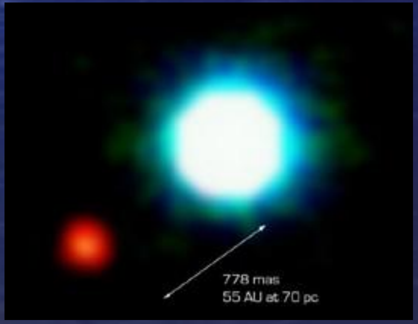
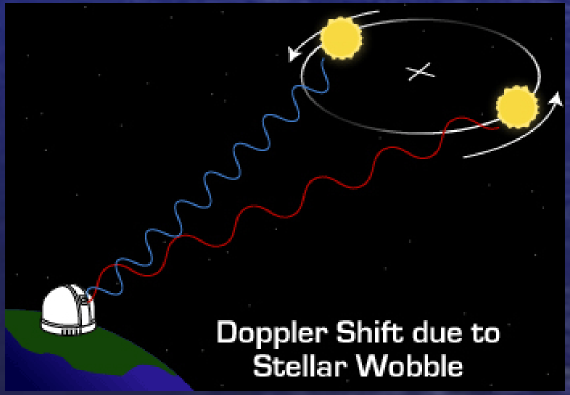
Extrasolar Planets

John Barnes





Extrasolar planets: Key questions

Fundamentally, we want to understand better our place in the universe:

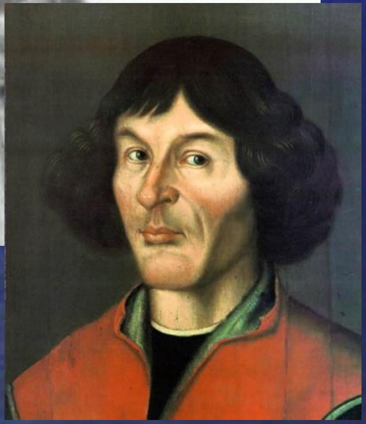
- How does a planetary system evolve around a star?
- Is our planetary system a common and/or typical example of the formation and evolution of planets?
- Are planetary systems a usual result of star birth or are planets rather rare and unusual phenomena?
- What causes the differences between the planets?
- What are the possibilities for friendly habitats and the existence of Life elsewhere in the Universe?

IAU planet definition (Prague meeting, August 4th 2006)

- A celestial body within the Solar System that
  (a) is in orbit around the Sun;
  (b) has sufficient mass for its self-gravity to overcome rigid body forces, so that it assumes a hydrostatic equilibrium (nearly round) shape; and
  (c) has cleared the neighbourhood around its orbit;

- or within another system
  (i) is in orbit around a star or stellar remnant;
  (ii) has a mass below the limiting mass for thermonuclear fusion of deuterium; and
  (iii) is above the minimum mass/size requirement for planetary status in the Solar System

The history of extrasolar planet hunting



- In 1584, when the Catholic monk Giordano Bruno asserted that there were "countless suns and countless earths all rotating around their suns," he was accused of heresy by the catholic church, and burned to death
- The Earth was dethroned as a supreme entity in the cosmos early in the 16th century, when Copernicus discovered that our planet orbits the Sun. His insight, while reluctantly accepted, changed Western thinking forever.

  - Wisely, he didn't allow his book, ***On the Revolutions of Heavenly Bodies***, to be published until the day he died in 1543

An astrometric wobble?

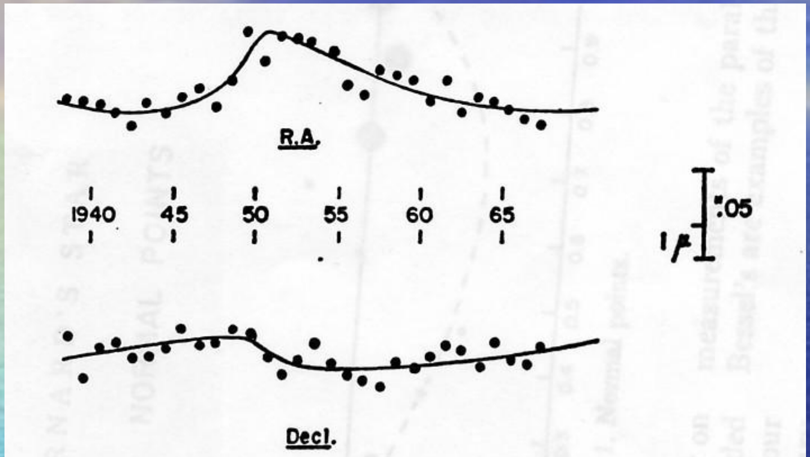
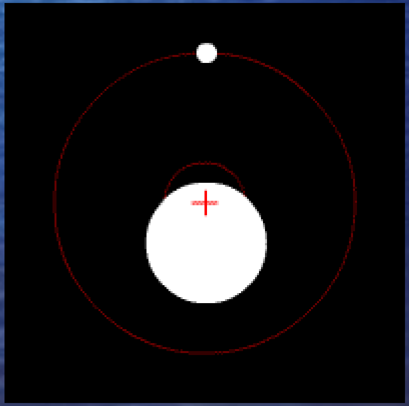


FIG. 1. Barnard's star: Yearly means, averaging 100 plates and weight 68; time–displacement curves for $P=25$ yr, $e=0.75$, $T=1950$.

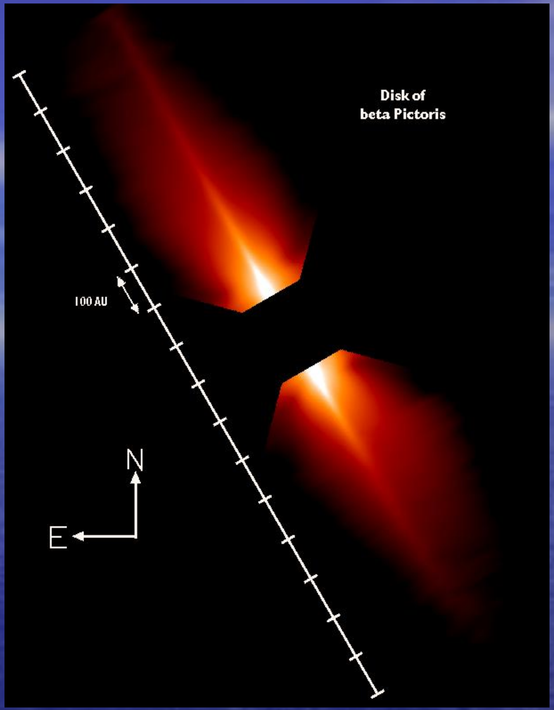
- Working at the Sproul Observatory (near Philadelphia), van de Kamp devoted most of his life to studying over 2,000 Schmidt plates of Barnard's Star that he and his students had taken from 1938-1962
- He claimed to detect a wobble in the movement of Barnard's Star revealing a 1.6 Jupiter mass planet in a 24 yr orbit

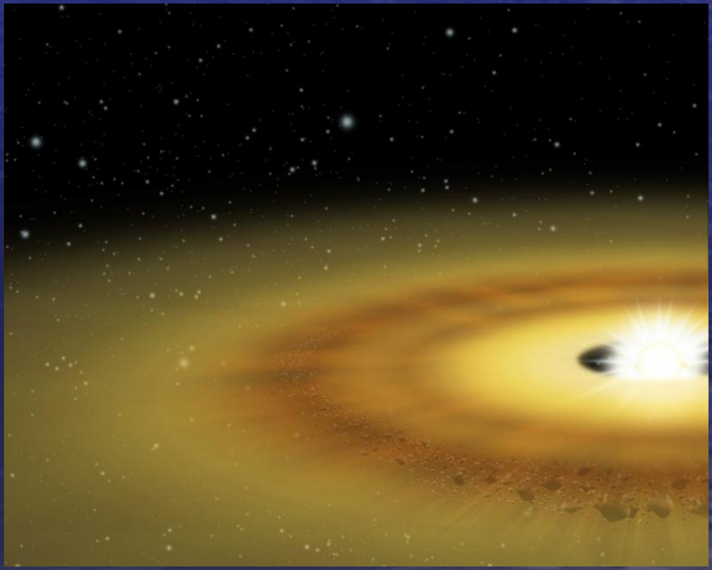


A wobbling star: Schematic showing a star, a planet, and their orbits around the system centre of mass

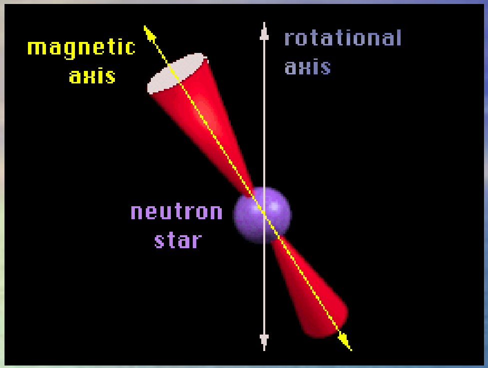
Planetary disks around other stars

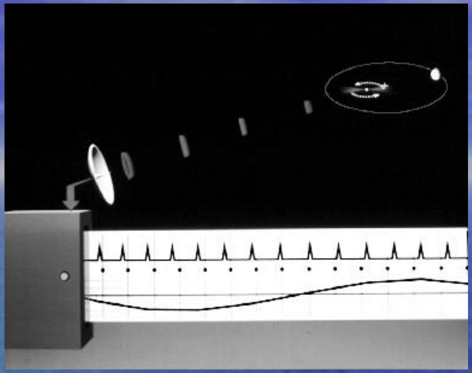
- Prospects for finding new worlds around other stars brightened in the 1980s
- Smith and Terrile made infrared observations of a disk of dust surrounding the star Beta Pictoris.
- Their discovery provided the first unambiguous proof that flattened disks of matter exist around stars other than the Sun
- The Beta Pictoris disk is a young planetary system in the making, and thus supports the standard model of solar system birth, where planets accrete from a disk of dust and gas surrounding a young star

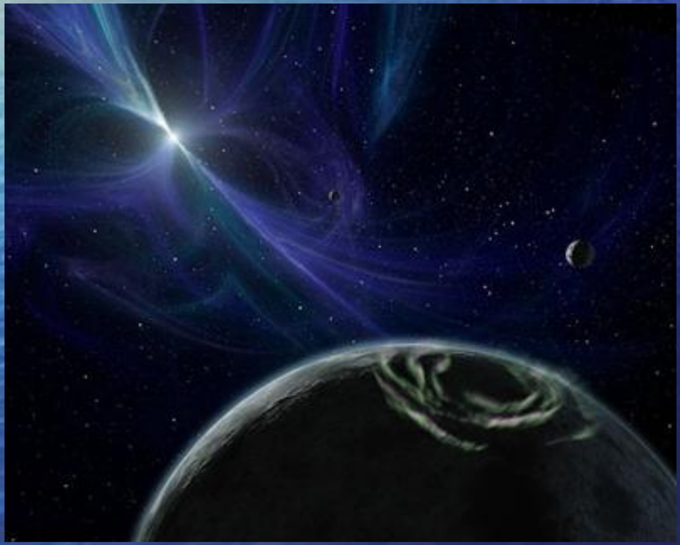




The first extrasolar planets found



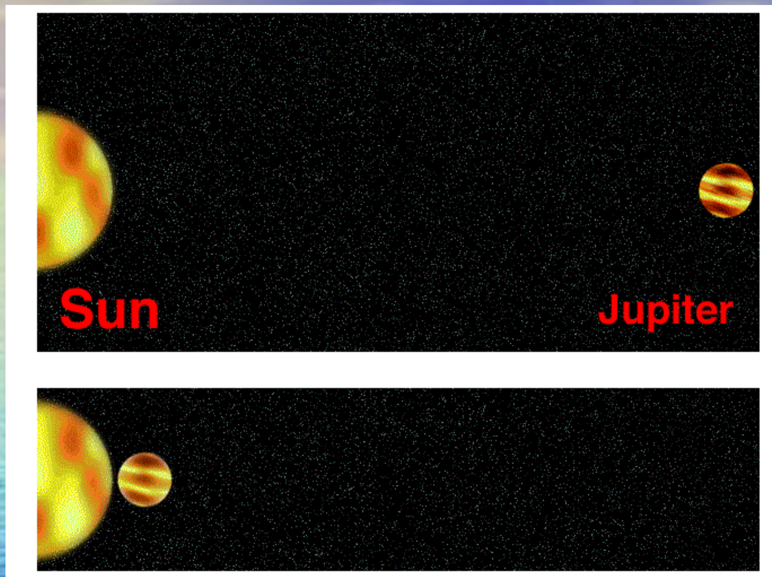


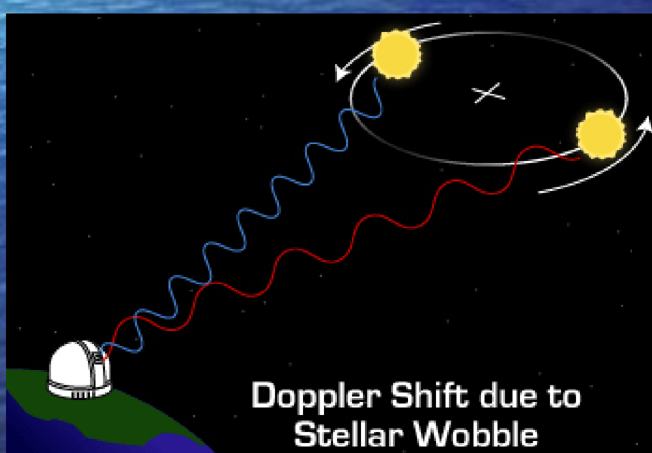


Planet masses 4.3, 3.9, 0.02 earth masses, orbiting with P=66, 98, 25 days (all within a "Mercury" size orbit)

