Extrasolar Planets

Introduction

So far: have looked at planets around our Sun

Physics question:

Is our Solar System normal?

⟹ 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

Indirect Methods: search for evidence for. . .

- . . . gravitational interaction with star in radial velocity
- . . . gravitational interaction with star in motion of star
- . . . influence of planet on light from behind planet (gravitational lensing)

For time reasons: will look at direct imaging and radial velocity measurements only. . .

Direct Imaging

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

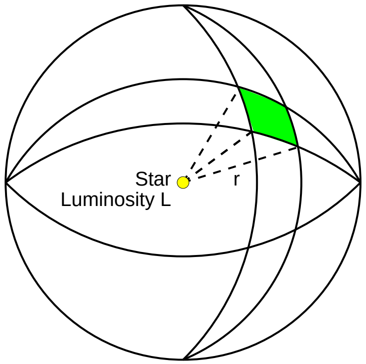
⟹ Requires two ingredients:

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

Direct Imaging: Contrast, III

Estimate intensity contrast between star and planet:

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



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 $1\,\mathrm{m}^2$ at distance r (“flux”):

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

units: $\mathrm{W\,m^{-2}}$ or $\mathrm{erg\,cm^{-2}\,s^{-1}}$

Direct Imaging: Contrast, IV

Plugging in typical numbers:

Earth:

distance: $r = 1\,\mathrm{AU} = 150 \times 10^6\,\mathrm{km}$

$\Longrightarrow P \sim 1380\,\mathrm{W\,m^{-2}}$ (“solar constant”).

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

$\Longrightarrow$ Total power received: $P_{\text{total},\oplus} = 1.74 \times 10^{17}\,\mathrm{W}$.
Of this, about 30% is reflected, i.e., $L_{\oplus} = 5.2 \times 10^{16}\,\mathrm{W} \sim 10^{-10}\,L_{\odot}$.

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, V

Plugging in typical numbers:

Jupiter:

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

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

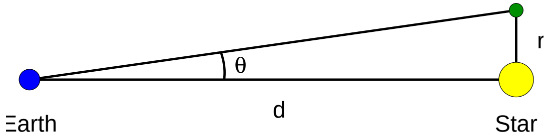
$\Longrightarrow$ Total power received: $P_{\text{total},\text{♃}} = 8.2 \times 10^{17}\,\mathrm{W}$.
Of this, about 30% is reflected, i.e., $L_{\text{♃}} = 2.5 \times 10^{17}\,\mathrm{W} \sim 6 \times 10^{-10}\,L_{\odot}$.

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, I



How close on sky are images of Sun and planet?

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

(for small θ: Taylor series: $\tan\theta \sim \theta + (1/3)\theta^3 + \ldots$; “small angle approximation”)

Typical distances to nearby stars: $d \sim 100\,\mathrm{Ly} = 9.5 \times 10^{17}\,\mathrm{m}$,
typical distances in planetary system: $r \sim 1\,\mathrm{AU} = 1.5 \times 10^{11}\,\mathrm{m}$,

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

($1'' = 1\,\mathrm{arcsec} = 1/3600\,\mathrm{deg}$).

Direct Imaging: Angular Separation, V

Optics: **resolving power** of telescope with diameter D:

