Extrasolar Planets

Introduction

So far: have looked at planets around our Sun

Physics question:

Is our Solar System normal?

$\Longrightarrow$ Are there planets around other stars?

can then compare solar system with other systems.

To answer these questions, we need to detect extrasolar planets.

Detection Methods

Possible ways to detect extrasolar planets:

Direct Method:

- . . . direct imaging of planet (visual binary)

Indirect Methods: search for evidence for. . .

- . . . radial velocity: Motion of host star (spectroscopic binary)
- . . . periodic variation of proper motion of the star (like Sirius) astrometric binary
- photometry: light curves: occultation (transits)
- others (not discussed here):
  - . . . influence of planet on light from behind planet (gravitational lensing)
  - . . . time of flight variations (pulsars, pulsating stars)

Direct Imaging

In order to make an image of an extrasolar planet, need to separate images of star and planet with telescope

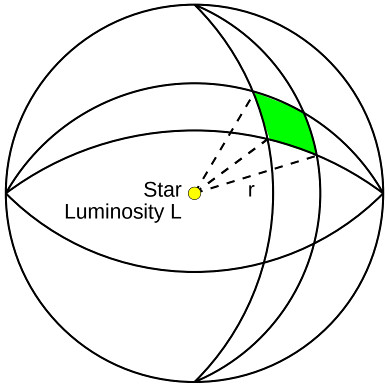
$\Longrightarrow$ Requires two ingredients:

1. “contrast” (relative intensity of star and planet)
2. “resolving power” of telescope (angular distance between star and planet)

Direct Imaging: Contrast

Estimate intensity contrast between star and planet:

Solar system: Luminosity of Sun $L = 3.90 \times 10^{26}$ W $=: L_\odot$



This power is emitted isotropically into all directions.

$\Longrightarrow$ Energy received per second on whole area of sphere of radius r (area $A = 4\pi r^2$) equals L as well!

$\Longrightarrow$ Energy falling per second on area of 1 m^2 at distance r ("flux"):

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

units: W m^{-2} or erg cm^{-2} s^{-1}

Direct Imaging: Contrast

Plugging in typical numbers:

Earth:

distance: $r = 1$ AU $= 150 \times 10^6$ km

$\Longrightarrow P \sim 1380$ W m^{-2} ("solar constant").

Total power received by Earth: projected solar facing area $A = \pi r_\oplus^2 = 1.26 \times 10^{14}$ m^2

$\Longrightarrow$ Total power received: $P_{\text{total},\oplus} = 1.74 \times 10^{17}$ W.

Of this, about 30% is reflected, i.e., $L_\oplus = 5.2 \times 10^{16}$ W $\sim 10^{-10} L_\odot$.

The luminosity of the Earth is 10 billion times weaker than that of the Sun.

in infrared, luminosity contrast is only 10 million, but still rather weak. . .

Direct Imaging: Contrast

Plugging in typical numbers:

Jupiter:

distance: $r = 5.2$ AU $= 7.8 \times 10^8$ km $\Longrightarrow P \sim 51$ W m^{-2}

Total power received by Jupiter: projected solar facing area $A = \pi r_{♃}^2 = 1.6 \times 10^{16}$ m^2

$\Longrightarrow$ Total power received: $P_{\text{total},♃} = 8.2 \times 10^{17}$ W.

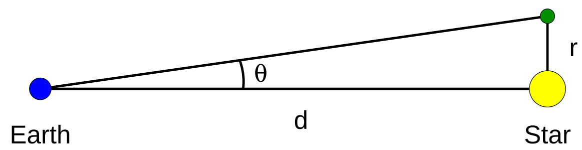
Of this, about 30% is reflected, i.e., $L_{♃} = 2.5 \times 10^{17}$ W $\sim 6 \times 10^{-10} L_\odot$.

The luminosity of Jupiter is ~1 billion times weaker than that of the Sun.

$\Longrightarrow$ For typical planets around solar type stars, we need to be able to detect intensity contrasts of better than 1:1 billion.

$\Longrightarrow$ Not doable now, but not unrealistic to achieve in your lifetime ("coronagraphs"). . .

Direct Imaging: Angular Separation



How close on sky are images of Sun and planet?

$$\tan\theta = \frac{r}{d} \quad\Longrightarrow\quad \theta \sim \frac{r}{d}$$

Typical distances to nearby stars: $d \sim 100$ Ly $= 9.5 \times 10^{17}$ m,

typical distances in planetary system: $r \sim 1$ AU $= 1.5 \times 10^{11}$ m,

$$\Longrightarrow \quad \theta = \frac{r}{d} = 1.57 \times 10^{-7}\,\text{rad} = 9 \times 10^{-6}\,\text{deg} = 0.03''$$

Direct Imaging: Angular Separation

Optics: resolving power of telescope with diameter D:

$$\alpha = \frac{12''}{D/1\,\mathrm{cm}} \tag{2.8}$$

$\Longrightarrow$ to resolve 0.03″, need $D = 4$ m, so doable

BUT

Earth atmosphere limits resolution to $\sim$0.5″ (“seeing”)