- The first true extrasolar planet was discovered in 1994, by Alexander Wolszczan, a radio astronomer
- Wolszczan discovered 3 planets orbiting pulsar PSR B1257+12, in the Virgo constellation.
- A pulsar is a dense, rapidly spinning remnant of a supernova explosion
- He observed regular variations in the pulsed radio signal from the pulsar, indicating the gravitational effects of orbiting planets
- These worlds couldn't support life though, as they would be permanently bathed in high-energy radiation

The first planet around a Sun-like star





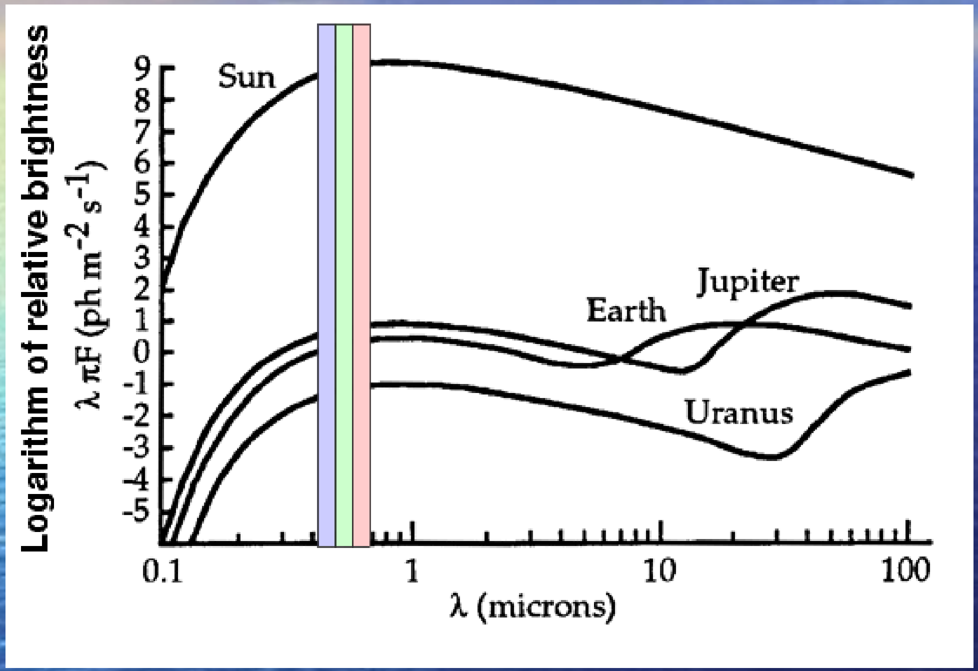
- The first discovery of a planet orbiting a star similar to the Sun came in 1995 (the year van de Kamp died).
- The Swiss team of Michel Mayor and Didier Queloz of Geneva announced that they had found planet orbiting 51 Pegasi.
- Their planet was 0.5-2 Jupiter masses and no more than twice its mass. They had observed it indirectly, using the radial velocity method.
- Three months later, Marcy and Butler confirmed the Swiss discovery -- and turned up two more planets. By the end of the 20th century, several dozen worlds had been discovered.

Planet hunting techniques

- The main challenge in finding planets is their extreme faintness compared to their host stars
- Different search methods deal with this in different ways
- There are 5 different approaches

  - Direct imaging – while trying to minimise interference from the star
  - Astrometric wobble – planet's effect on the position of the star
  - Radial velocity Doppler wobbles – planet's effect on the velocity of the star
  - The transit method – planet's effect on the apparent brightness of the star
  - Microlensing – planet's effect on the brightness of background stars
- These different techniques have advantages and disadvantages

Direct imaging

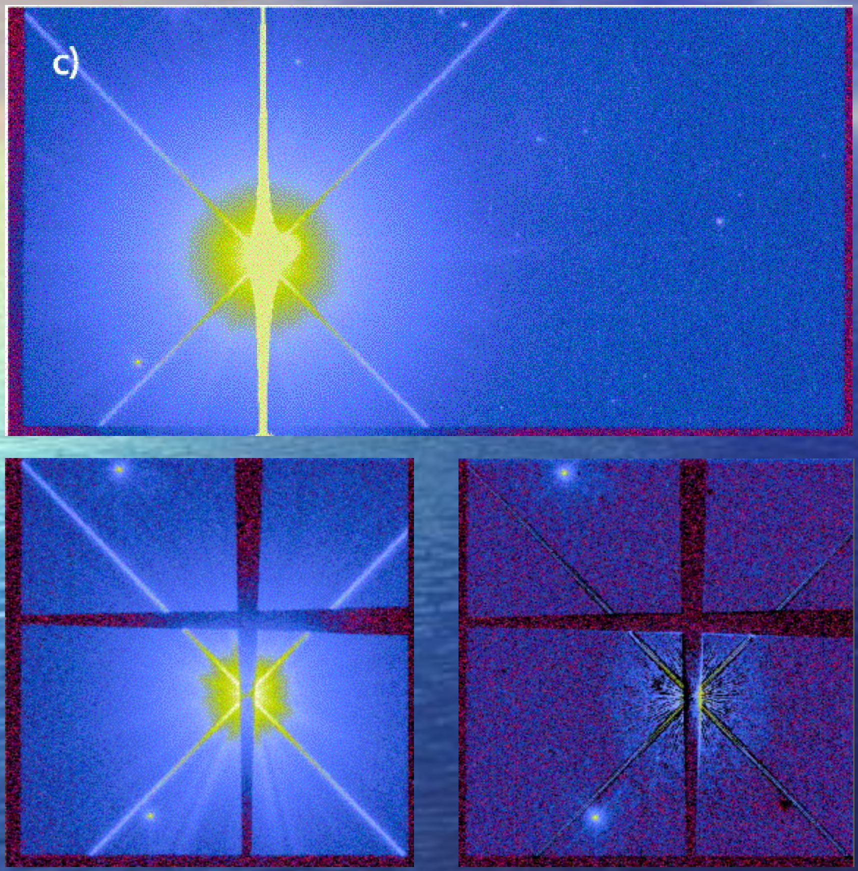


- The simplest way to find planets around other stars is simply to LOOK for them: point a big telescope at a nearby star and see if there are any faint points of light around the star. Unfortunately, the difference in brightness between even a faint star and a planet (even a giant planet) is very large
- In the visible part of the spectrum, Jupiter is ~8 orders of magnitude fainter than the Sun, and the Earth about 8.5

  - Jupiter: 100,000,000 times fainter than the Sun

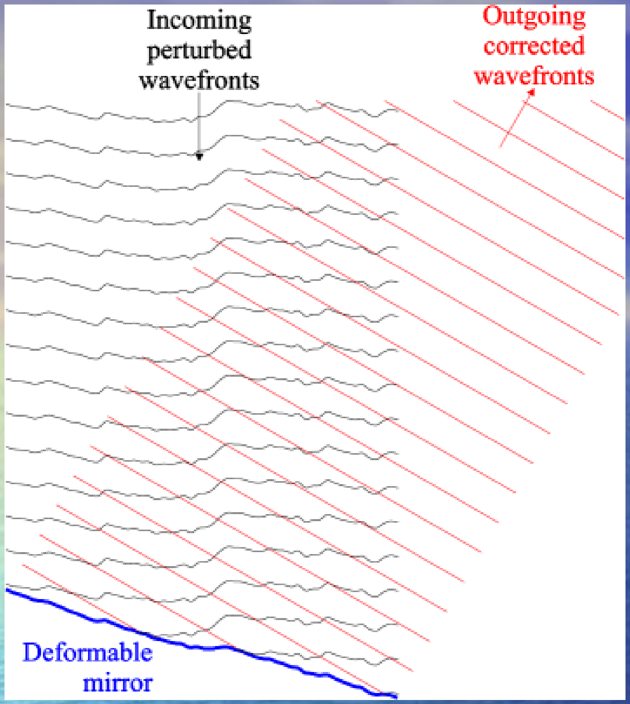
  - Earth: 300,000,000 times fainter than the Sun

Using a coronagraph



Example of a coronagraph: the STIS camera on the HST

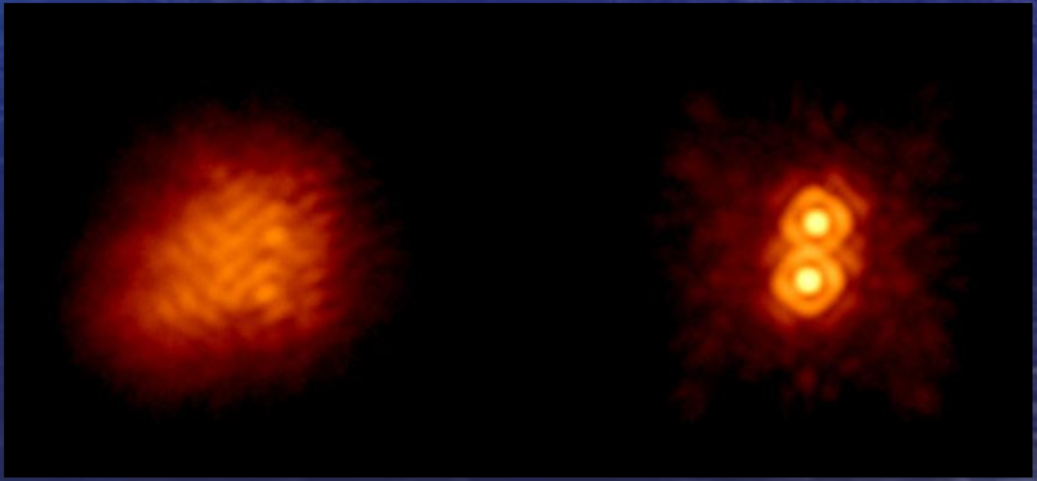
- Even if a tiny fraction of a star's light is scattered out into the wings of the Point Spread Function (PSF), it may overwhelm any planet in orbit around it
- By placing bars, disks, or other opaque objects in the optical path from telescope to camera, one can block a lot of a star's light
- One can reduce the scattered light more by subtracting a model of the PSF from the image
- Even so, a significant amount of scattered light remains



Adaptive optics

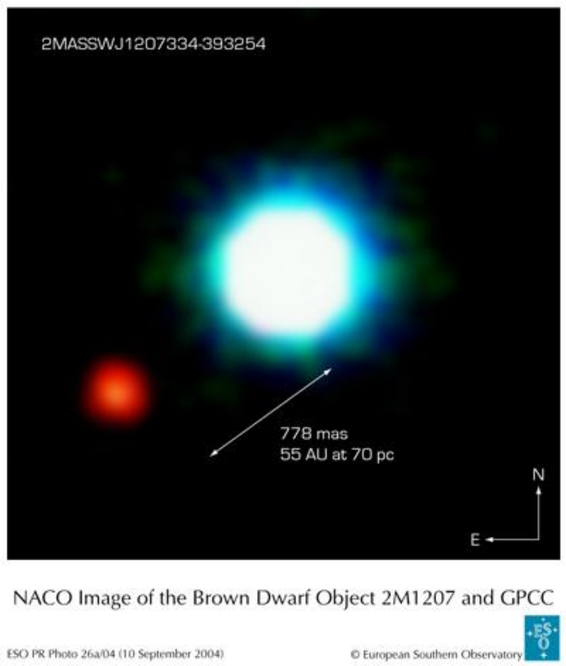
- An alternative way to reduce scattered light in the PSF wings is with AO
- Uses a deformable mirror to correct for the effects of rapidly changing optical distortion from the turbulent atmosphere
- In other words, remove the effects of "seeing"

Hales telescope at Mt. Palomar

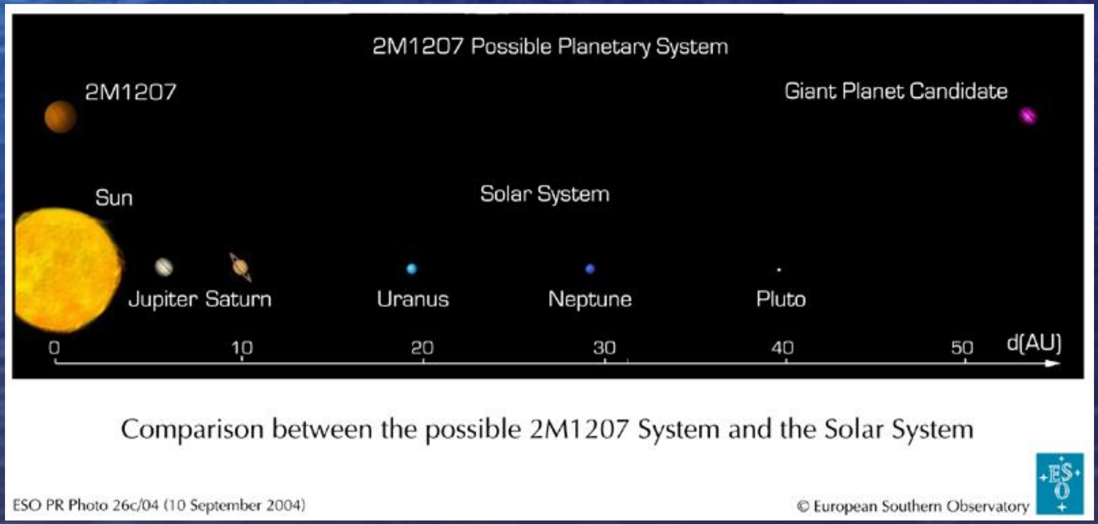


IW Tau: a young T-tauri binary revealed

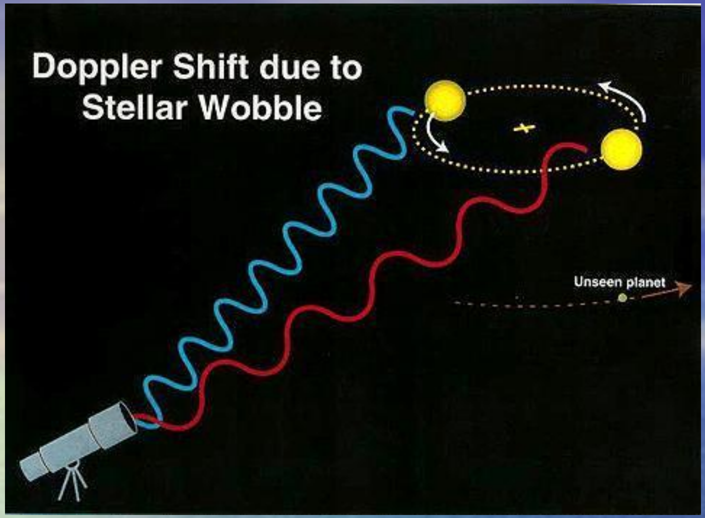
A planet imaged?