$$\alpha = \frac{12''}{D/1\,\mathrm{cm}} \qquad (8.8)$$

$\Longrightarrow$ to resolve $0.03''$, need $D = 4\,\mathrm{m}$, so doable

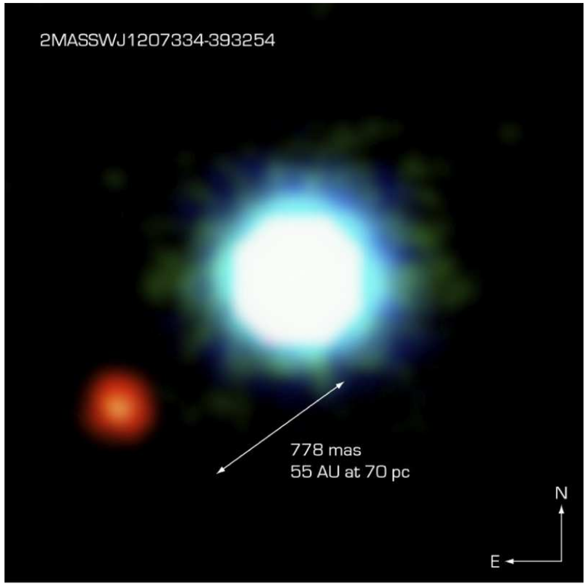
BUT

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**: 2 missions in the next decade(?): 4–6 m telescope (TPF-C); multiple 3–4 m telescopes (TPF-I, w/ESA)

ESA: **Darwin**: 3 $\gtrsim$3 m telescopes, launch planned for 2015



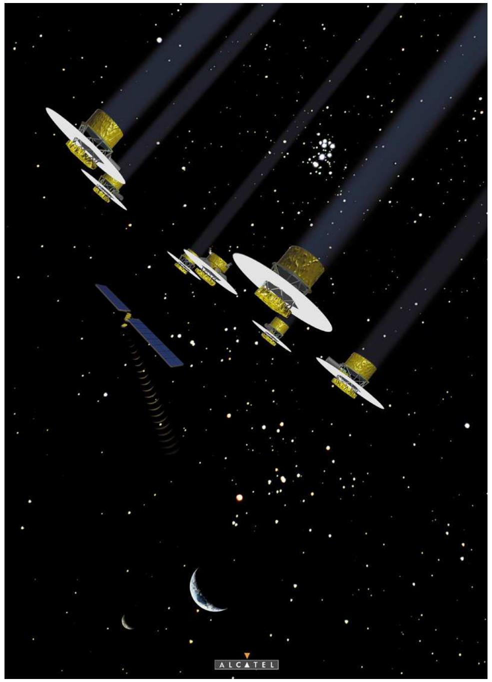
The Brown Dwarf 2M1207 and its Planetary Companion
(VLT/NACO)

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

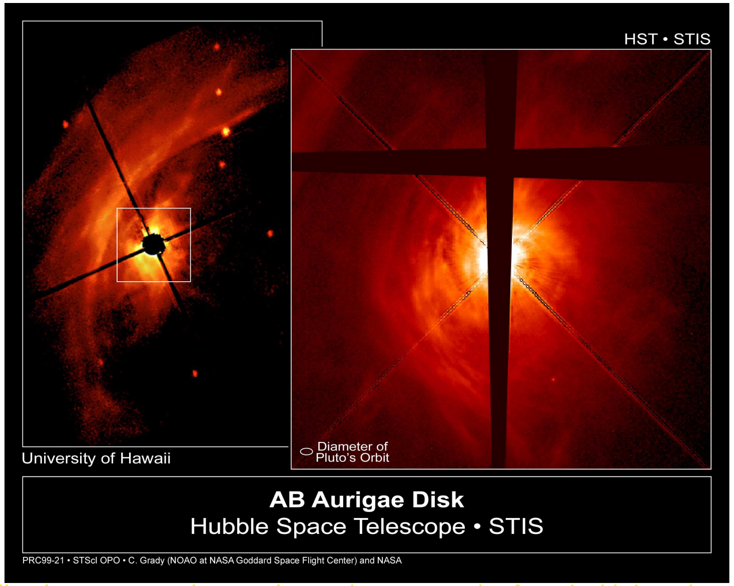
Using adaptive optics, it is possible to obtain diffraction limited resolution in the near infrared.

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× Neptune distance, distance to system $59 \pm 7\,\mathrm{pc}$.



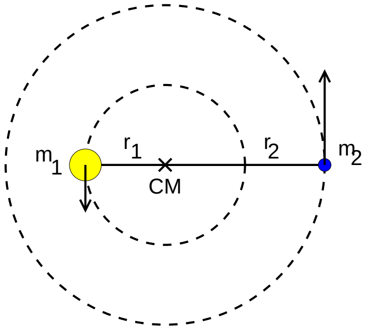
One possible configuration of ESA’s Darwin mission: several free-flying mirror spacecraft plus one spacecraft serving as communications hub.



