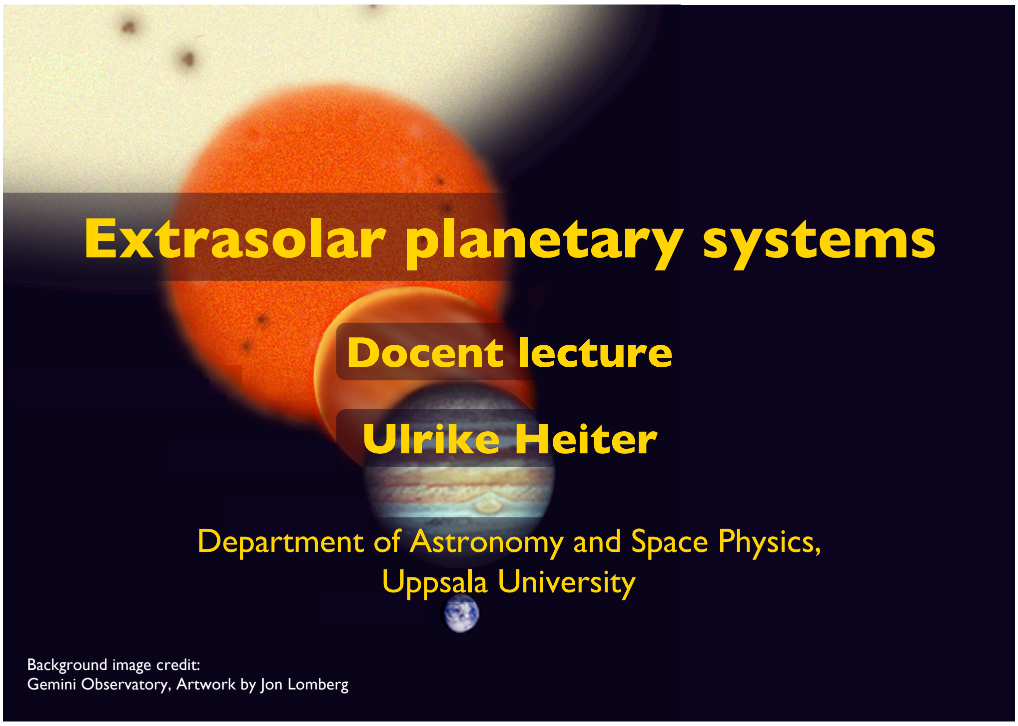


Outline

- Other worlds throughout history
- Definition of ”Planet”
- Searching for extrasolar planets
  - Detection methods
  - Detection history
- Census of extrasolar planets
  - Properties of planets and planet hosts
  - Comparison to Solar System
- Outlook

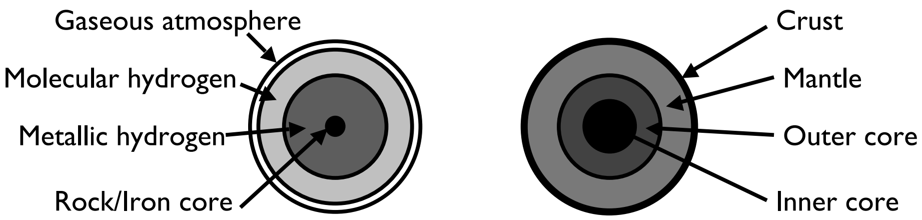
Other worlds throughout history

- 300 B.C. – Epicurus
  ”The number of world-systems is infinite. These include worlds similar to our own and dissimilar ones.”
  Letter to To Herodotus – epicurus.info
- 1584 – Giordano Bruno
  ”Innumerable suns exist; innumerable earths revolve around these suns …”
- 1750 – Thomas Wright
  – An original theory or new hypothesis of the universe
  ”… a Universe of worlds all covered by mountains, lakes, seas, grasses, animals, rivers, rocks, caves, …”