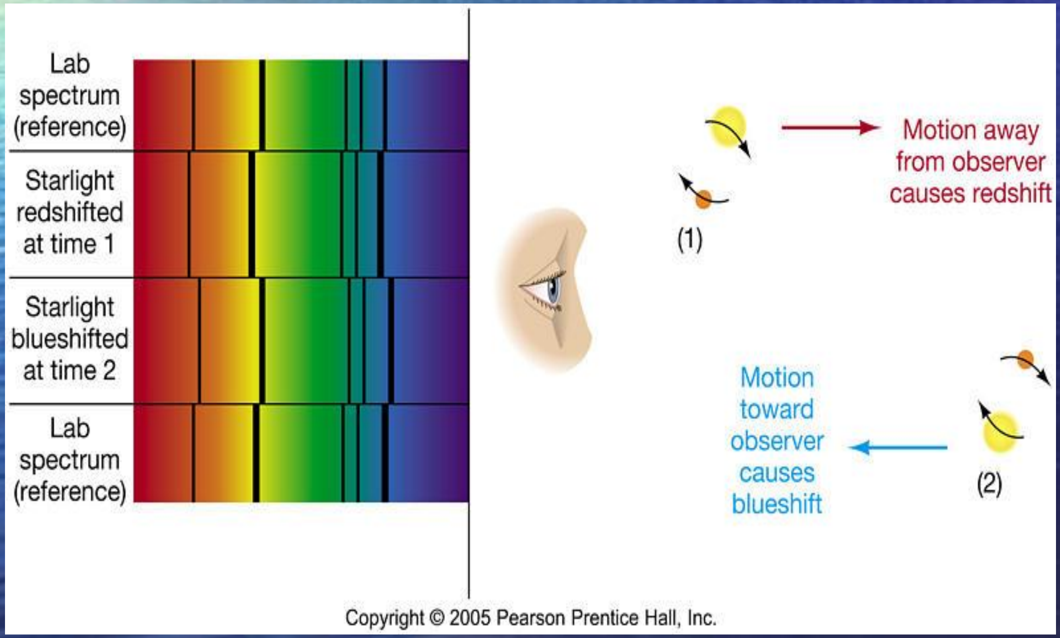
- In September, 2004, astronomers using the European Very Large Telescope (VLT) announced that they may have detected a very large planet orbiting around another star by direct imaging
- They used three techniques to increase their chances of seeing a planet against the glare of its star:
- They selected an intrinsically faint target (ie the brown dwarf) – with a mass ~25 times the mass of Jupiter
- They observed in the near-infrared (wavelengths of 1000-3500 nm), where the star/planet contrast is minimal
- They used AO to compensate for the atmospheric seeing
- The "planet" has a mass of ~8 times the mass of Jupiter, T ~ 1600K

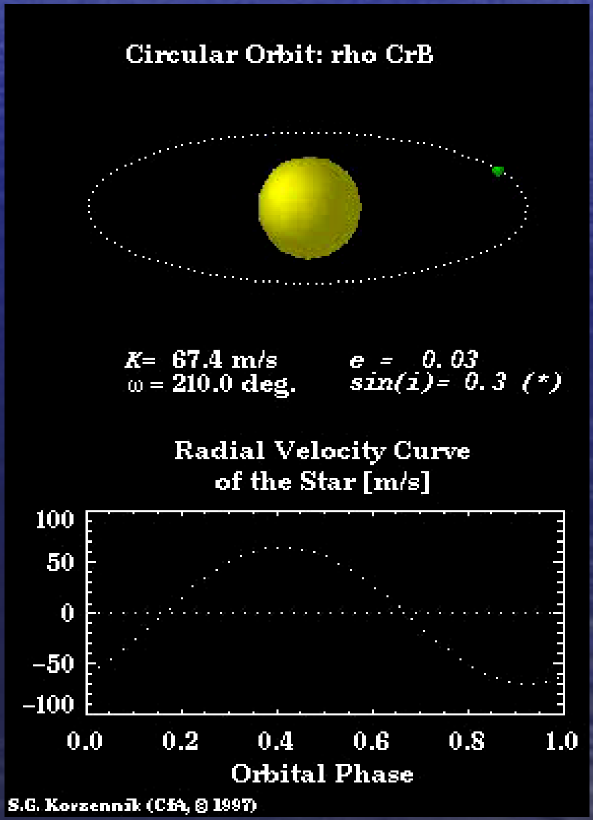


Radial velocity detection

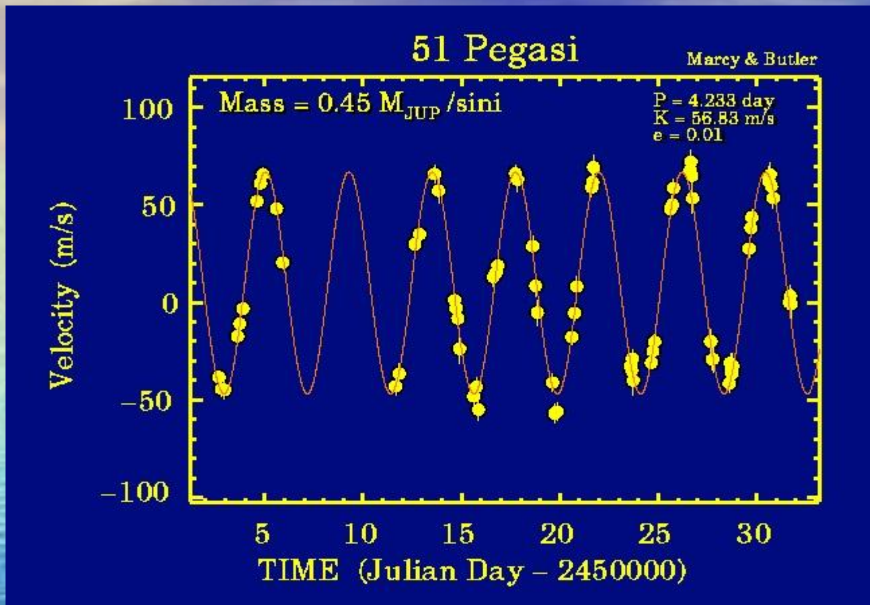


- Doppler wobble of central star induced by the orbiting planet
- Can be measured with sensitive spectrographs



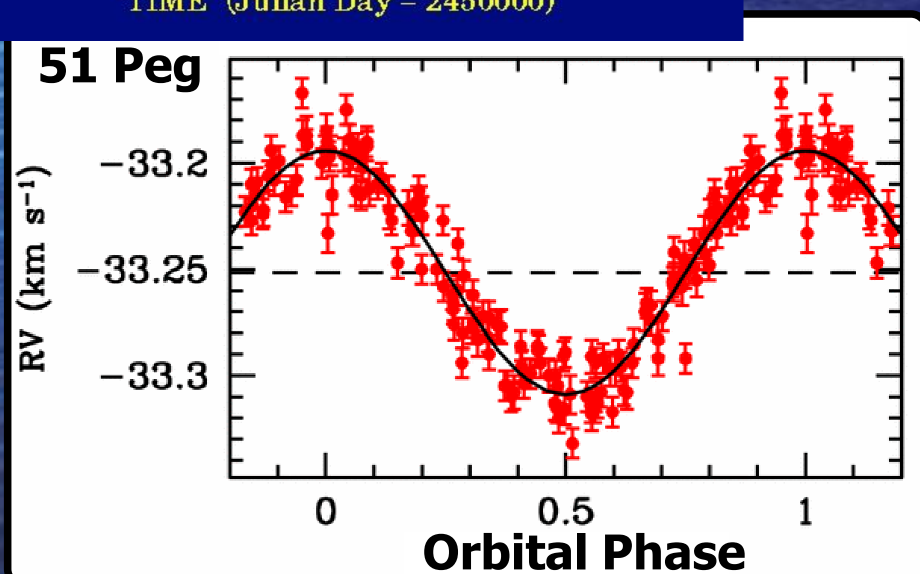


Radial velocity - planetary orbit



- Period from radial velocity curve and stellar mass from spectral type

K III gives orbital radius, a



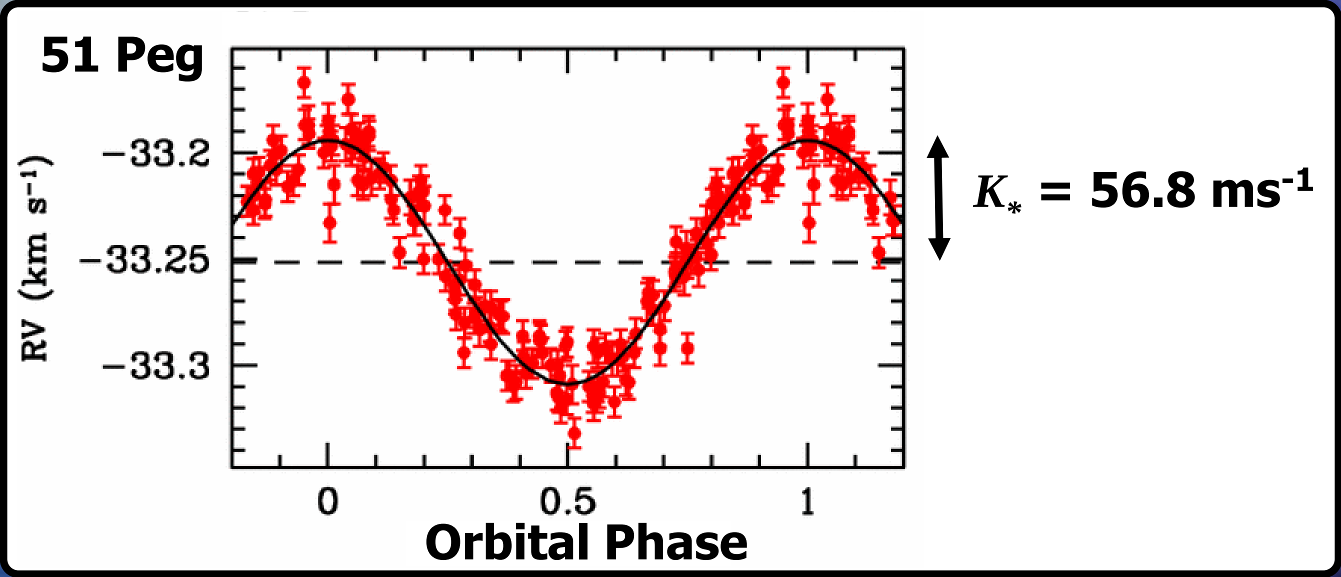
$$\frac{a^3}{G(M_* + M_p)} = \frac{P^2}{4\pi^2}$$

Since $M_p \ll M_*$

$$a = \left(\frac{GM_*}{4\pi^2}\right)^{1/3} P^{2/3}$$

Radial velocity amplitude

- The amplitude of the stellar wobble K_* can be measured

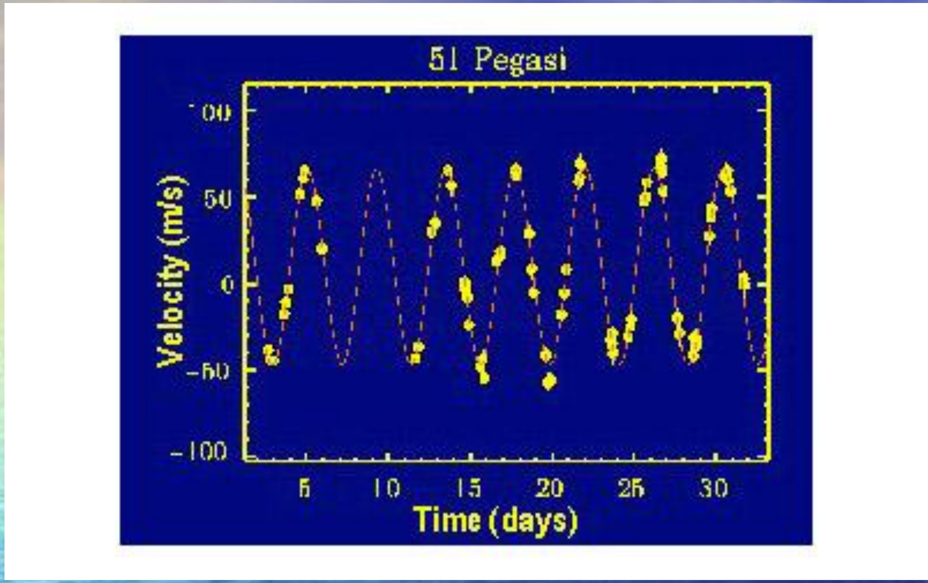


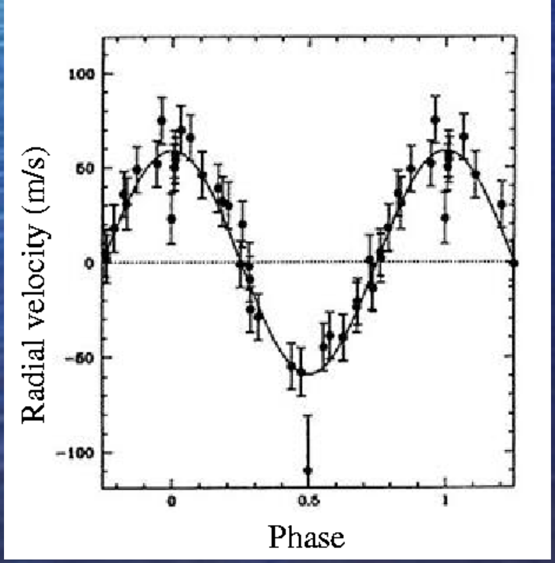
- The *minimum planetary mass* $M_p \sin i$ can be determined.