. . . while planets around normal stars have yet to be found with imaging methods, direct imaging of the region close to a star is in principle doable with Hubble Space Telescope, but angular resolution not yet good enough.

Radial Velocity Measurements

If we cannot see planet directly ⟹ 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

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

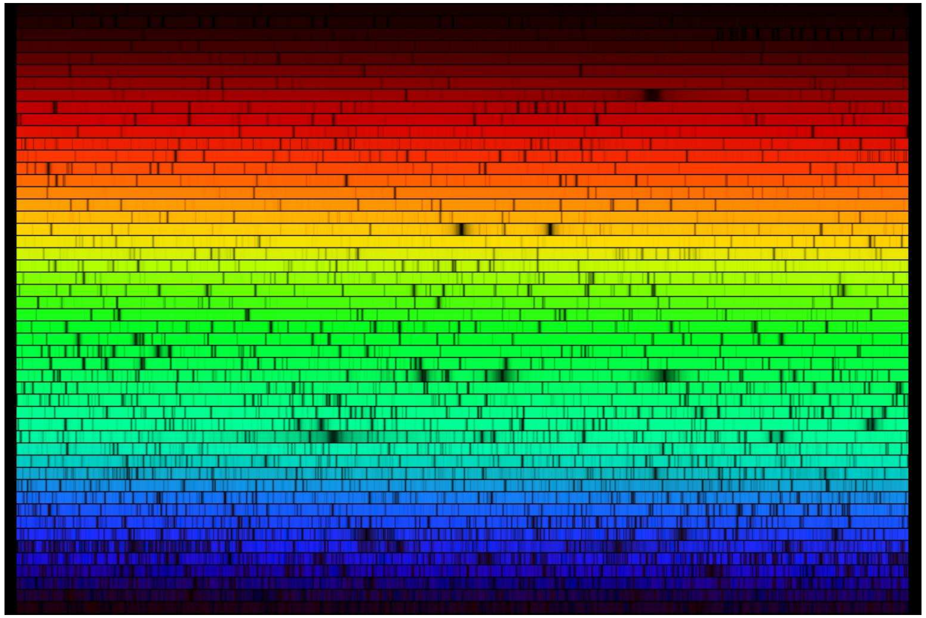
Example: Sun vs. Jupiter:
$m_1 = 2 \times 10^{30}\,\mathrm{kg}$, $m_2 = 2 \times 10^{27}\,\mathrm{kg}$, $r_2 = 5.2\,\mathrm{AU} = 7.8 \times 10^{11}\,\mathrm{m}$, $P_\mathrm{J} = 11.9\,\mathrm{yr} = 3.76 \times 10^{8}\,\mathrm{s}$
$\Longrightarrow v_1 = 13.1\,\mathrm{m\,s^{-1}} \sim 50\,\mathrm{km\,h^{-1}}$

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

Radial Velocity Measurements

To detect planets, need to be able to measure star velocities with precision to much better than $13\,\mathrm{m\,s^{-1}}$.

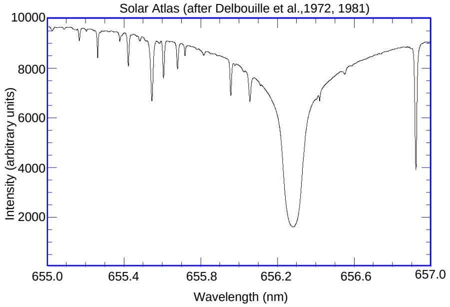
Measure motion of stars using spectroscopic methods.



N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

Absorption line spectrum of the Sun: Fraunhofer Lines

Radial Velocity Measurements



Using modern spectrographs, position of absorption lines can be measured with very high precision.

Example: Hα line from hydrogen in solar spectrum.