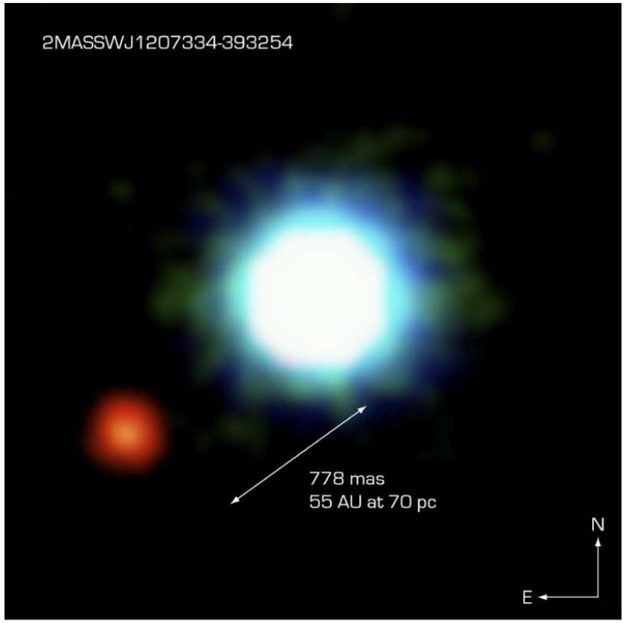
Currently, direct detection of extrasolar planets around solar-type stars is not doable from ground, although it is technologically feasible from space.

NASA: Space Interferometry Mission and Terrestrial Planet Finder: cancelled

ESA: Darwin: cancelled

James Webb SpaceTelescope (JWST): 6.5m mirror

direct planet imaging possible, but no large-scale surveys, launch: 2018



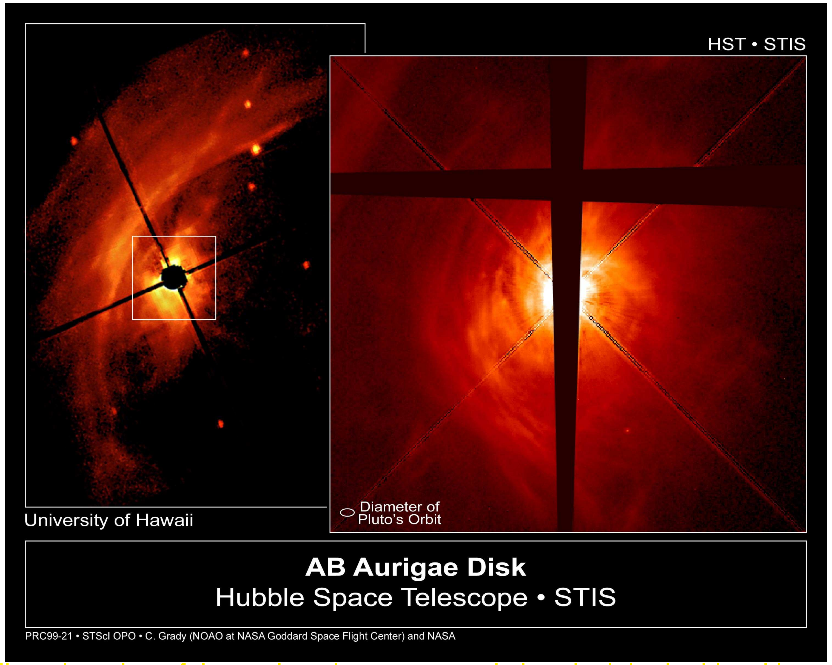
The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

ESO PR Photo 14a/05 (30 April 2005) ©ESO

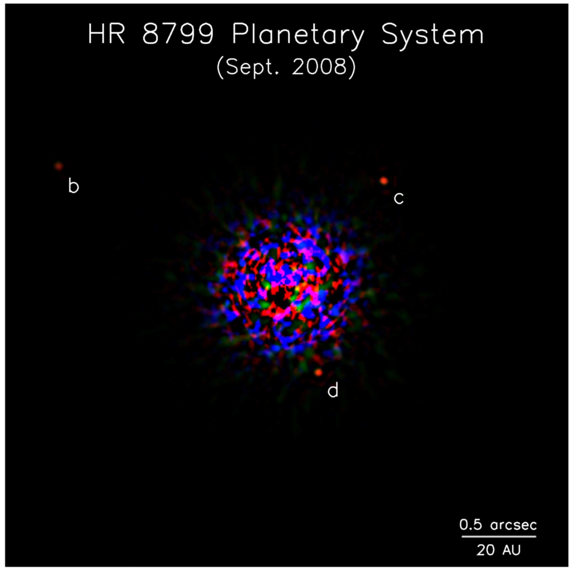
Using adaptive optics, it is possible to obtain diffraction limited resolution in the near infrared.

Contrast is still a problem, however, for one very dim star (a “brown dwarfs”) a planetary companion was detected in early 2005 with the VLT and confirmed in 2006 with HST.

Distance between star and planet: $\sim 2\times$ Neptune distance, distance to system 59 ± 7 pc.