$$M_p \sin i \simeq \left(\frac{P}{2\pi G}\right)^{1/3} K_* M_*^{2/3} (1-e^2)^{1/2}$$

eccentricity - i.e. how elliptical the orbit is. A circular orbits has e = 0

The first radial velocity planet



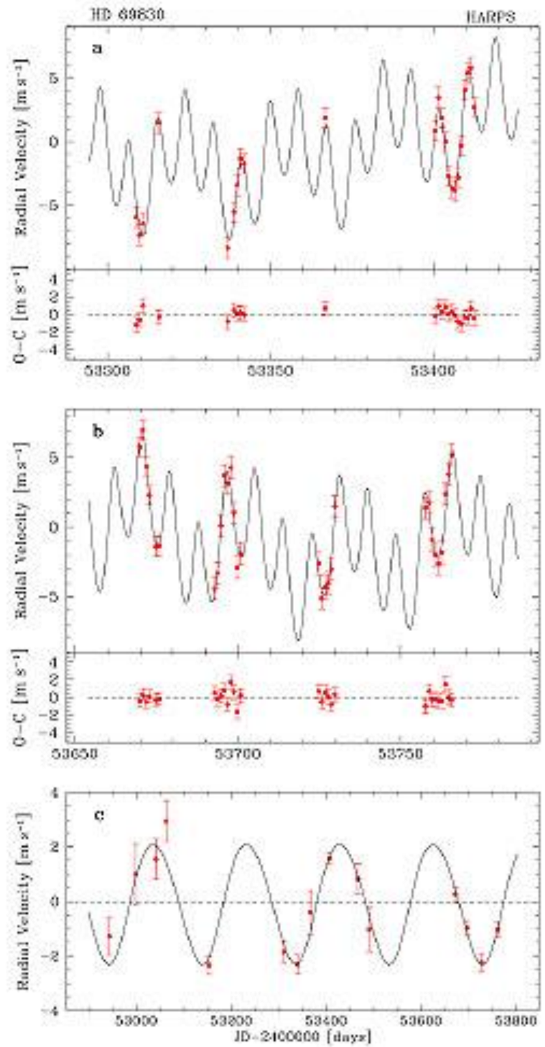


- 51 Pegasi (a solar-like star)
- Radial velocities measured of a few weeks
- A +/-60m/s wobble seen with a period of 4.2 days
- Phase-folded data shows a circular orbit
- The planet has Msini=0.5M_{Jup} and a separation of 0.052AU

  (c.f. Mercury which orbits at 0.39AU)

Multiple Doppler planets

- Wobbles on top of wobbles can also reveal multiple planet systems



Radial Velocity Measurements of HD 69830 (HARPS/3.6m)

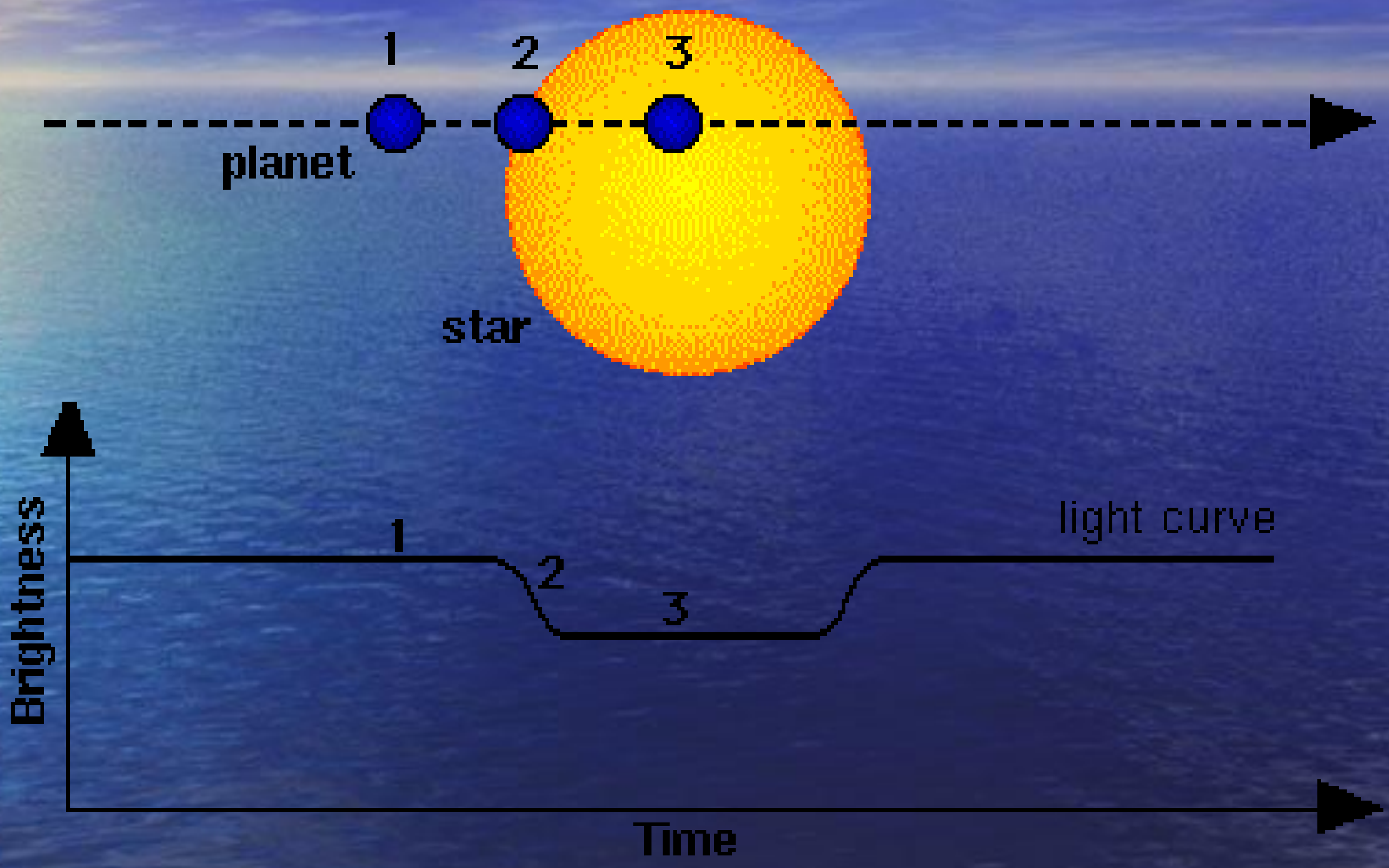
ESO Press Photo 18c/06 (18 May 2006) © ESO

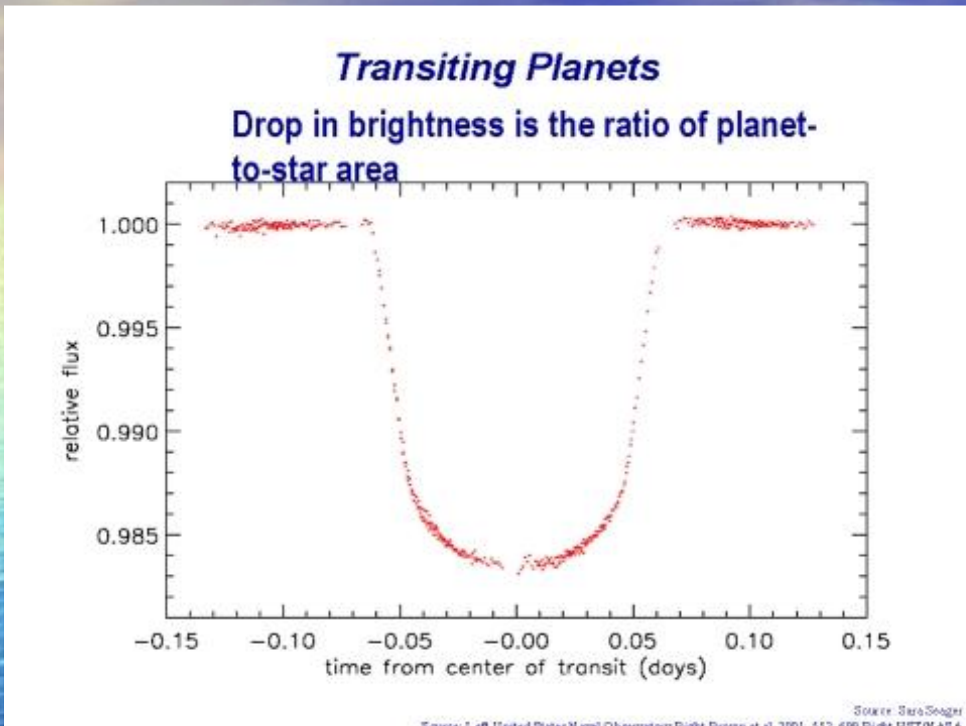
Artist View of Planetary System Around HD 69830

ESO Press Photo 18b/06 (18 May 2006) © ESO

HD 69830 (K0V): A planetary system containing 3 Neptune-like planets
(P = 9, 32, 197 d, a = 0.08, 0.19, 0.63 AU)

The transit method





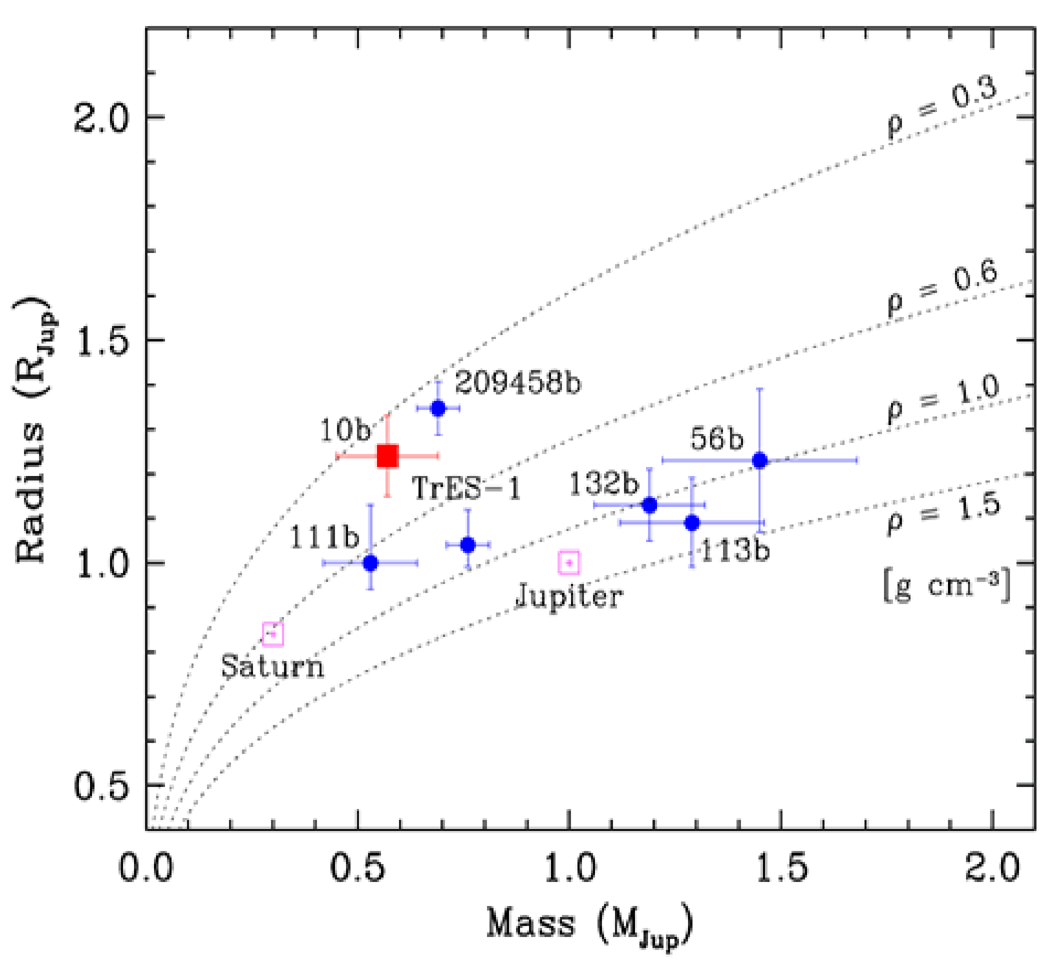
HD 209458 transiting planet
This star is a G0 star (ie Sun-like)

