But how could a Jupiter-like planet be formed so near to its parent star? (It can't.)

$\Rightarrow$ direct evidence for **planetary migration**

If most stars form planetary systems in which giant planets migrate, any Earth-like planets that form may be expelled from the system, or might not ever form.
What is the chance of this happening?

Evolution of Planetary Systems

Upsilon Andromedae A - discovered by Doppler method

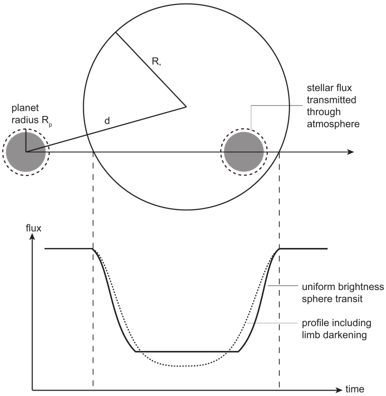


This artist's illustration of Upsilon Andromedae A, a system discovered by Doppler method, where three Jupiter-type planets orbit the yellow-white star Upsilon Andromedae A. The discovery was made by joint observations with the Hubble Space Telescope, the Hobby-Eberly Telescope, and other ground-based telescopes.

Two planets are several times more massive than Jupiter. The third planet, mass 75% that of Jupiter, is so close to the star it completes a full orbit every 4.6 Earth days. The orbits of two of the planets are inclined by 30 degrees with respect to each other. This surprising finding will impact theories of how planetary systems form and evolve, suggesting that violent events can disrupt planets' orbits after a planetary system has formed.

Atmospheric Characterization

Stellar light (spectrum) is modified during transit because some light passes through the planetary atmosphere. Can measure this via the transit depth $f(\lambda)$ or a planetar radius $R_p(\lambda)$.



Transmission spectroscopy works by observing the transit at two wavelengths:

- one where atmosphere is entirely transparent $\Rightarrow$ radius R_p
- one where it absorbs (is *optically thick*) up to n scale heights $\Rightarrow$ radius $R_p + nH_p$

Atmospheric Characterization

Favorable factors for transmission spectroscopy:

- small star
- high temperature atmosphere
- low mean molecular weight
- highly absorbing species

Atmospheric Characterization

Favorable factors for transmission spectroscopy:

- small star
- high temperature atmosphere
- low mean molecular weight
- highly absorbing species

What might prevent us from seeing a transmission spectroscopy feature even if we have the required sensitivity?

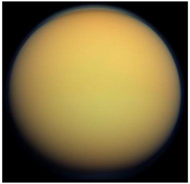
Atmospheric Characterization

Favorable factors for transmission spectroscopy:

- small star
- high temperature atmosphere
- low mean molecular weight
- highly absorbing species

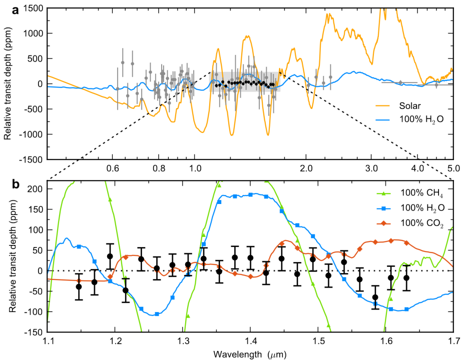
What might prevent us from seeing a transmission spectroscopy feature even if we have the required sensitivity?

Clouds: Not only water, but also such as SiO_2, TiO_2...
Hazes: Small solid particles, normally formed via photochemistry



Atmospheric Characterization

Hubble Space Telescope transmission spectroscopy of GJ 1214b: analysis shows the atmosphere is almost certainly obscured by clouds.



Transmission spectrum measurements (black and grey points) of GJ 1214b compared to model spectra.
Credit: Kreidberg et al. (2014)

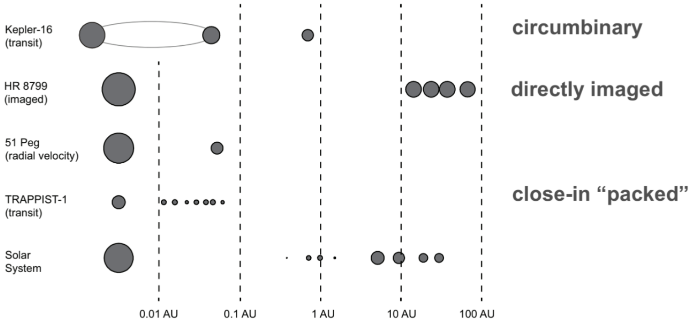
What we have learned

Many of the new solar systems don't look at all like our own, e.g.:

- Many have higher eccentricity in most of their orbits.
- Higher fraction of high-mass planets very close to their parent stars.
- Many planets are *super-Jupiters* (up to 10 times more massive than Jupiter).

The $\sim$ 1700 planets we have detected to date are only a sub-set of potential planets out there.

Properties of extrasolar planetary systems



Summary

Some key exoplanet websites:

- Exoplanets.org (exoplanets discovered so far): `www.exoplanets.org/`
- Exoplanet Encyclopaedia (exoplanets discovered so far): `www.exoplanet.edu`
- NASA Archive: `exoplanetarchive.ipac.caltech.edu`
- Kepler mission: `www.nasa.gov/mission_pages/kepler/`
- Open Exoplanet Catalog: `www.openexoplanetcatalogue.com`
- Habitable Zone Gallery: `www.hzgallery.org`
- Systemic: `oklo.org`
- Hack an Exoplanet: `https://hackanexoplanet.esa.int/challenges-size/`