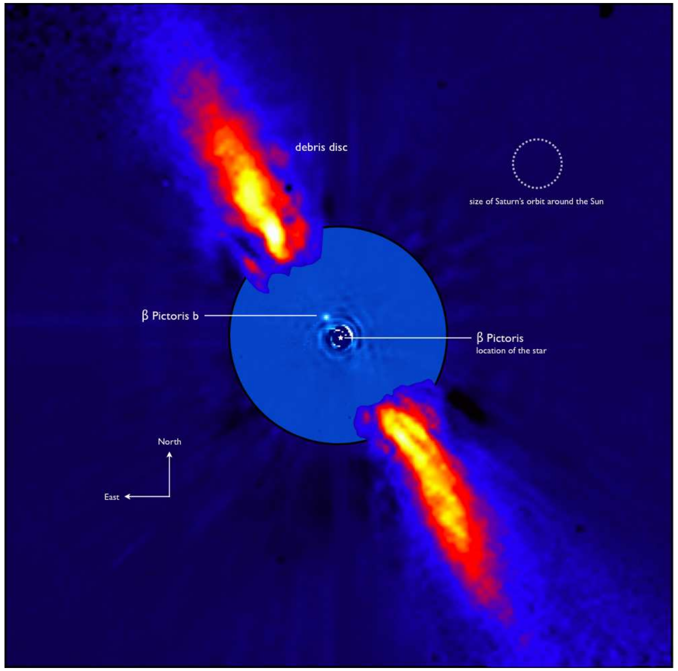
…direct imaging of the region close to a star is in principle doable with modern technology (HST, VLT, et al.)



C. Marois (NRC-HIA), IDPS survey and Keck Observatory

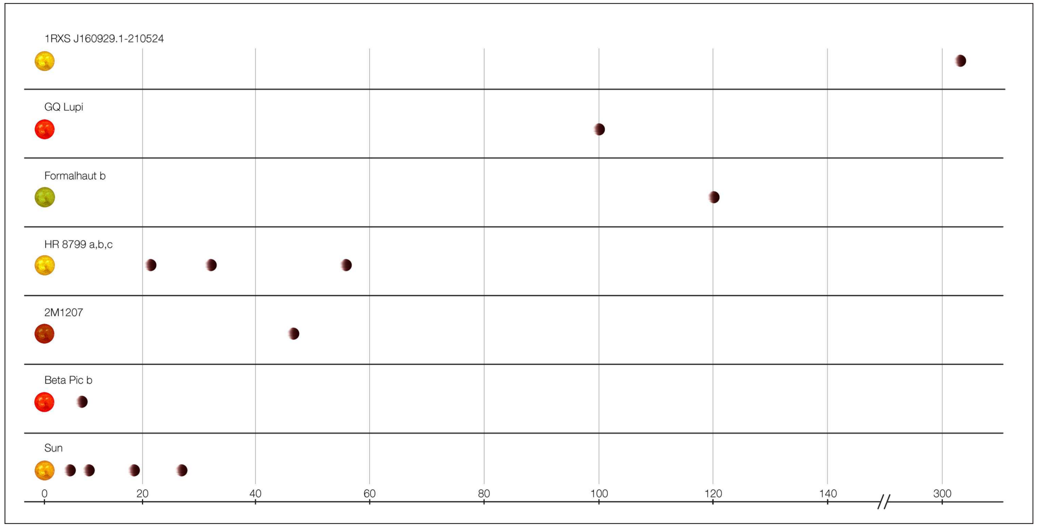
13.11.2008: Direct imaging of planetary system around HR 8799 announced; distances 68, 38, and 24 AU from star (constellation Pegasus; $d = 39$ pc).

2010: detection of another planet, e, at distance $\sim$15 AU from star



ESO

21.11.2008: Direct imaging of planet with ESO-VLT and NACO instrument announced (planet around β Pictoris, 1000$\times$ fainter than star).



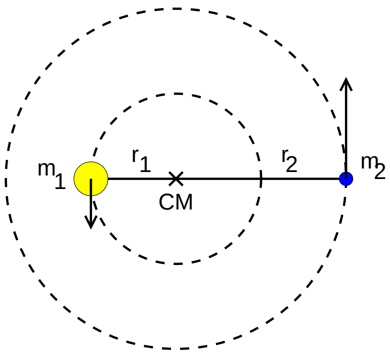
ESO

Overview of some systems with imaged planets

47 systems (51 planets) in total as of Nov 5, 2014 (5PM)

Radial Velocity Measurements

If we cannot see planet directly $\Longrightarrow$ use indirect methods.



Two-body problem: Star and planet move around common center of mass:

$$m_1 r_1 = m_2 r_2$$

For circular orbits and orbital period P, velocity of star due to action of planet is

$$v_1 = \frac{2\pi r_1}{P} = \frac{2\pi}{P} \cdot \frac{m_2}{m_1} \cdot r_2$$

Example: Sun vs. Jupiter:

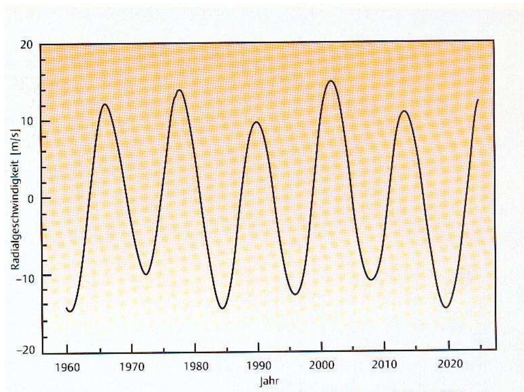
$m_1 = 2 \times 10^{30}$ kg, $m_2 = 2 \times 10^{27}$ kg, $r_2 = 5.2$ AU $= 7.8 \times 10^{11}$ m, $P_J = 11.9$ yr $= 3.76 \times 10^8$ s