Planet radius = $1.32R_{Jup}$

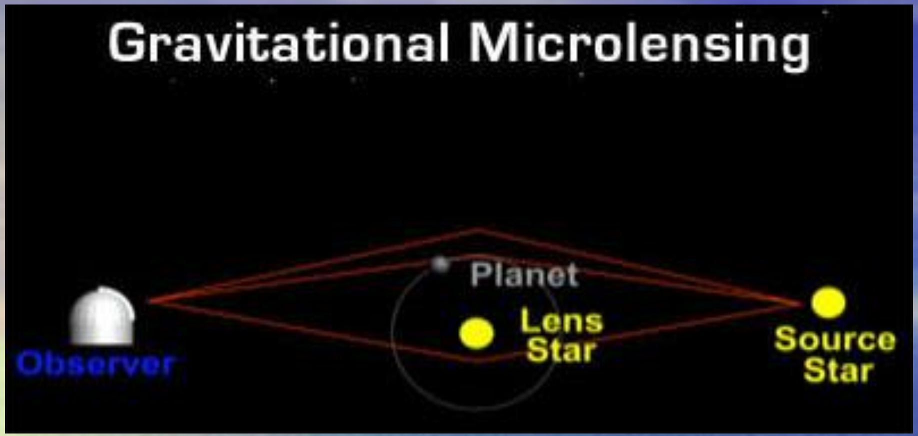
Relative size is the key

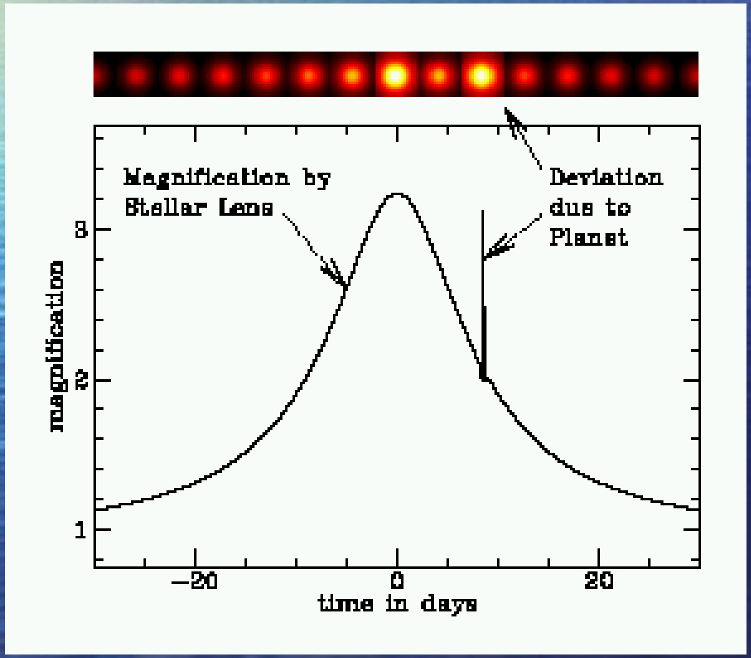
- A transit depth of 1.7% (e.g. opposite) corresponds to a planet-to-star area ratio of 0.017
- So the relative planet-to-star radii are the square root of 0.017=0.13

Density information



With planet radii from the transit depth, and planet mass from radial velocity follow-up, it is possible to measure planet densities – extrasolar planets show evidence for different interior structure





Microlensing planets

- Einstein's General Theory of Relativity says that light rays can be bent by gravity
- Light rays from a distant star can be bent by the gravitational field of a nearby star along the line of sight
- The nearby star behaves like a lens, whose focusing action makes the distant source star appear brighter than it would otherwise be
- This alignment is only temporary, since the two stars are moving relative to one another
- The result is thus a brightening and then dimming of the source star
- When a planet is orbiting the lens star, its own gravitational field can contribute to the bending of light rays, and it behaves like a defect in the lens
- If alignment is just right, this defect will produce a narrow spike in the brightness of the source star, which can be used to infer the presence of the planet

Limitations of the different methods

- All planet hunting methods are more sensitive to more massive planets. In addition;
- Direct imaging
  - limited by faintness of planets
  - limited by PSF of star
  - better at finding widely separated giant planets around young stars
- Astrometric
  - limited by the distances of stars
  - limited by the long periods of wide planets
- Radial velocity
  - preferentially finds close-in massive planets
  - limited by the long periods of wide planets
- Transit
  - limited to close-in planets (higher probability of alignment)
- Microlensing
  - Sensitive over a wide range of separation
  - But each event can only be measured once

306 Extrasolar planets

As of 4th September 2008

(see www.exoplanet.eu)

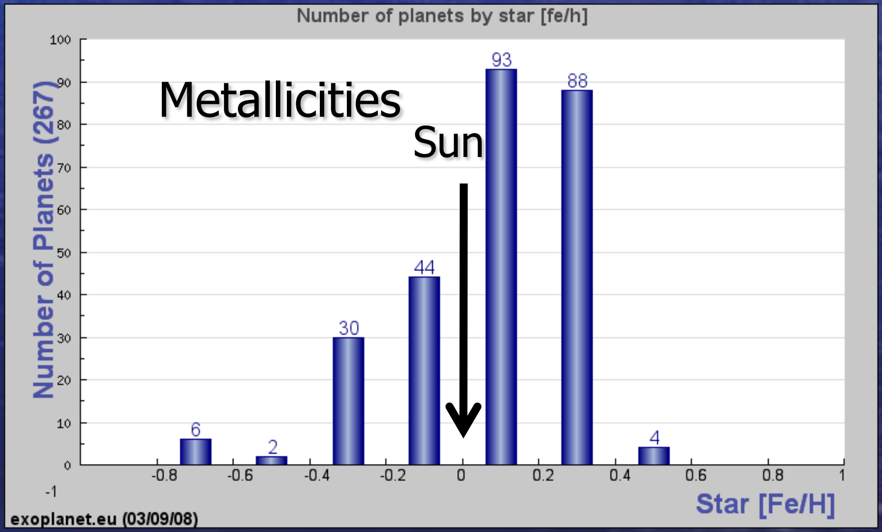
- Radial Velocity -289 (248 systems, 29 multiple)
- Transit - 52 (all confirmed by radial velocity)
- Microlensing - 7
- Direct Imaging – 5 controversial
- Astrometry (1 confirmation)
- Other - 5

- Cluster and free-floating (3 controversial)
- Circumstellar (disks around ~15% of stars)

- STRICTLY MOST ARE 'CANDIDATES' .. HEAVY BURDEN OF PROOF

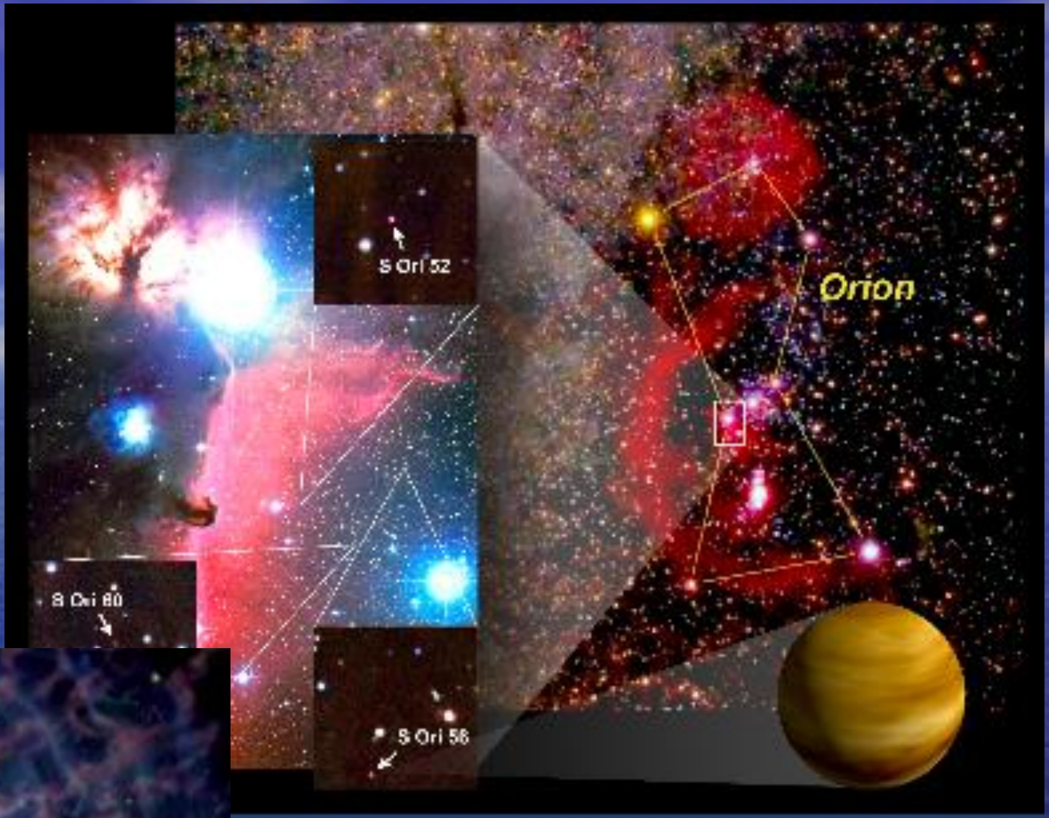
Highly varied properties

- 51 Peg, Jupiter in 3 day orbit!
- Approximately 1 in 100 stars hosts a 'hot Jupiter' (roaster)
- 0.02 Mearth (pulsar planet PSR 1257 +12b) to 13 Jupiter masses (defined as less than 13 Jupiter masses)
- Most with much higher eccentricities than Solar System planets
- Metallicities from -0.7 to 0.5 dex (5x less to 3x higher than Sun)



- Distances from 3 to 6500pc
- Multiple planet systems indicate resonant orbits
- We now know the densities of more planets outside the Solar System than inside

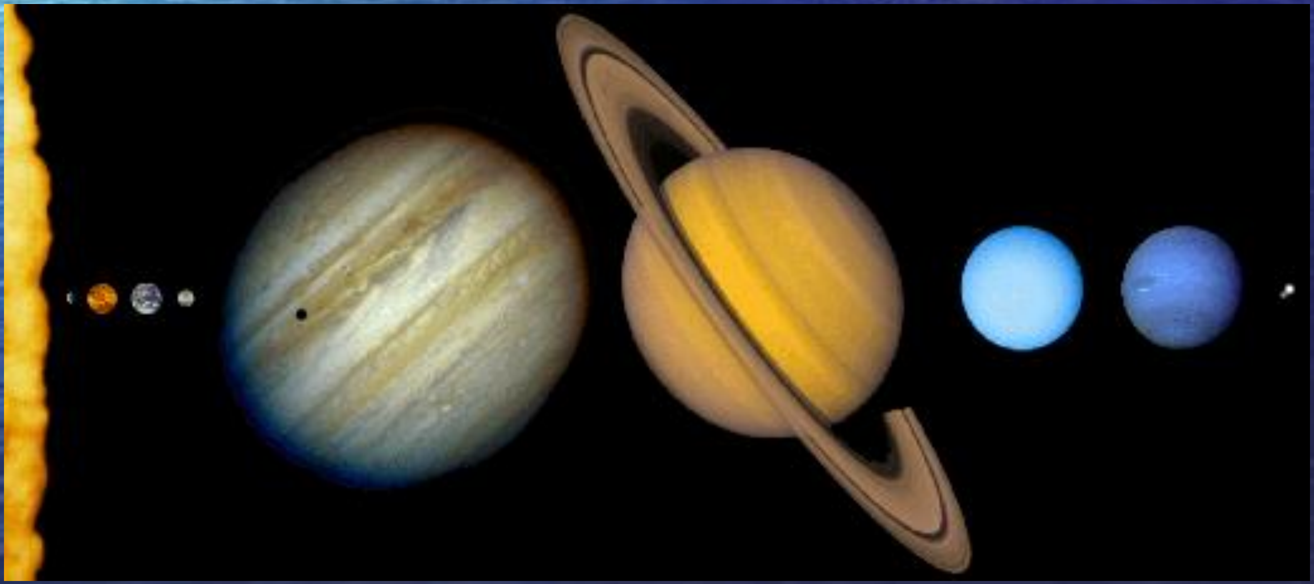
Robust



- Range of properties, e.g. in metallicity and eccentricity
- Range of environments, e.g., pulsar planets to Orion free-floating planetary mass objects indicate

Frequency of Planet hosting stars?

- >12% of FGK stars host at least one planet
- **1% of FGK stars host 'hot Jupiter'**
- At least 1 in 10 stars hosts a multiple planet system



NOT yet sensitive to
our Solar System
Around any local star.

Hot Jupiters – atmospheres

- How can we learn about the atmospheres of planets?

Photometry

- Secondary eclipse: (star + planet light) – (star light)

  E.g. Spitzer Space Telescope Infrared observations have successfully measured temperatures of planets

Transit Spectroscopy

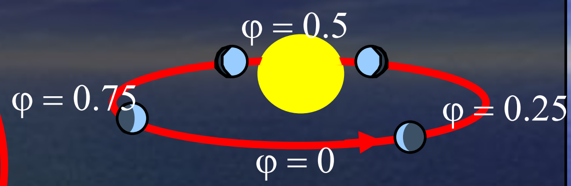
- Measure size of planet at different wavelengths

Spectroscopy

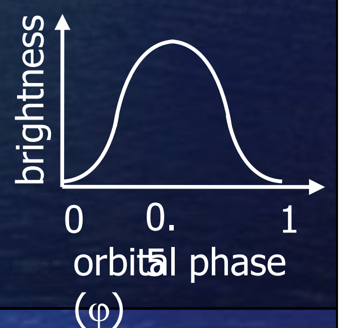
- e.g. Reflected light or direct spectroscopic detection in the infrared