Definition of Planet today

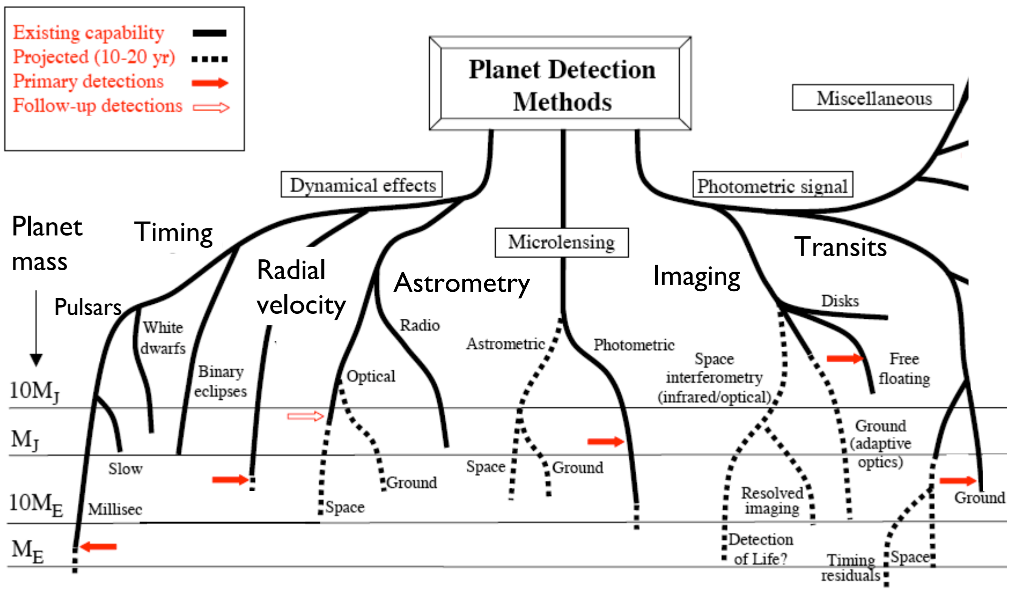
- Working definition of extrasolar planets of International Astronomical Union (can change in future)
- Objects with masses below the limiting mass for thermonuclear fusion of deuterium – currently calculated to be 13 Jupiter masses – that orbit stars or stellar remnants
- Minimum mass/size same as that used in our Solar System
- Objects with masses above the limiting mass for thermonuclear fusion of deuterium but below the limiting mass for fusion of hydrogen are ”brown dwarfs”.

Planet classification (solar system)