$\Longrightarrow v_1 = 13.1\,\mathrm{m\,s^{-1}} \sim 50\,\mathrm{km\,h^{-1}}$

Example: Sun vs. Earth gives $v_1 = 10\,\mathrm{cm\,s^{-1}} \sim 0.8\,\mathrm{km\,h^{-1}}$

Radial Velocity Measurements

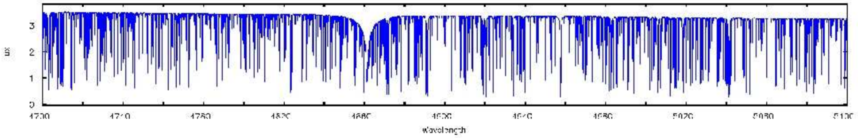
Doppler motion of the Sun due to all planets in the solar system as an observer in the ecliptic would have measured:



- Superposition of sinusoidal radial velocity curves.
- amplitude = $13\,\mathrm{m\,s^{-1}}$
- Largest effect due to Jupiter.

need to measure stellar radial velocity to much better than $13\,\mathrm{m\,s^{-1}}$.

Radial Velocity Measurements



Doppler motion of the Sun: $\frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}} = \frac{v}{c}$;
$v = 13\,\text{m}\,\text{s}^{-1} \Longrightarrow \Delta\lambda/\lambda = 4 \times 10^{-8}$,
Line broadening due to thermal motion of the light emitting ions:

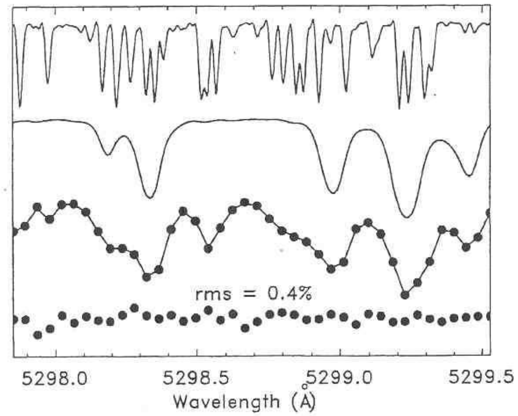
$$v_{\text{therm}}^2 = \frac{2kT}{Am_{\text{H}}} \Longrightarrow \frac{\Delta\lambda}{\lambda} = \left(\frac{2kT}{Am_{\text{H}}c^2}\right)^{1/2} \tag{7.1}$$

where A: atomic weight in atomic mass units (m_{H})
For the Sun ($T = 5780\,\text{K}$):

- Hydrogen: $v_{\text{therm}}(H) = 9.8\,\text{km}\,\text{s}^{-1} \Longrightarrow \frac{\Delta\lambda}{\lambda} = 3 \times 10^{-5}$
- Iron: $v_{\text{therm}}(Fe) = 1.3\,\text{km}\,\text{s}^{-1} \Longrightarrow \frac{\Delta\lambda}{\lambda} = 4 \times 10^{-6}$ (prefer heavy elements!)

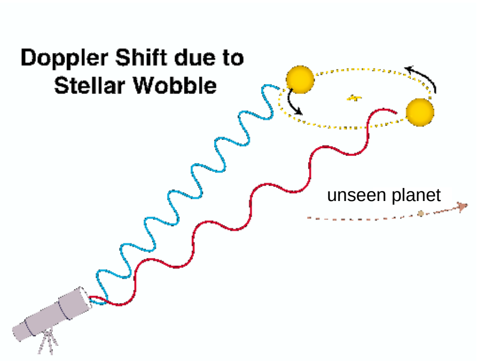
Intrinsic line widths are 400–3000 times larger than expected Doppler velocity.

Radial Velocity Measurements



- accuracy can only be reached by measuring tens of thousands of lines
- long term stability: very stable wavelength standard needed
- Iodine cell in front of spectrograph: Iodine vapor at about 50° C. High mass (127), low temperature $\Longrightarrow$ sharp lines.
- cross correlation of spectra.
- works with cool stars, e.g. solar-like (sufficient number of lines).

Results



G. Marcy

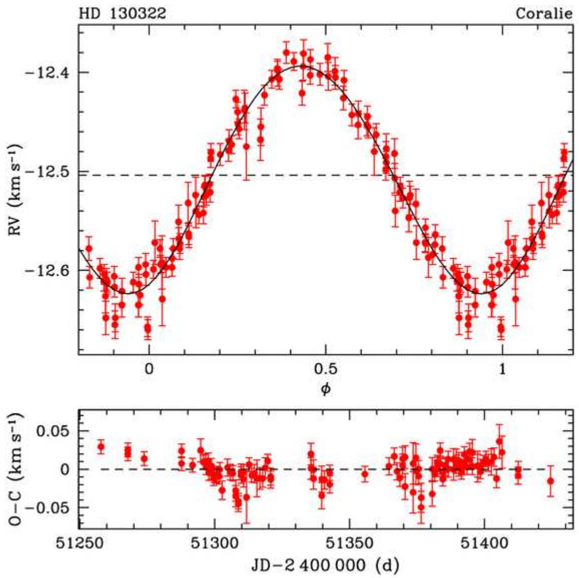
How to hunt extrasolar planets using the Doppler Detection Method:

1. get access to *lots* of telescope time
2. get access to *very good* spectrograph
3. measure for years, to determine changes in velocity of stars due to motion of star around CM

As of Nov 5, 2014, 1849 extrasolar planets were known.