Reflected light: variation with orbit

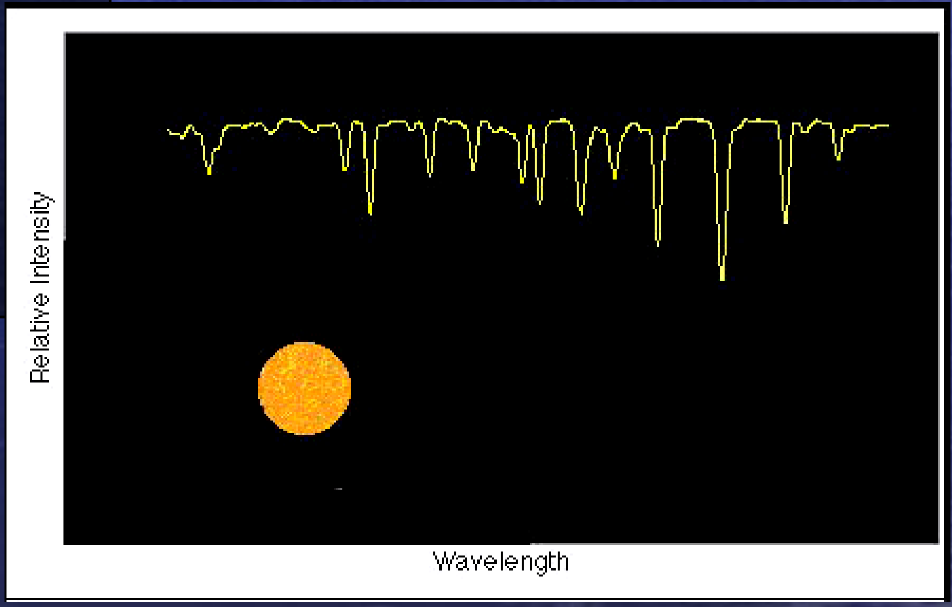
Planetary phases



$i > 0°$, brightness variation with orbital phase

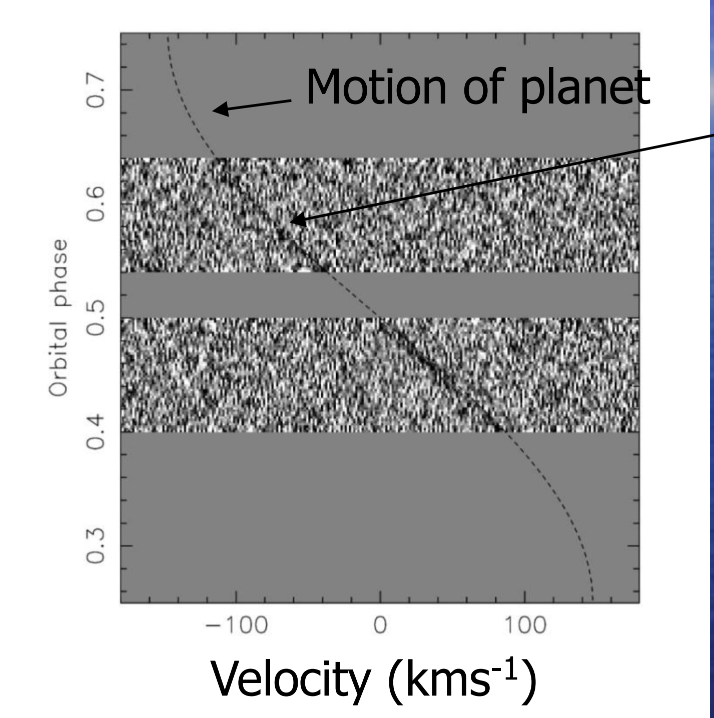


$i = 0°$ (face on) no brightness variation



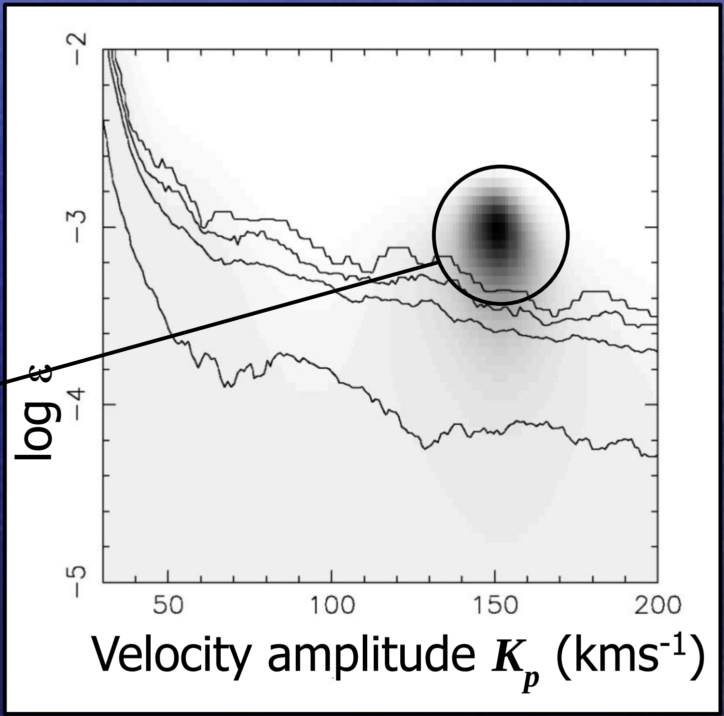
- Planet shows phases like Venus, hence its brightness varies with orbital phase
- In INFRARED, planet shows phases due to heated inner face of the planet

Example - a model planet



Simulated data - may spectra stacked up and plotted as a greyscale

Planet is 1000x fainter (log ε = -3) than the star)



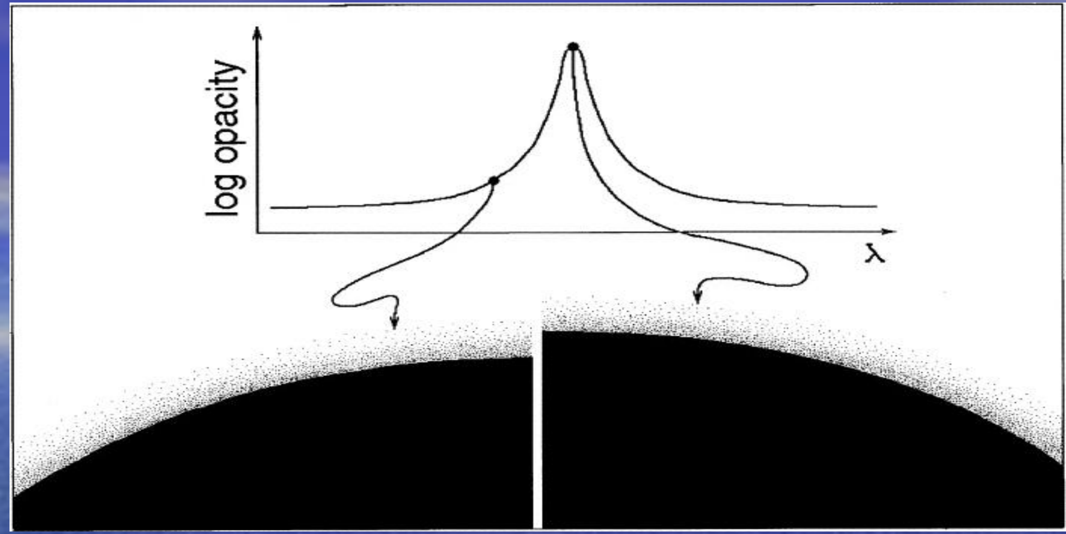
- No planet detected by reflected light – implies dark, unreflective atmosphere
- Planet not seen in IR where models predict it should be – absorption lines in models may not be adequate

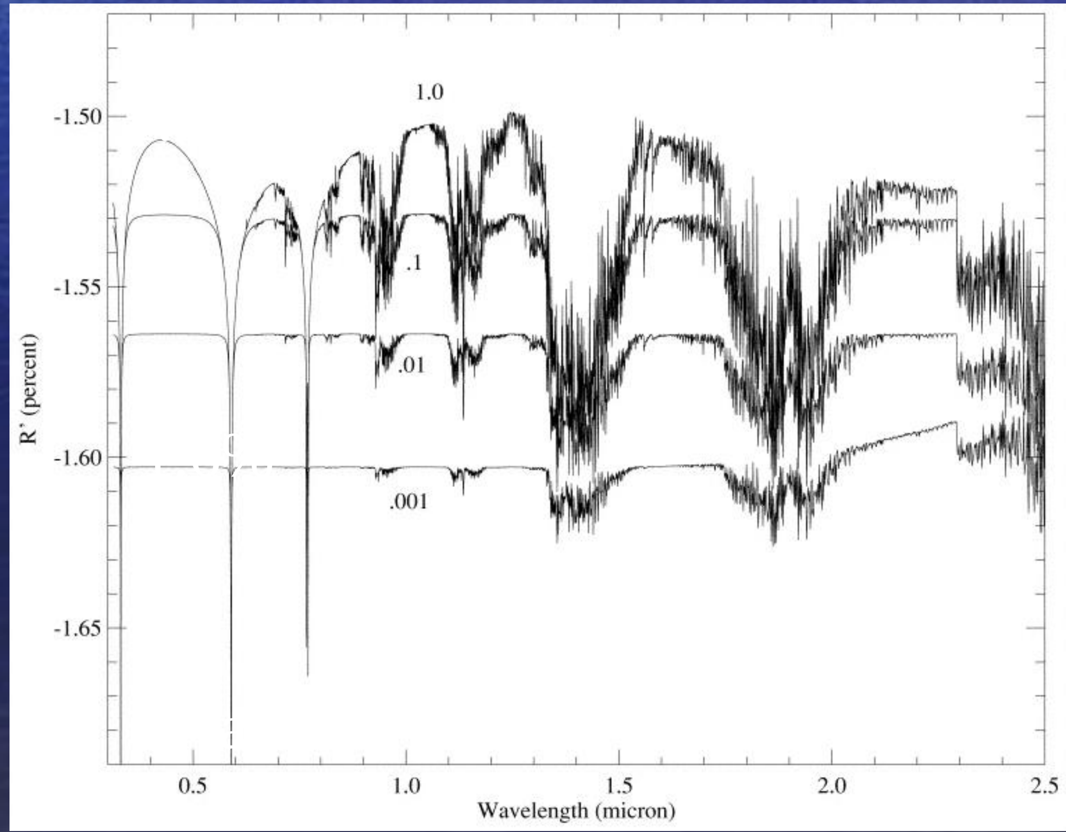
Transit Spectroscopy

Molecules or objects absorb stellar light passing through atmosphere ---> atmosphere appears opaque ---> effective area of planet appears larger (larger transit depth) ---> radius of planet appears larger

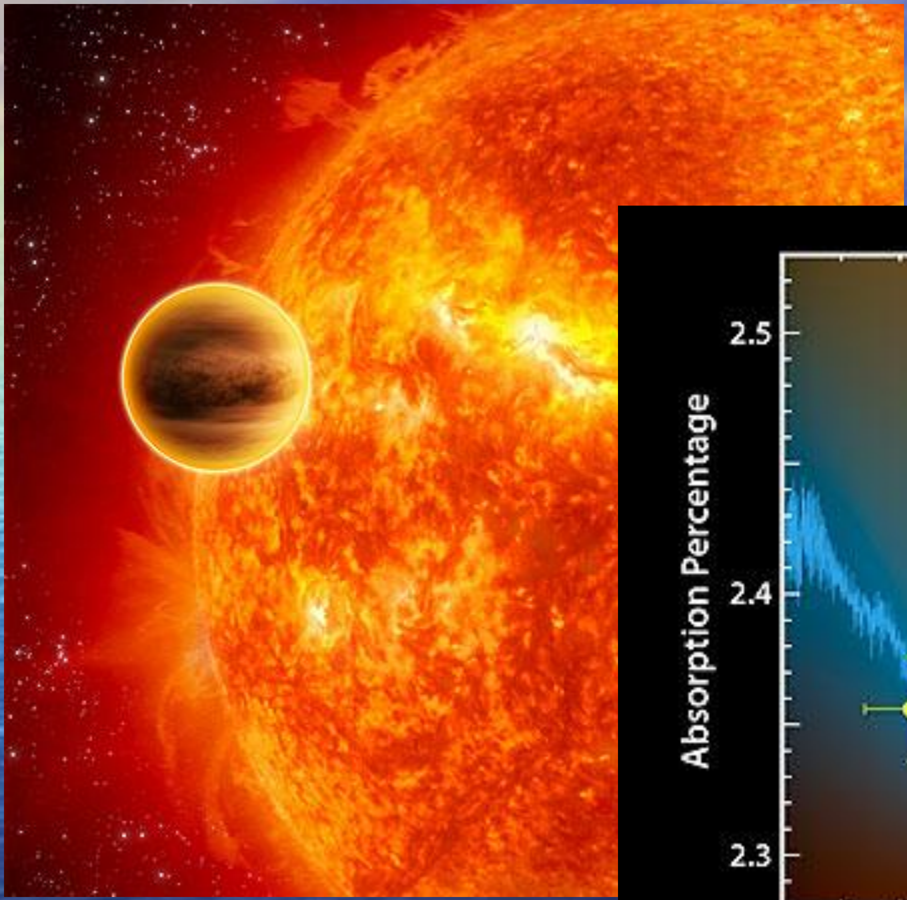
- planetary atmosphere
- composition
- cloud decks
- winds