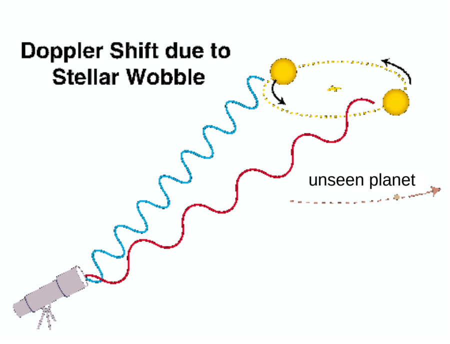
but: Light, such as all waves, suffers from Doppler-effect: Lines emitted from moving star are Doppler shifted:

$$\frac{\lambda_\text{observed} - \lambda_\text{emitted}}{\lambda_\text{emitted}} = \frac{v}{c}$$

⟹ Can use line shifts to detect extrasolar planets!

. . . but need good spectrograph: $v = 13\,\mathrm{m\,s^{-1}} \Longrightarrow \Delta\lambda/\lambda = 4 \times 10^{-8}$, which is only doable by using many tricks.

Results, I



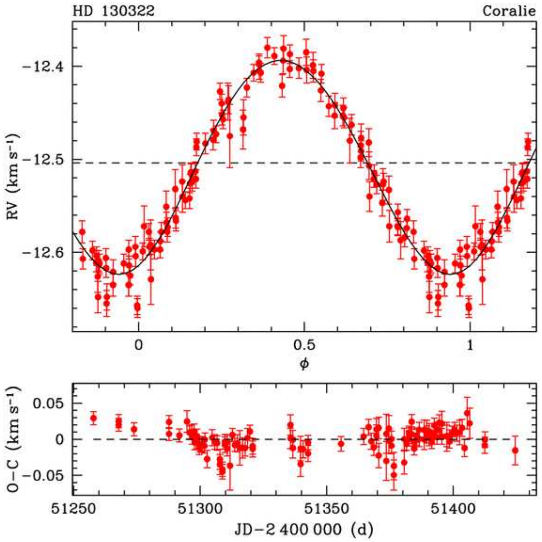
G. Marcy

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 2006 November 28, 195 extrasolar planets were known, circling 172 stars.

Results, II

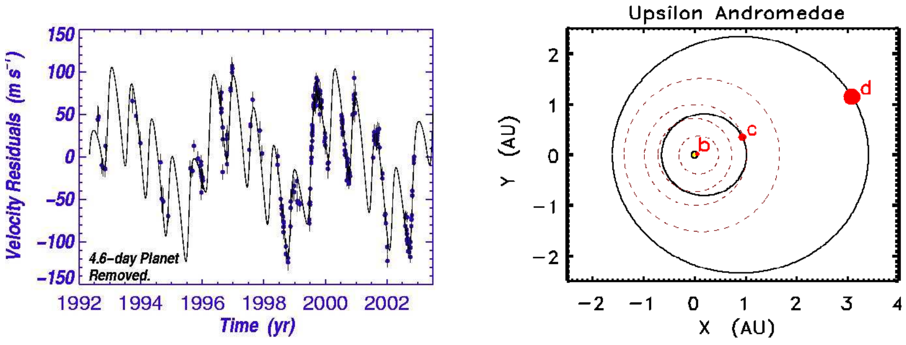


Example: Changing radial velocity of HD 130322 results in discovery of Jupiter-mass planet (Udry et al., 2000).

Here: velocity amplitude: 115 m s^{-1}.

Radial velocity = velocity along our line of sight.

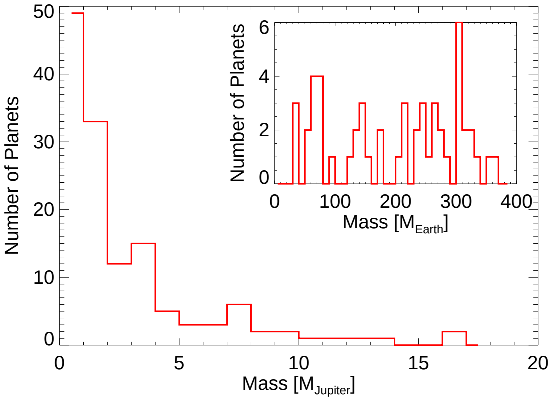
Results, III



G. Marcy/UC Lick

Velocity signature and orbits of the three planets around υ Andromedae.