Lots of information can be found at `http://www.exoplanet.eu/`

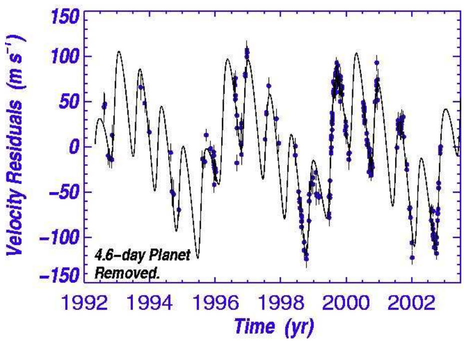
Results

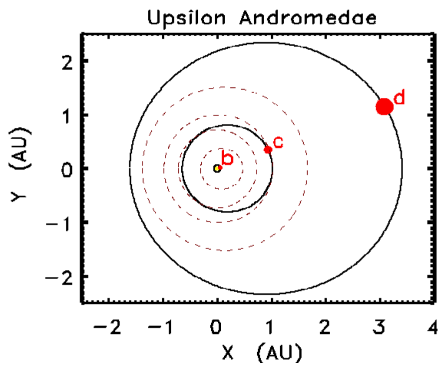


Example: Changing radial velocity of HD 130322 results in discovery of Jupiter-mass planet (Udry et al., 2000).
Here: velocity amplitude: $115\,\text{m}\,\text{s}^{-1}$.

Radial velocity = velocity along our line of sight.

Results

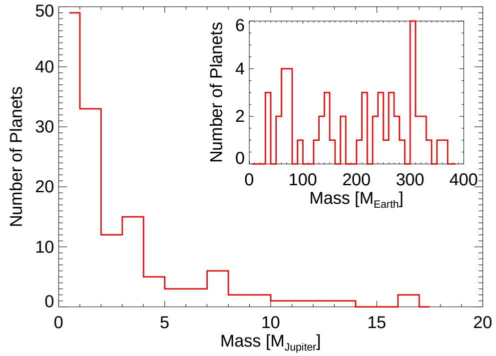




G. Marcy/UC Lick

Velocity signature and orbits of the three planets around υ Andromedae in meantime: four planets.

Results: Mass limits



- Only mass function can be directly derived:

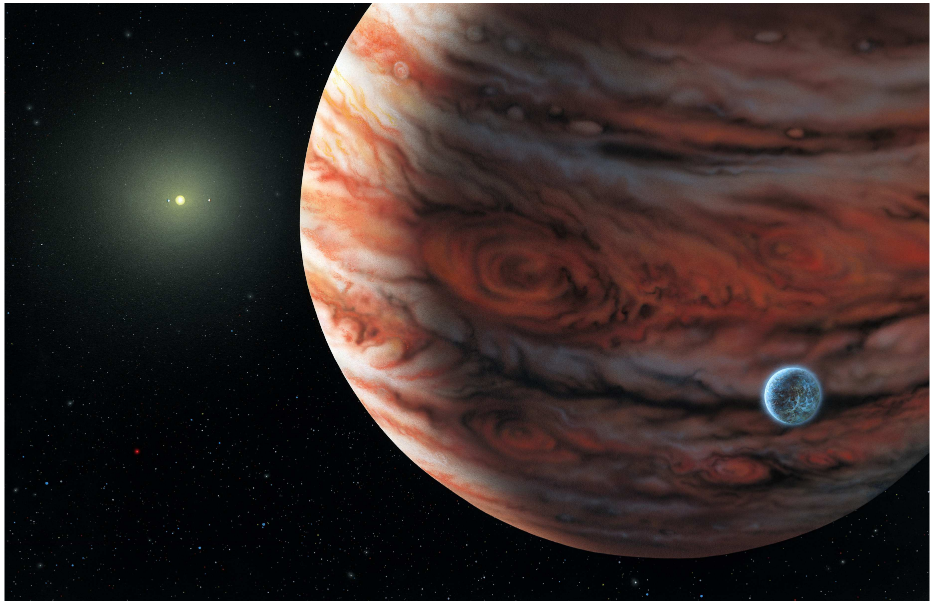
$$f(M) = \frac{M_p (\sin i)^3}{\left(1+\frac{M_s}{M_p}\right)^2} = \frac{P K_s^3}{2\pi G} \qquad (7.2)$$

- mass of the star M_s from spectroscopy $\Longrightarrow M_p \sin i$, i.e., lower limit to the planet´s mass M_p; inclination remains indetermined
- Many planets found have $M_p \sin i > M_♃$ ($M_♃$ = 318 $M_\oplus$)

Selection effect: large $M \Longrightarrow$ larger velocity amplitude $\Longrightarrow$ easier to detect!

So, the fact that we have not seen many Earth-like planets does not mean that they are rare, just that we cannot detect them efficiently.