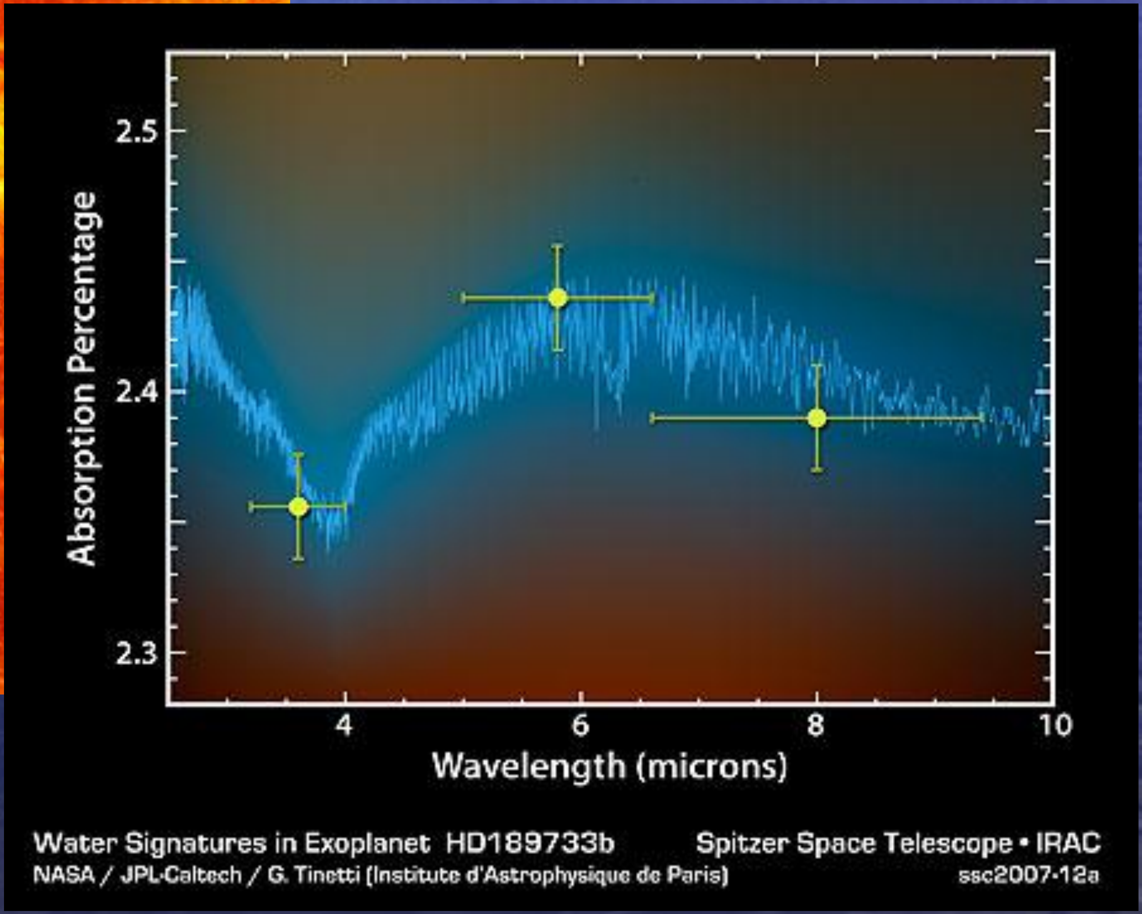
transit depth



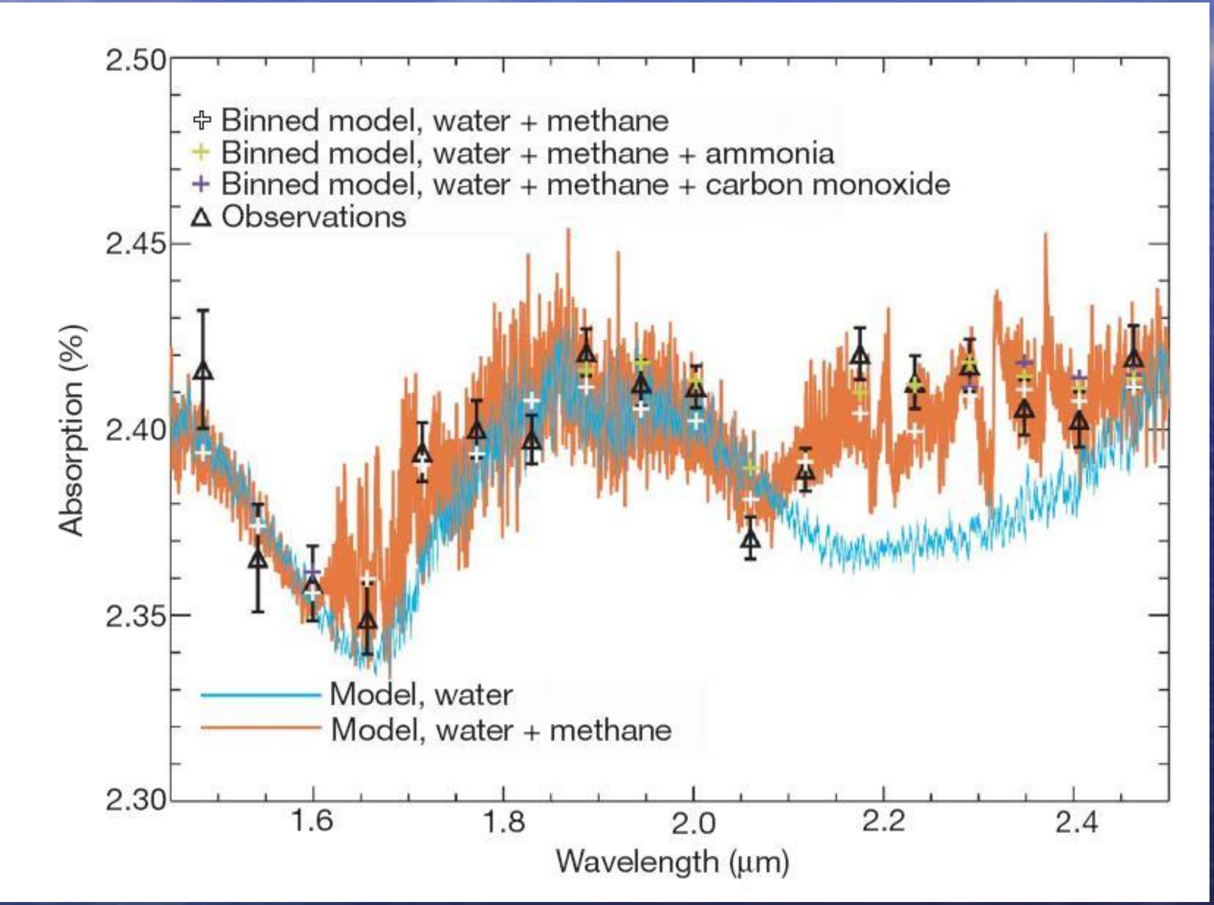


Water in a Hot Jupiter Atmosphere

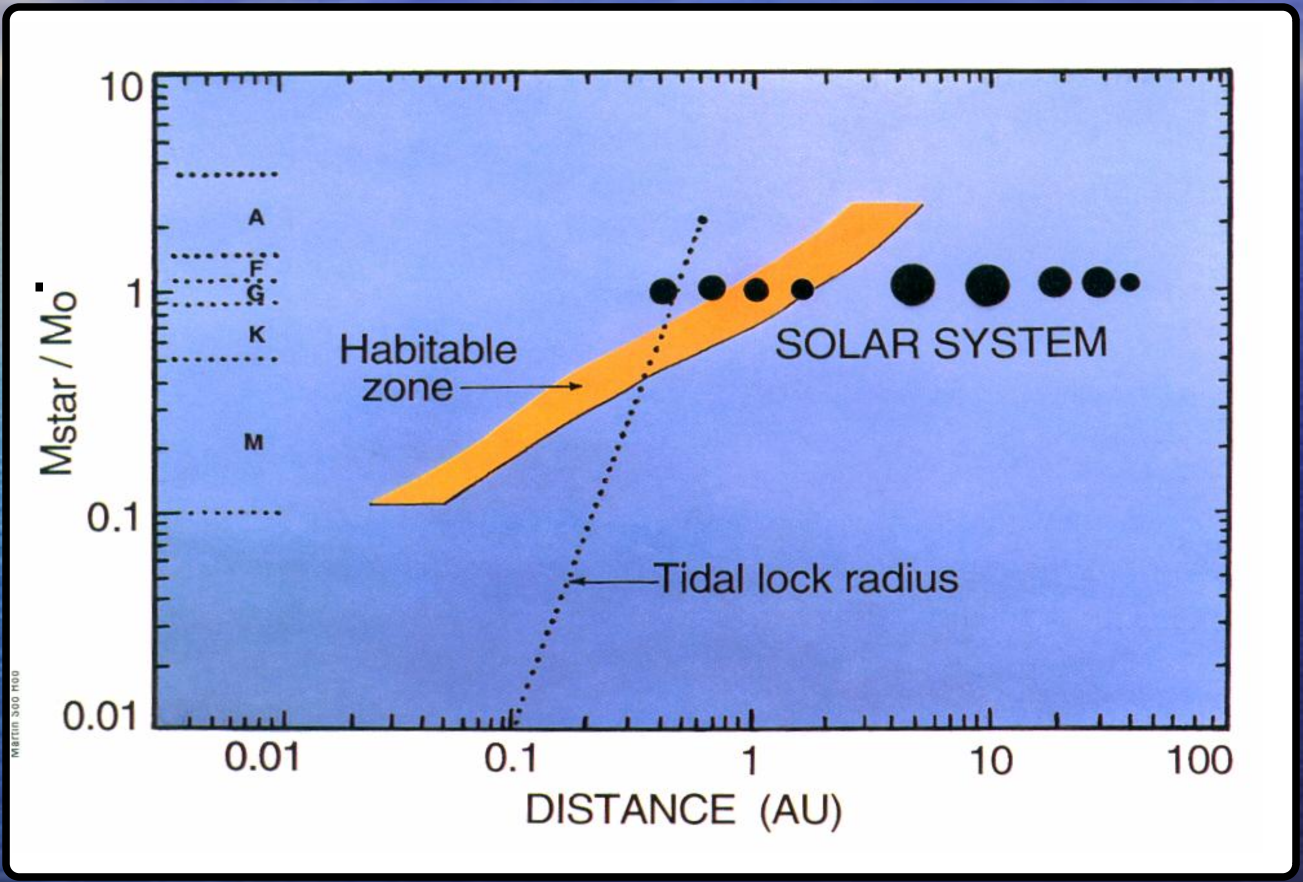




Organic molecules in a Hot Jupiter atmosphere

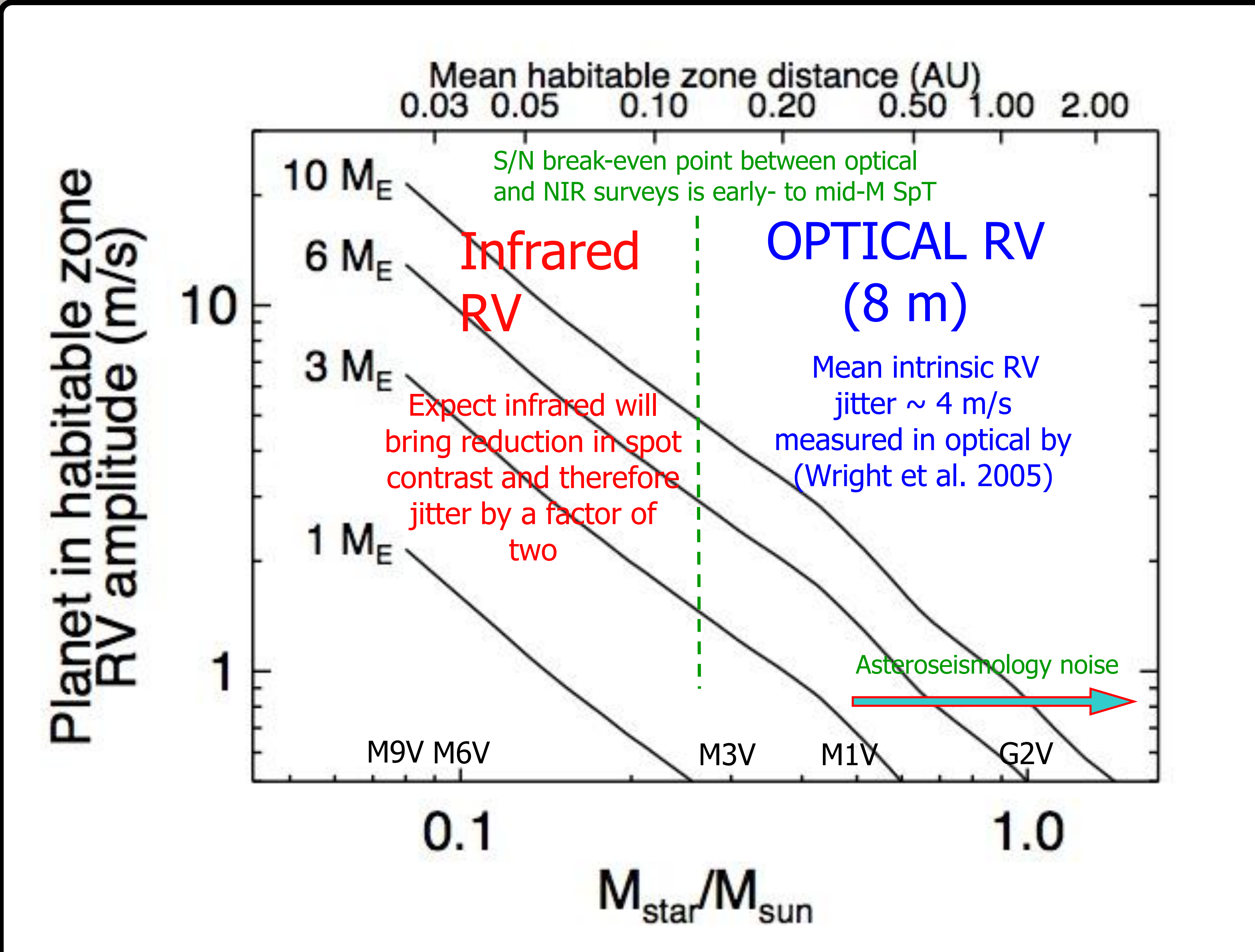


Habitable zone is more accessible around M dwarfs when observed in the NIR



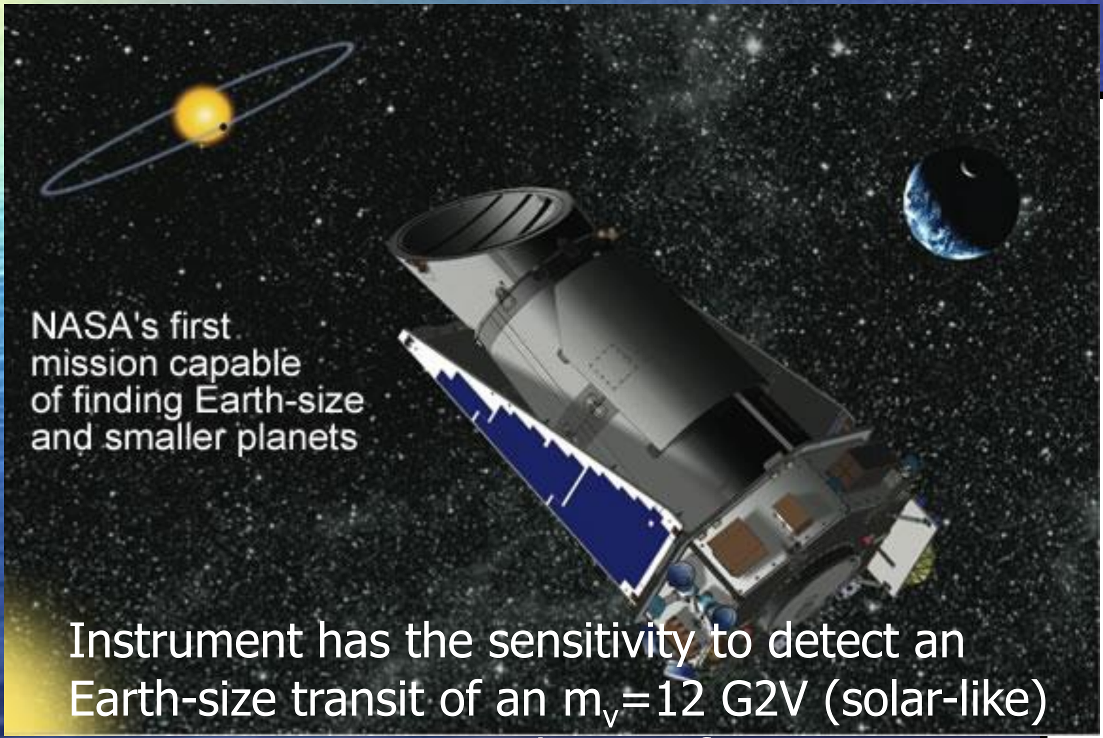
M Star Planet Habitability: Special issue of Astrobiology (February 2007), including review by Tarter *et al.*