Results: Mass, I



Many (most!) Planets found have $M > M_{♃}$

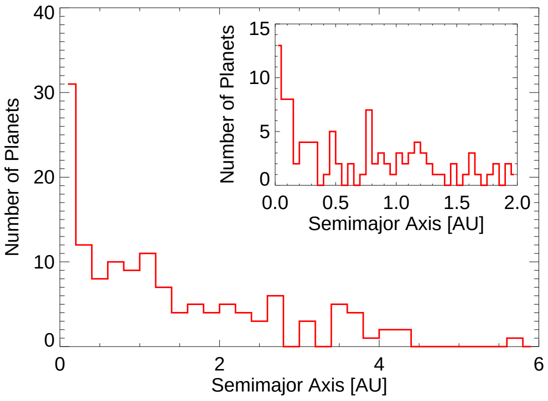
$M_{♃} = 318\,M_{\oplus}$

Selection effect: large $M \Longrightarrow$ larger velocity amplitude

$\Longrightarrow$ easier to detect!

So, the fact that we have not seen any Earth-like planets does not mean that they do not exist, just that we cannot detect them yet. Smallest mass found so far: 7.5 $M_{\oplus}$ around Gliese 876

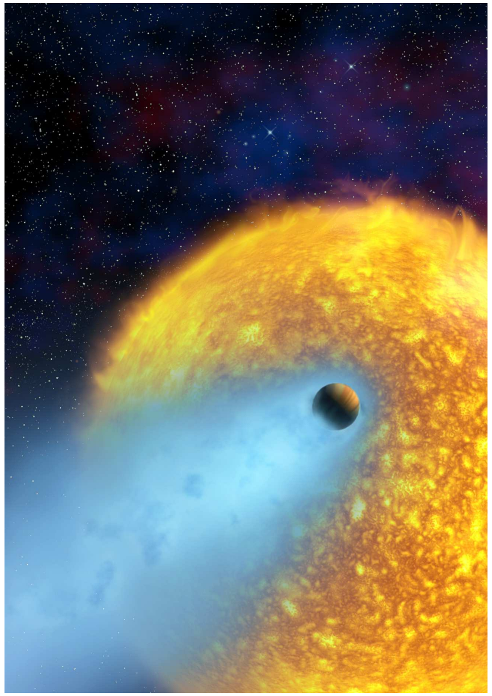
Results: Semimajor Axis, I



Most planets found are close to companion star!

Selection effect: small $a \Longrightarrow$ short period

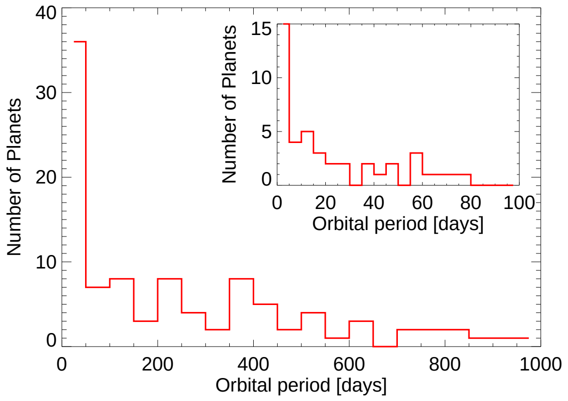
$\Longrightarrow$ detectable in small amount of time (years, not decades)



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

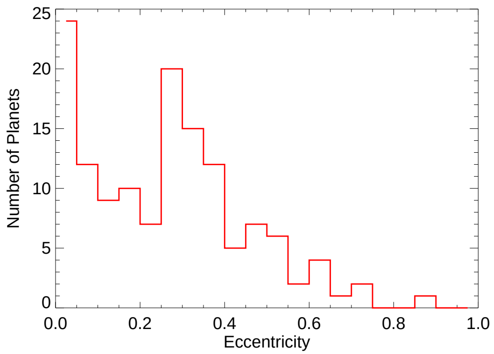
Results: Period



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



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.