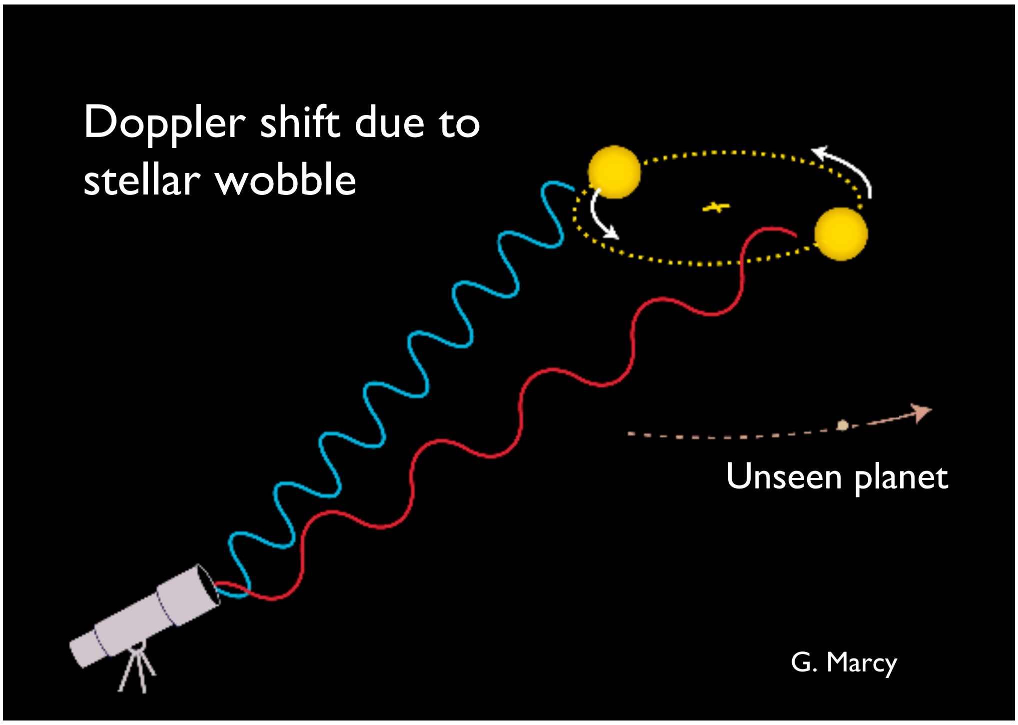


- Gas giant planets
- Composed mainly of low-density gas (hydrogen, helium)
- High mass ($>0.005M_J$)
- rapid rotation
- rings and many satellites

- Rocky small planets
- Composed mainly of high-density rock and metal
- Low mass ($<0.005M_J$)
- slow rotation
- no rings and few satellites



M. Perryman, 2004



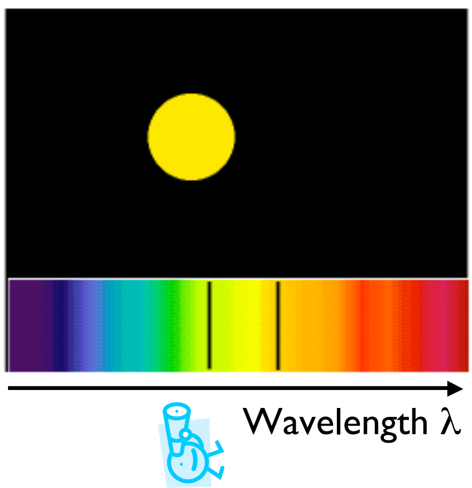
Radial velocity method

What is happening

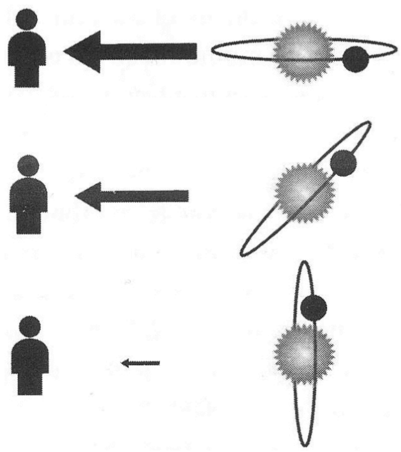
$$v_{\mathrm{max}} = \frac{\Delta\lambda_{\mathrm{max}}}{\lambda} c$$

N. Strobel (astronomynotes.com)

What we see



Inclination



$$i = 90^\circ \rightarrow v_{\mathrm{obs}} = v_{\mathrm{orbit}}$$

$$i < 90^\circ \rightarrow v_{\mathrm{obs}} = v_{\mathrm{orbit}} \sin i$$

$$i = 0^\circ \rightarrow v_{\mathrm{obs}} = 0$$

Book: Clark S., 1998, "Extrasolar planets"