SENSITIVITY NICHE

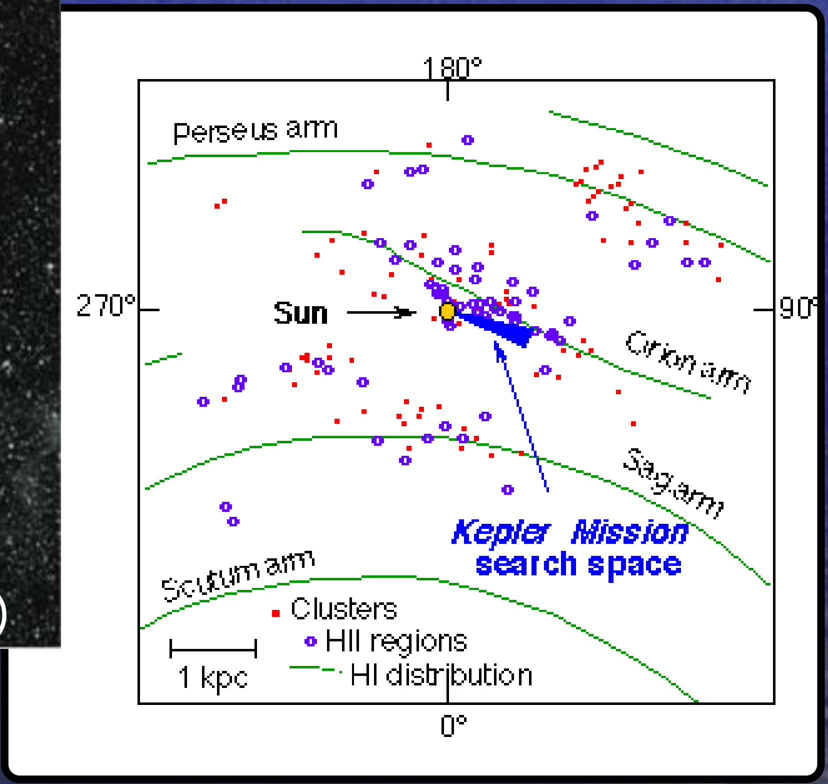


Kepler mission (Launch in Feb 2009)

- Use transit method to determine the percentage of terrestrial and larger planets there are in or near the habitable zone of a wide variety of stars

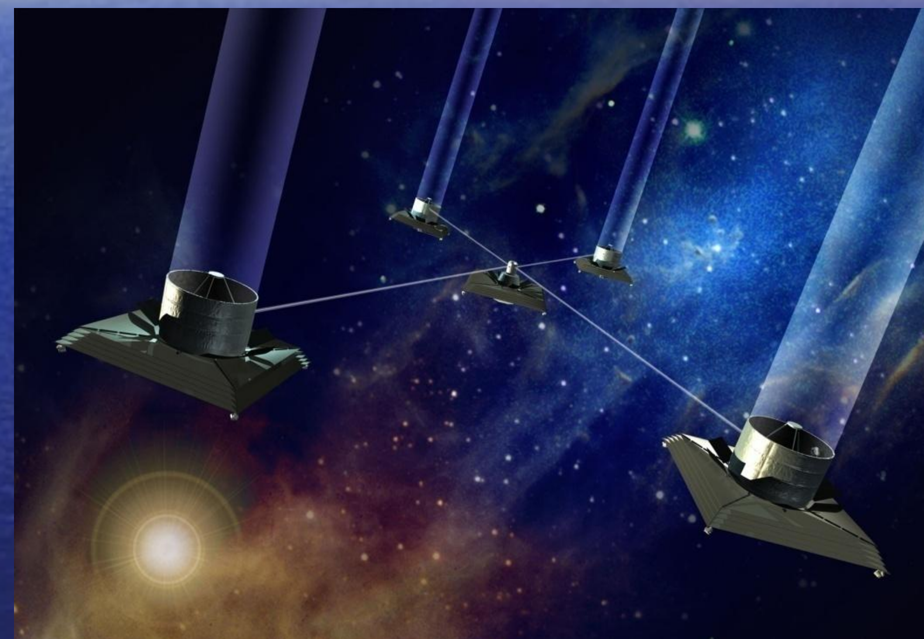


Instrument has the sensitivity to detect an Earth-size transit of an m_v=12 G2V (solar-like) star at 4 sigma in 6.5 hours of integration. Spectral bandpass from 400 nm to 850 nm.



DARWIN, ESA.
(Launch 2015)

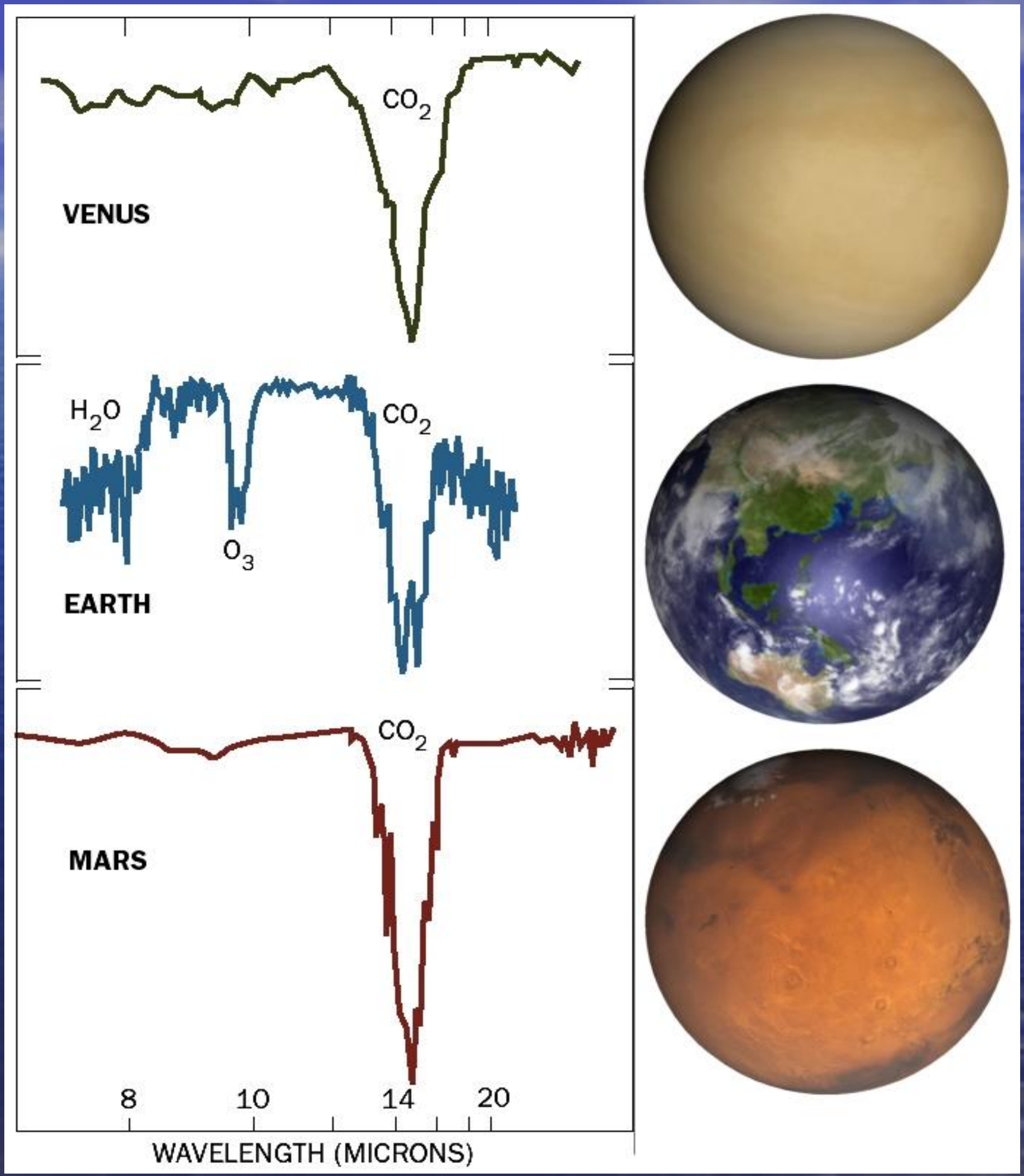
Terrestrial Planet Finder, NASA.
Launch 2015



Infrared free-flying interferometer to detect ozone, water, carbon monoxide in the spectra of nearly exoEarths

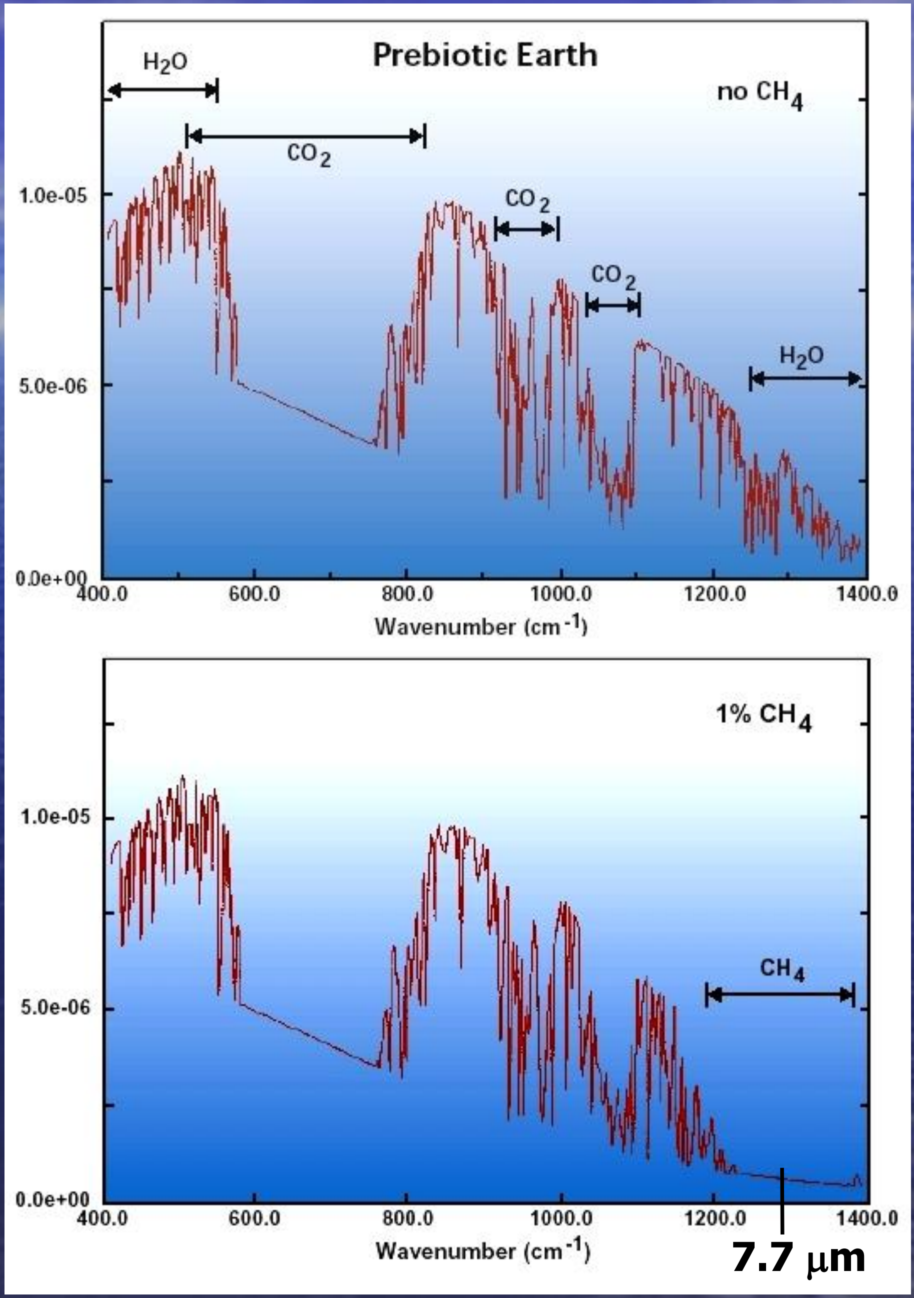
Terrestrial Spectra

- Ozone (O_3) indicative of life
- H_2O planet with oceans
- N_2O & CH_4, produced by bacteria and farming. Could indicate life, but not necessarily civilised.
- This information combined with planet radius, orbital radius, stellar spectral type could tell us if planet is habitable and shows signs of life



Prebiotic spectra

- Two spectra of methane (CH_4) present in the Earth's atmosphere.
  - Early prebiotic Earth shows no methane.
  - Later prebiotic Earth is modified by methane producing bacteria as shown in the second spectrum.



Summary

- Exciting time for planet discovery and characterisation
- Ground based infrared spectrographs will enable Doppler searches for Earth-mass planets around low mass stars
- Space based missions to search for an characterise Earth-mass planets – e.g. Kepler, Darwin, TPF