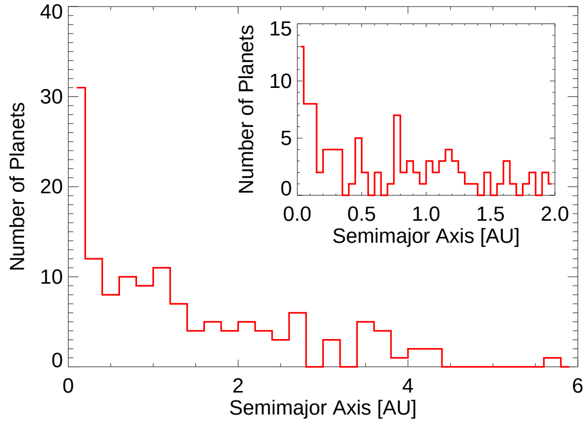
Smallest mass found so far: $>$ 0.01 $M_\oplus$ around Kepler 37 (but not using rv-method).



ESA press release, copyright 2002 Lynette Cook, `http://extrasolar.spaceart.org/`.

Jupiter-sized planet plus minor planets (left: detected, Jupiter-scale planet, right: hypothetical planet) around 55 Cancri.

Results: Semimajor Axis



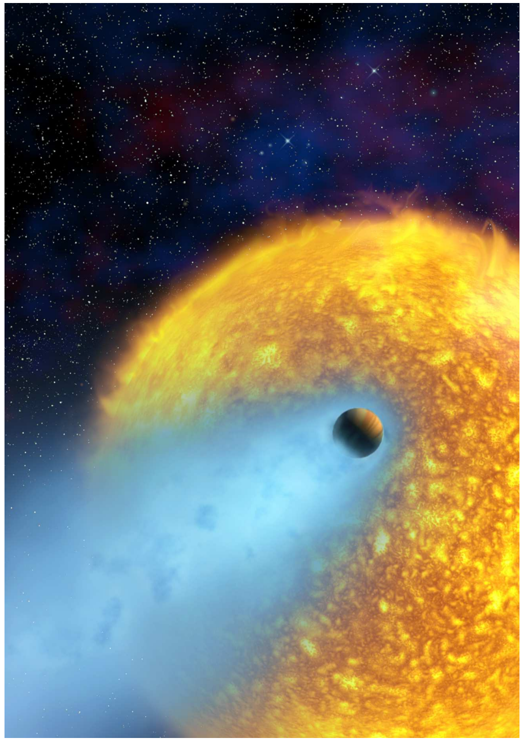
once planet mass estimated: semimajor axis from 3rd Kepler law (if star mass known):

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

Most planets found are close to companion star!

Selection effect: small $a \Longrightarrow$ short period

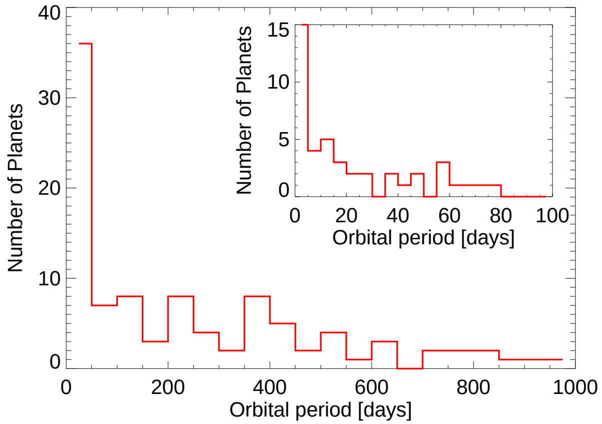
$\Longrightarrow$ detectable in small amount of time (years, not decades)



Jupiter-scale planets close to stars: "hot Jupiters"
e.g., HD 209458b, only 7 Million km from star: planet is evaporating (HST spectroscopy: mass loss is $10^7\,\mathrm{kg\,s^{-1}}$)!

ESA

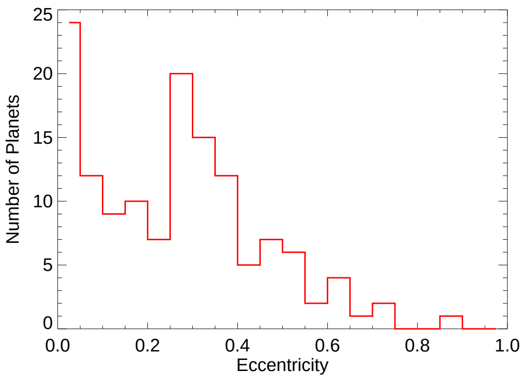
Results: Period



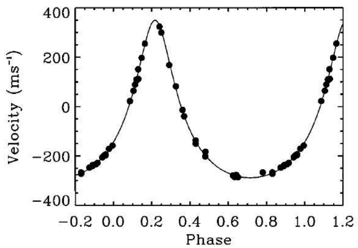
Most planets found in short orbits!

Statistics is direct consequence of the selection effect of the previous slide: short period planets are detectable during typical durations of observing runs...

Results: Eccentricity



70 Vir b: $e = 0.4$ (Marcy & Butler 1996, ApJ, 464, L147)



Many planets are in eccentric orbits!

different from solar system!