Orbital radius and planet mass from radial velocity method

- Orbital radius *R* from period *P* and Kepler's 3rd law

$$R^3 = \frac{G}{4\pi^2} P^2 (M_* + \cancel{M_{\mathrm{p}}})$$

- Planet mass M_p from momentum conservation

$$M_{\mathrm{p}} v_{\mathrm{p}} = M_* v_* \quad v_{\mathrm{p}} = \sqrt{\frac{GM_*}{R}} \quad v_* \sin i = v_{\mathrm{max}}$$

$$M_{\mathrm{p}} \sin i = \sqrt{\frac{RM_*}{G}} v_{\mathrm{max}}$$

Example: Sun + Jupiter

- Expected maximum radial velocity for inclination 90°

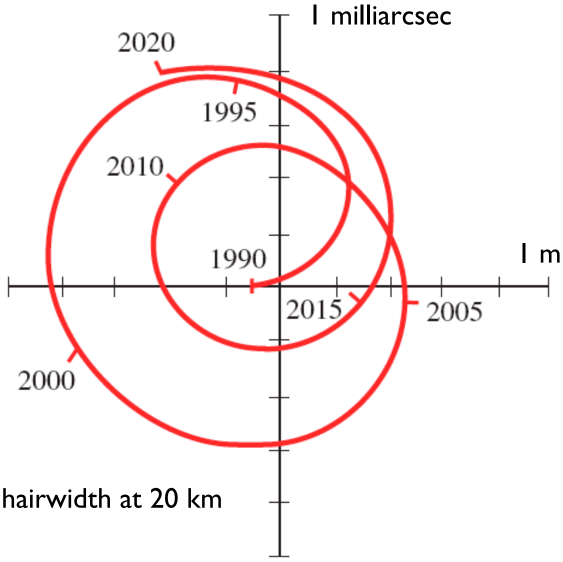
$$M_* = 1M_\odot = 2 \cdot 10^{30}\mathrm{kg}$$
$$R = 5.2\mathrm{AU} = 5.2 \cdot 1.5 \cdot 10^{11}\mathrm{m}$$
$$M_\mathrm{p} \approx 300 M_\mathrm{Earth} \approx 0.001 M_\odot \quad G = 7 \cdot 10^{-11}[\mathrm{SI}]$$

$$v_\mathrm{max} \approx 10^{-3} M_\odot \left(\frac{G}{RM_\odot}\right)^{1/2} \approx 10^{-3}\left(\frac{7 \cdot 10^{-11} \cdot 2 \cdot 10^{30}}{8 \cdot 10^{11}}\right)^{1/2}$$

$$\boxed{\approx 10\mathrm{m/s}}$$

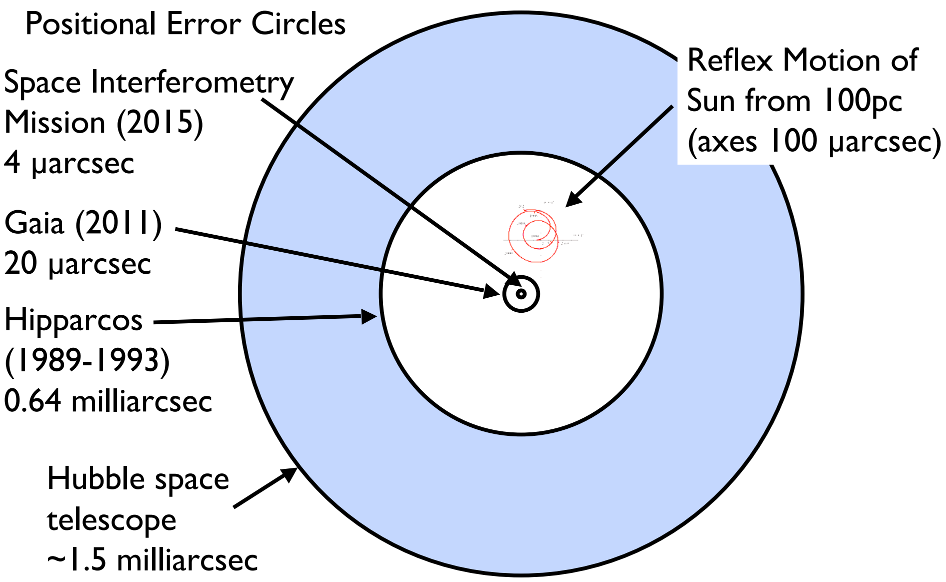
Earth-like planet: $v_\mathrm{max} \approx 10\mathrm{cm/s}$

