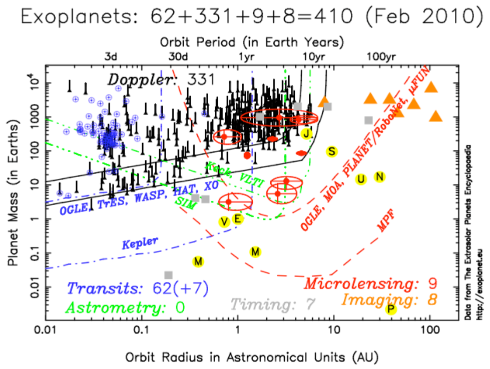


Data from: The Extrasolar Planet Encyclopaedia http://exoplanet.eu/

2009->10 Status of Exoplanet Searches

Direct Detection:

- 5->9 planets detected
- Sensitive to large planets in large orbits around faint stars
- Planet mass $m \sim 4$ - $20\ m_J$
- Orbit size $a \sim 46$ - 600 AU

Astrometry:

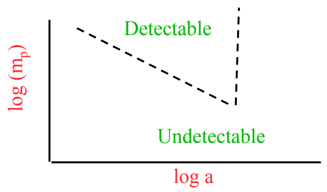
- 0 planets found by astrometry.
- a handful of known RV planet-star systems have been observed astrometrically, determining the planet mass without sin(i) ambiguity.

Astrometry Selection Function

Need to observe (most of) a full orbit of the planet:
No discovery for planets with $P > P_{survey}$

For $P < P_{survey}$, planet detection requires a star wobble several times larger than the accuracy of the measurements. ==> minimum detectable planet mass.

Planet mass sensitivity as a function of orbital separation



$$\Delta\theta = \frac{a_*}{d} \approx \left(\frac{m_p}{M_*}\right)\left(\frac{a}{d}\right)$$

$$m_p \propto a^{-1}$$

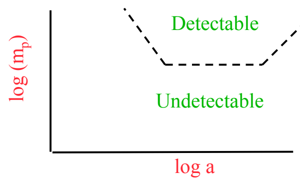
Direct Imaging Selection Function

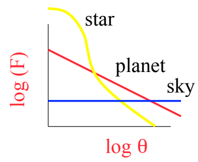
Need to detect feeble planet above the glare from the host star.
Large planets close to star are brighter.
Planets farther away from star are better separated from the glare.

$$\frac{Signal}{Noise} \propto \frac{F_p}{\left(F_* G(\theta) + F_{sky}\right)^{1/2}} \qquad \theta = \frac{a}{d} \qquad \frac{F_p}{F_*} = \frac{B_\nu(T_p)}{B_\nu(T_*)}\frac{r_p^{\,2}}{R_*^{\,2}}$$

Key is to suppress the star's light
Without also suppressing the planet's.

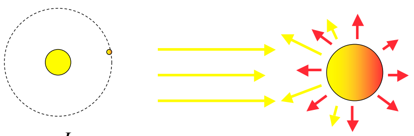
$$T_p = T_*\left(\frac{R_*}{2a}\right)^{1/2}(1-A)^{1/4}$$





Equilibrium Temperature

energy input from star = energy output from reflection + thermal radiation



$$F_{in} = \frac{L_*}{4\pi a^2} \qquad L_* = \sigma T_*^{\,4}\left(4\pi R_*^{\,2}\right)$$

$$L_{refl} = F_{in}\left(\pi r^2\right) A \qquad A = \text{albedo}$$

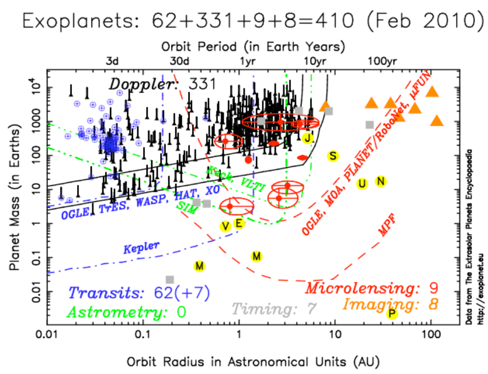
$$L_{therm} = F_{in}\left(\pi r^2\right)(1-A) = \sigma T_{eq}^{\,4}\left(4\pi r^2\right)$$

$$\sigma T_*^{\,4}\frac{R_*^{\,2}}{a^2}\left(\pi r^2\right)(1-A) = \sigma T_{eq}^{\,4}\left(4\pi r^2\right)$$

$$T_{eq} = T_*\left(\frac{R_*}{2a}\right)^{1/2}(1-A)^{1/4}$$

$$T_{eq} = T_*\left(\frac{R_*}{2a}\right)^{1/2}(1-A)^{1/4}$$

Note that T_{eq} is independent of the planet size.
Applies to dust grains, asteroids, planets …



Data from: The Extrasolar Planet Encyclopaedia http://exoplanet.eu/

Doppler Selection Function

Need to observe (most of) a full orbit of the planet:

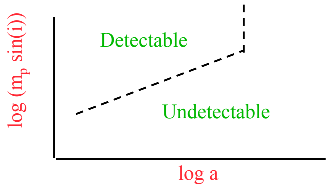
No discovery for planets with $P > P_{survey}$

For $P < P_{survey}$, planet detection requires a star wobble Vobs several times larger than the accuracy of the measurements. ==> minimum mass of detectable planet.