Might be selection effect due to our existence:

Jupiter in eccentric orbit in our solar system

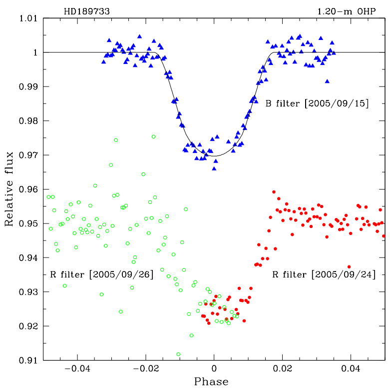
$\Longrightarrow$ strong disturbances of Earth's orbit $\Longrightarrow$ no life!

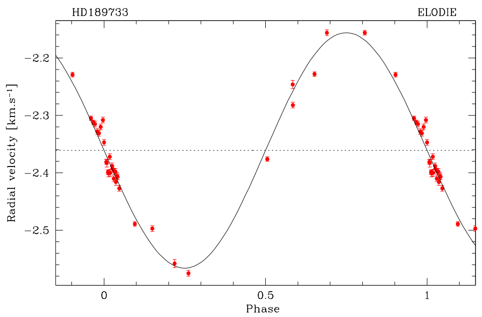
So, in some sense Copernican principle does *not* always seem to hold!

D.M.Hardy / PPARC

But not all is bleak – HD 70642 ($d = 90$ ly): discovered by Hugh Jones (Liverpool John Moores University): Jupiter mass planet at 3 AU from solar-like star in circular orbit
$\Longrightarrow$ stable Earths are possible.

Transits



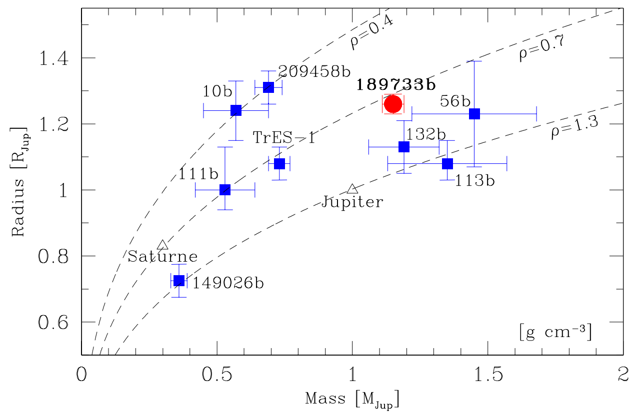


Planetary transit: occultation of the star by the planet

$\Longrightarrow$ inclination known

Can determine mass *and* radius of the planet!

Transits



- Masses and radii: $\Longrightarrow$ density
- many similar to Saturn and Jupiter
- several less dense than Saturn and Jupiter
- inflated by heating by host star

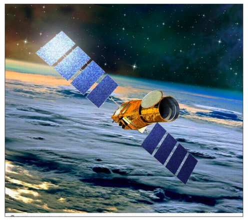
Low densities $\Longrightarrow$ these planets are made of gas!

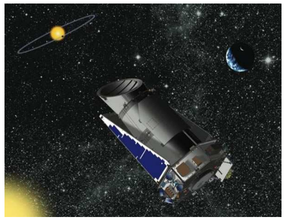
Transits

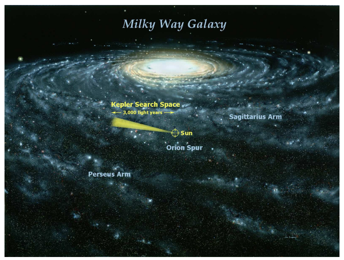
transit detections: currently most productive technique

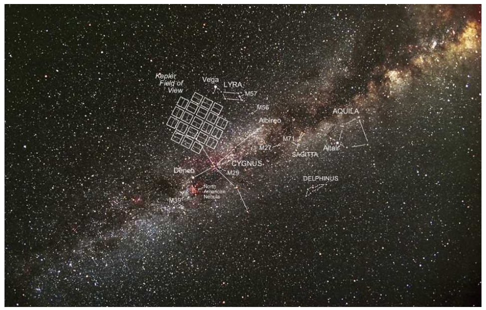
- COROT (ESA) & Kepler (NASA) space missions
- long-term photometric monitoring of fields in Milky Way
- both missions terminated