Displacement of the Sun due to planets as seen from a distance of 10 parsecs

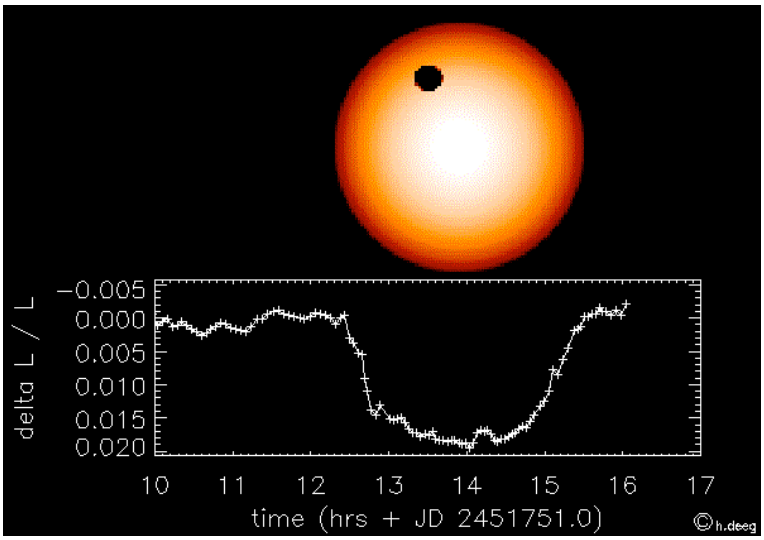


1 milliarcsec = hairwidth at 20 km

Astrometric precision of space telescopes



Planet transiting in front of star



Observations of HD 209458 by Deeg and Garrido with 0.9m telescope (Granada)

The road towards planet detection

- Early 1900s: Precision of spectroscopy a few 1000 m/s
- 1950s: Idea for "cross-corellation" spectrograph: mask with slits at expected locations of spectral lines in front of photodetector → slide observed spectrum along mask → minimum amount of light for match
- Built about 20 years later by Roger Griffin: 240 slits → a few 100 m/s precision

Book: Mayor, M. and Frei, P.-Y., 2003, "New worlds in the Cosmos - the discovery of Exoplanets"

The road towards planet detection

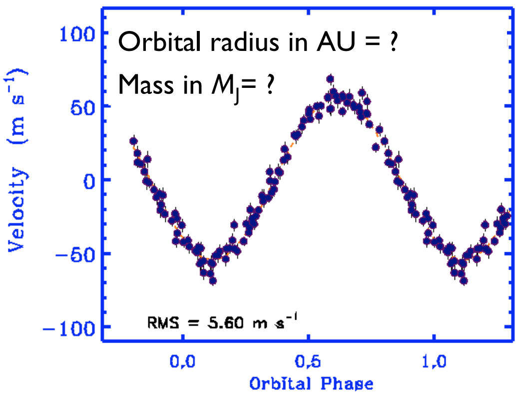
- 1979: B. Campbell and G. Walker (Canada) build spectrograph which includes container filled with hydrogen fluoride → additional absorption lines without Doppler shift – installed at 3.6m telescope on Hawaii
- Test measurements on the Sun → 15 m/s precision
- Jupiter's orbital period around Sun almost 12 years
- Selected 20 stars and measured each six times per year for seven years
- 1988: discovered v_{max}= 25 m/s variation in γ Cephei
- First extrasolar planet?
- No! (1992: explained by rotation of star)