Planet mass sensitivity as a function of orbital separation

$$V_* \approx \left(\frac{m_p}{M_*}\right)\sqrt{\frac{GM_*}{a}}$$

$$m_p \sin(i) \propto a^{1/2}$$



2009->10 Status of Exoplanet Searches

Data from: The Extrasolar Planet Encyclopaedia http://exoplanet.eu/

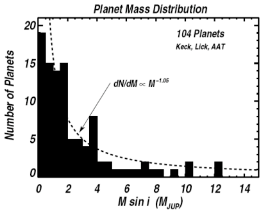
Radial Velocity :

- 260 -> 399 planets as part of 224 -> 339 planetary systems.
- 25 -> 41 multi-planet systems
- Mostly FGK-dwarfs, Sun-like stars. Some lower mass M-dwarfs
- Lower mass limits: $m \sin(i) \sim 5\ m_E$ to $20\ m_J$.
- Orbital semi-major axis: $a \sim$ 0.02 AU to ~8 AU.

Observed distribution :

- Observed mass function dN/dm ~ 1/m (more small planets)
- dN/d(log(m)) approx constant, but: steps up at $a > 1$ AU
- cutoffs at $a < 0.02$ AU and $m \sin(i) > 10\ m_J$
- ~12% of solar-type stars have gas giant planets with $a < 10$ AU
- ~ 1% of solar-type stars have hot Jupiters - $a < 0.1$ AU
- Except at very small radii, typical planet has significant eccentricity (most planets NOT on circular orbits -- unlike our solar system)
- More planets around stars with high metalicity.

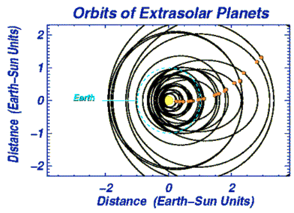
Planet Mass Distribution



- Observed distribution of companion masses dN/dm rises towards low mass.
- Selection effects make low-massive planets hard to detect.
- True mass function probably rises even more steeply than observed mass function.
- Suggests many more terrestrial planets than giants -- however, giants form differently than terrestrial planets.
- We currently have little direct knowledge of the mass distribution of terrestrial planets.
- Lack of companions with $M \sin i > 10\ M_J$ (the brown dwarf desert)

Eccentric (non-circular) Orbits

Not yet well understood.



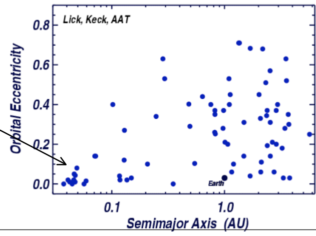
Early star-star encounters?

Planet-planet interactions?

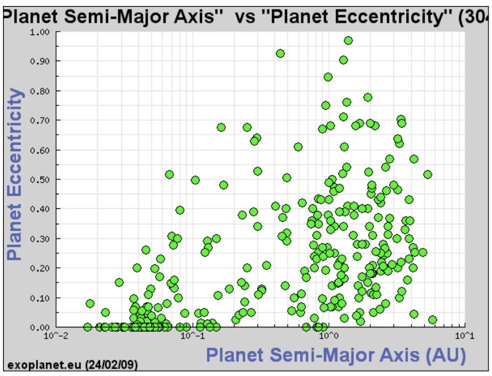
Eccentricity pumping.

Small planets ejected?

Tidal circularisation.

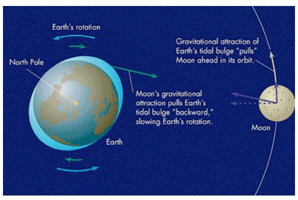


Current Eccentricity Distribution



Planets on non-circular orbits are common

Tidal Circularisation of Hot Jupiter Orbits



- Close-in planets, with small orbital separation *a,* tend to be more circular.
- Likely due to evolution of the orbit due to tidal interactions with the star: **tidal circularization.**

Star becomes slightly ellipsoidal in shape due to gravitational interaction with the planet. If star spins more slowly than planet orbits, bulge on star lags behind planet, planet loses angular momentum, and falls into a more circular orbit.

Tidal circularization too slow to affect Solar System planets. They are too far from the Sun.