  $\Longrightarrow$ archives for candidate detection

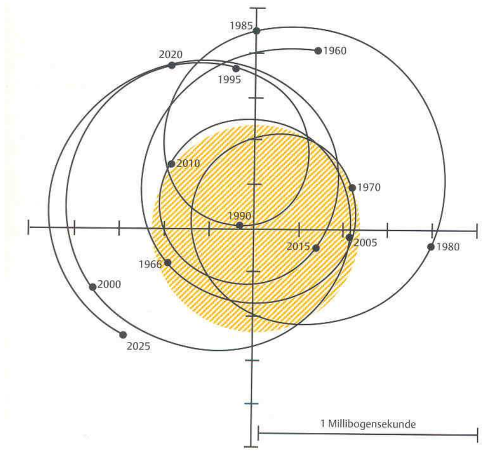




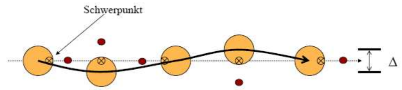




Astrometry

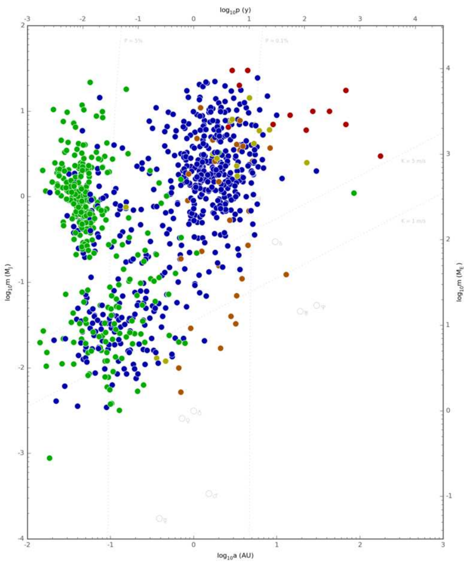


Motion of the Sun around the center of gravity viewed from above from 10 pc distance



- astrometric binary
- discovery of Sirius B
- how large is the effect if star carries a solar system?
- measure periodic wobble of the proper motion
- need precision <1 mas, not achieved yet
- GAIA astrometric mission of ESA to be lauched in 2013

Results: Overview



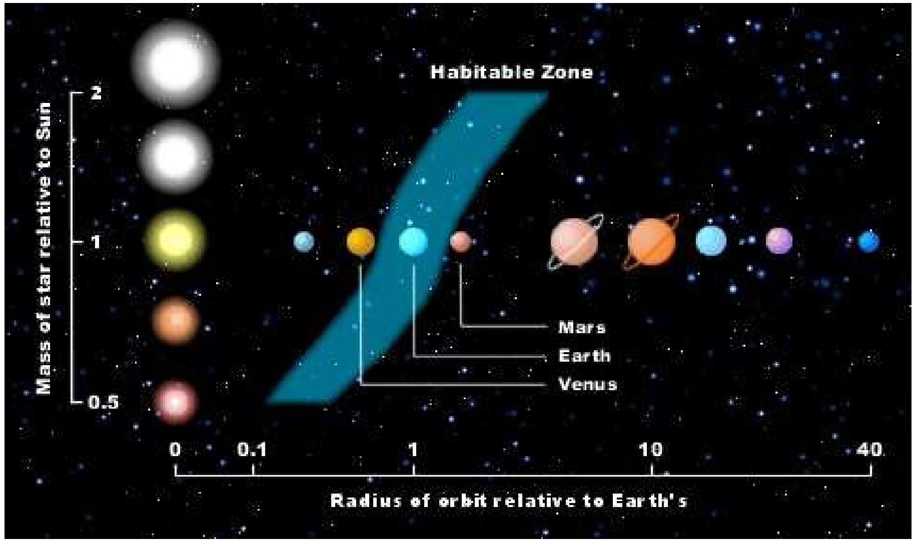
exoplanet masses vs. orbital periods

- detectional bias different for different detection methods
- planet with properties similar to Earth not found yet

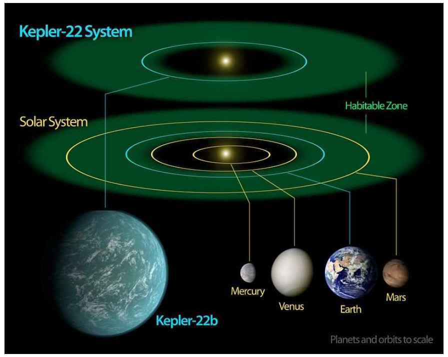
detection method:

- radial velocity (dark blue)
- transit (dark green)
- timing (dark purple)
- direct imaging (dark red)
- microlensing (dark orange)
- Solar System planets for reference

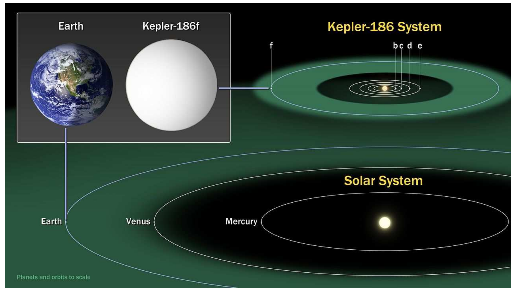
Habitable Zone



Habitable Zone



- Kepler-22: G5 V star
- superearth?
  $P = 290\,\mathrm{d}$, $d \approx 30500\,\mathrm{km}$



- Kepler-186: M dwarf
- terrestrial planet?
  $P = 130\,\mathrm{d}$, $d = 1.11 \pm 0.14\, R_\oplus$

Summary

Detections: of the 1849 planets known to date (05.11.2014):

- 579 were discovered through Doppler motion, 1163 are transiting
- 51 were discovered through imaging

Properties:

- Hot Jupiters: very close orbits (periods of few days, e.g. 51 Peg)
- Jupiters on very eccentric orbits (70 Vir)
- Jupiters on nearly circular orbits and long periods (e.g. 47 UMa)
- Planets with masses similar to Saturn, Neptune, Earth, . . .
- 471 planetary systems: HD10180, KOI-351 have seven planets
- currently 8 planets in habitable zones (+35 candidates)
- Kepler-62e = Super-Earth: mass of $1.61 \pm 0.05 M_\oplus$
  rocky (silicate-iron) composition

$\Longrightarrow$ extrapolation: 100-400+ billion planets in Milky Way