The road towards planet detection

- 1992: G. Marcy and P. Butler (Lick Observatory) build spectrograph with molecular iodine gas absorption cell, installed at 3m telescope
  → $\boxed{\text{10 m/s}}$ precision
- Observe 25 stars for 2 years → find nothing
- 1993: M. Mayor and D. Queloz (Geneva) build cross-correlation spectrograph with numerical mask → 1.9m telescope in Provence
  → $\boxed{\text{15 m/s}}$ precision
- Their goal: find brown dwarfs in short orbits around solar-type stars

51 Pegasi

- 1994: Mayor and Queloz find variations in 51 Peg data with v_{max}= 59 m/s and period = 4.2 days



$1\ \mathrm{AU} \approx 1.5 \cdot 10^{11}\ \mathrm{m}$

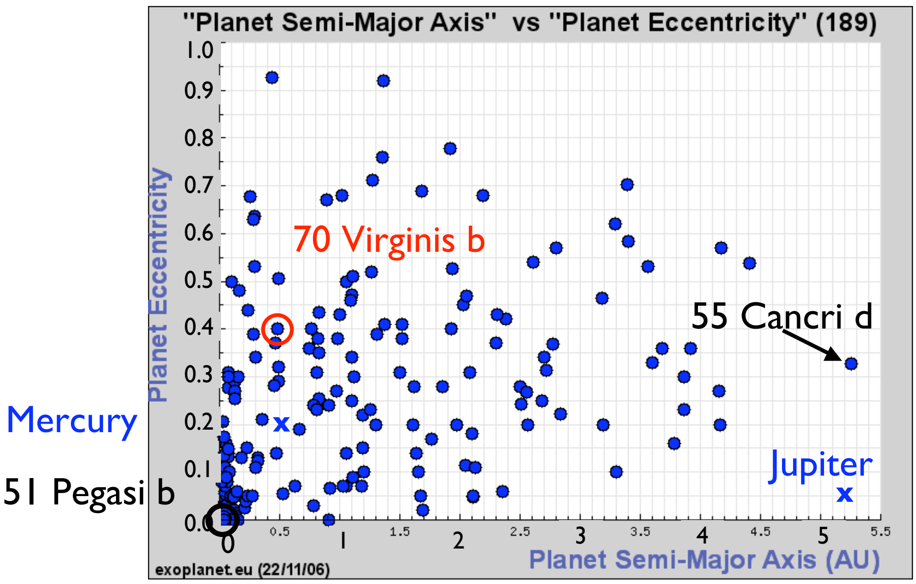
$M_J \approx 2 \cdot 10^{27}\ \mathrm{kg}$

$1\ \mathrm{day} \approx 9 \cdot 10^{4}\ \mathrm{s}$

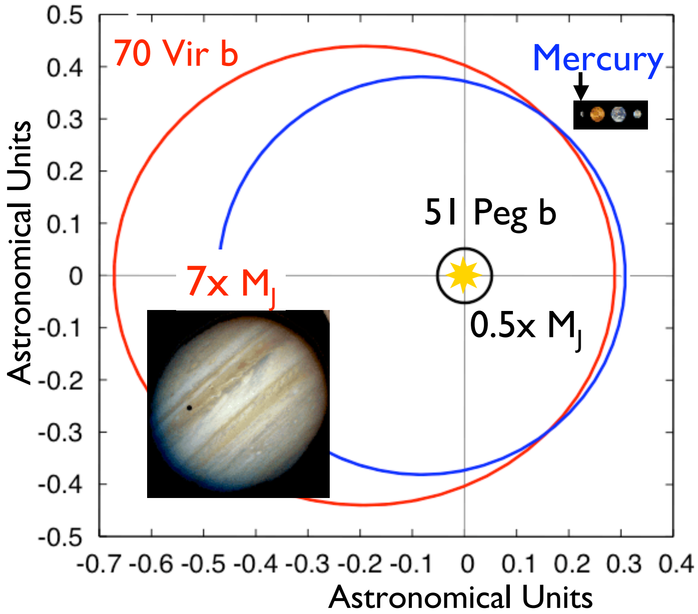
Extrasolar planets!