High metalicity of planet host stars

(metals = elements heavier than He)

more metals --> more planets

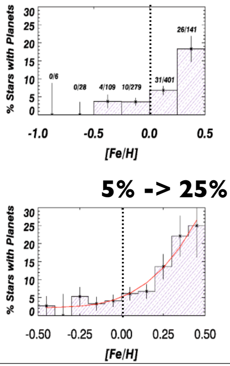
Enhanced planet formation ?

Pollution of stellar atmosphere?

Santos (2003)

Fischer & Valenti (2004)

5% -> 25%



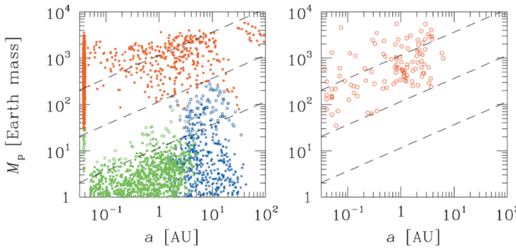
Lessons from Doppler Wobble Planets

- > 5% of Sun-like stars host a Jupiter
- Metalicity matters: 5% -> 25%
- Orbits differ from Solar System
  - wide range of orbit radii (Hot Jupiters with $P \sim$ 1-10d)
  - wide range of eccentricities
- New formation/evolution processes
  - Migration -- usually inspiral
  - eccentricity pumping (planet-planet scattering)
  - ejection of smaller planets
- Is our solar system typical or rare ?
  - Jupiter analogs detectable in a few more years.

Formation / Migration Simulations

Core accretion + migration simulation by Ida & Lin (2004), showing gas giants, ice giants, rocky planets.

Doppler wobble planets.



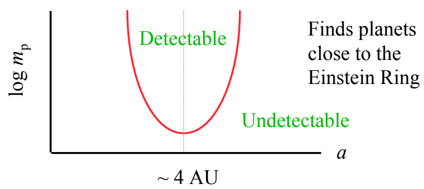
2009->10 Status of Exoplanet Searches

Transits:
- 35 -> 69 transiting planets (3 in multi-planet systems).
- Planet radius $r \sim 0.7\text{-}1.4\ R_J$. Only technique to observe planet radii.
- Planet mass $m \sim 23\ m_{Earth}$ -- $13\ m_{Jup}$
- Orbital size $a \sim 0.02 - 0.2$ AU (close to parent star!)

Microlensing:
- 6 ->10 microlens planets (1 multi-planet system)
- Target stars are mostly M-dwarfs, typically faint and far away
- Planet mass $m \sim 5\ m_E - 3\ m_J$
- Orbit size $a \sim 2 - 5$ AU

Pulsar planets:
- 5 planets detected in 3 planetary systems
- Planet mass $m \sim 0.02\ m_E$ (the mass of our Moon!), $4\ m_E$, and $2\ m_J$
- Orbit size $a \sim 0.2 - 0.5$, 23 AU
- Life is very unlikely to be found on these planets

Microlensing Seletion Function



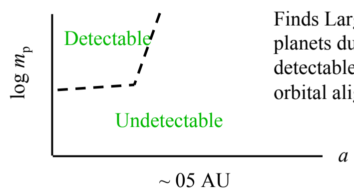
Finds planets close to the Einstein Ring

Can find planets down to Earth mass.

Typical lens stars 0.3 Msun

Typical orbit size $\sim R_E \sim$ 4AU

Transits Selection Function



Finds Large Hot planets due to need for detectable `wink' and orbital alignment.

Can find Hot Jupiters (from the ground)

Hot Earths (from space) Maybe.

Typical stars G, K stars 0.5 - 2 Msun

Typical orbit size ~ 0.05 AU,

Lack of Transits in 47 Tuc

A long HST observation monitored ~34,000 stars in the globular cluster 47 Tuc looking for planetary transits.

Locally: 1% of stars have hot Jupiters
~ 10% of those show transits

⇒ Expect 10^{-3} x 34,000 ~ few tens of planets

None were detected. Possible explanations:

- Low metallicity in cluster prevented planet formation
- Cluster environment destroyed discs before planets formed
- Stellar fly-bys ejected planets from bound orbits

All of these seem plausible - make different predictions for other clusters.

Summary

- Different indirect methods are sensitive to different portions of the log m_p – log a domain.

- Direct Imaging -- larger planets in large orbits ($a > 40$ AU).
- Radial velocity studies find large planets with orbits out to ~10 years ($a \leq 8$ AU).
- Astrometry favours long-period planets ($a \geq 40$ AU) but the orbit times are on the order of decades.
- Transits strongly favour short-period (Hot) planets, giving radii and masses, hence densities, for Hot Jupiters to Neptunes from the ground, perhaps soon Hot Earths from space (Kepler).
- Microlensing detects cool planets ($3 \leq a \leq 12$ AU) down to Earth mass (Cool Earths).