- First planet published by Mayor & Queloz, 1995, Nature 378
- Confirmed by Marcy & Butler at Lick Observatory
- About one year later, Marcy & Butler found short-period planets around 47 Ursa Majoris and 70 Virginis
- Since 2002, about 30 planets per year detected
- Today: 209 planets around 179 stars (21 multiple planet systems) → Statistical examination of their properties
- The Extrasolar Planets Encyclopaedia http://exoplanet.eu/ maintained by Jean Schneider (Paris Observatory)

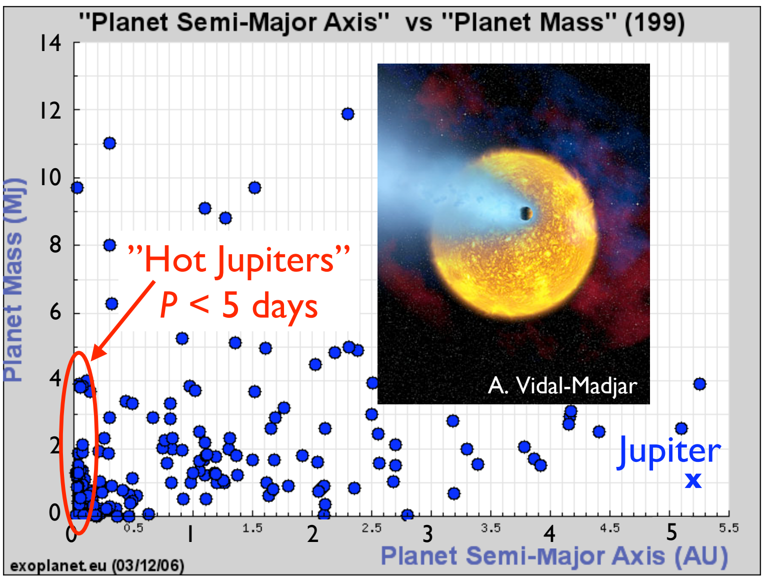
Planet orbits

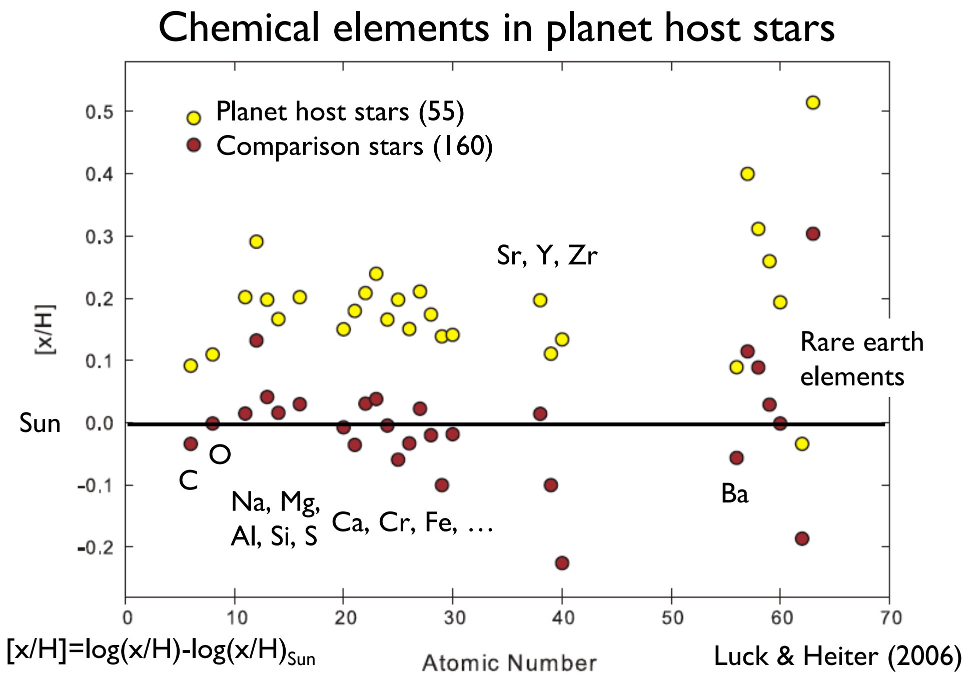


Planet orbits

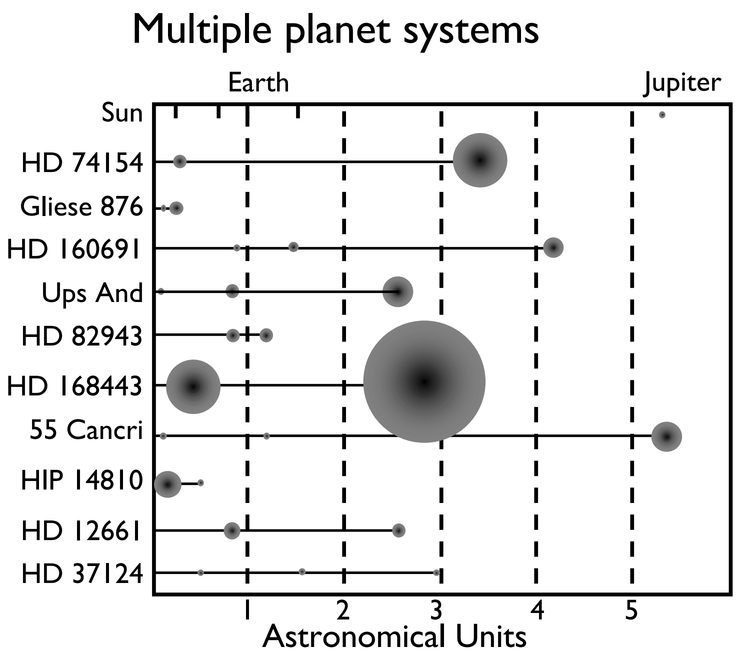


Planet masses





Chemical elements in planet host stars
Planet host stars (55)
Comparison stars (160)
[x/H]
Sun
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
C
O
Na, Mg,
Al, Si, S
Ca, Cr, Fe, …
Sr, Y, Zr
Ba
Rare earth
elements
0
10
20
30
40
50
60
70
[x/H]=log(x/H)-log(x/H)Sun
Atomic Number
Luck & Heiter (2006)



Multiple planet systems
Earth
Jupiter
Sun
HD 74154
Gliese 876
HD 160691
Ups And
HD 82943
HD 168443
55 Cancri
HIP 14810
HD 12661
HD 37124
1
2
3
4
5
Astronomical Units

Outlook

- Ground-based instruments with high precision and long time baselines (16–18 years)
  - High Resolution Spectrograph on 9.2m Hobby-EberlyTelescope in Texas: 3–4 m/s (Cochran et al.)
  - HIRES spectrograph on 10m Keck telescope on Hawaii: 1–2 m/s (Butler et al.)
  - HARPS instrument on ESO 3.6m telescope (Chile): better than 1 m/s (Lovis et al.)

Outlook – space missions

- Astrometry
  - Gaia – http://www.esa.int/science/gaia
  - SIM – http://planetquest.jpl.nasa.gov/
- Transit search
  - COROT – will survey 120 000 stars with sensitivity to rocky planets – launch 21st Dec
    http://exoplanet.eu/corot.html
  - Kepler – will observe more than 100000 stars looking for Earth-mass planets – launch Oct. 2008
    http://kepler.nasa.gov/

Summary

- Radial velocity method most successful for finding planets so far
- Jupiter-mass planets in close orbits
- Limitations
  - Mass uncertainty due to inclination
  - Limited to bright stars
- Planetary systems found so far are different from Solar system
- Near-future ground instruments and space missions will be able to find Earth-like planets

The End