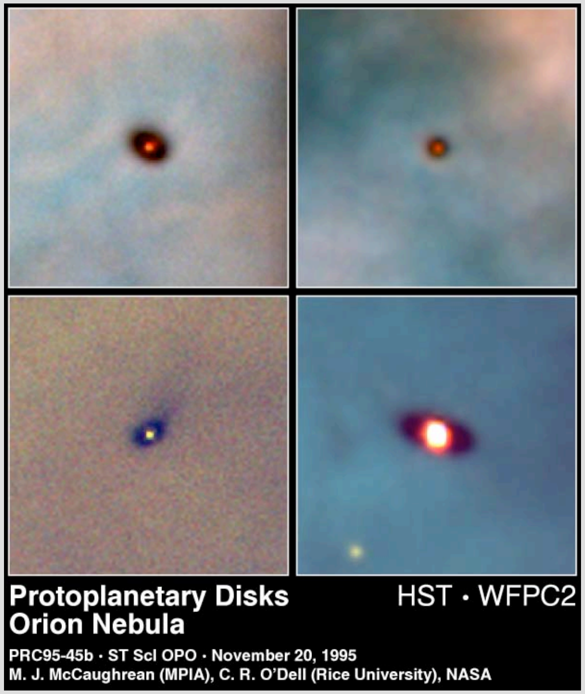
Detecting extrasolar planetary systems



Nearest star forming region to the Sun is TW Hydrae association at d ~ 50 pc

Recall 1 au subtends an angle of 1 arc sec at d = 1 pc

Jupiter's orbit (a = 5 au) has an angular radius of ~ 0.1 arc sec at d = 50 pc

Can't directly image planets in the process of forming within protoplanetary disks

Consider planet, radius R_p, at distance from star a. Fraction of starlight intercepted:

$$f = \frac{\pi R_p^2}{4\pi a^2}$$

$$\text{Earth}: R_p = 6.4 \times 10^8 \text{ cm}, a = 1.5 \times 10^{13} \text{ cm}, f = 5 \times 10^{-10}$$

$$\text{Jupiter}: R_p = 7.1 \times 10^9 \text{ cm}, a = 7.8 \times 10^{13} \text{ cm}, f = 2 \times 10^{-9}$$

If the planet reflected all the intercepted starlight, then the magnitude difference between the planet and the star would be:

$$m = -2.5 \log F + \text{constant}$$

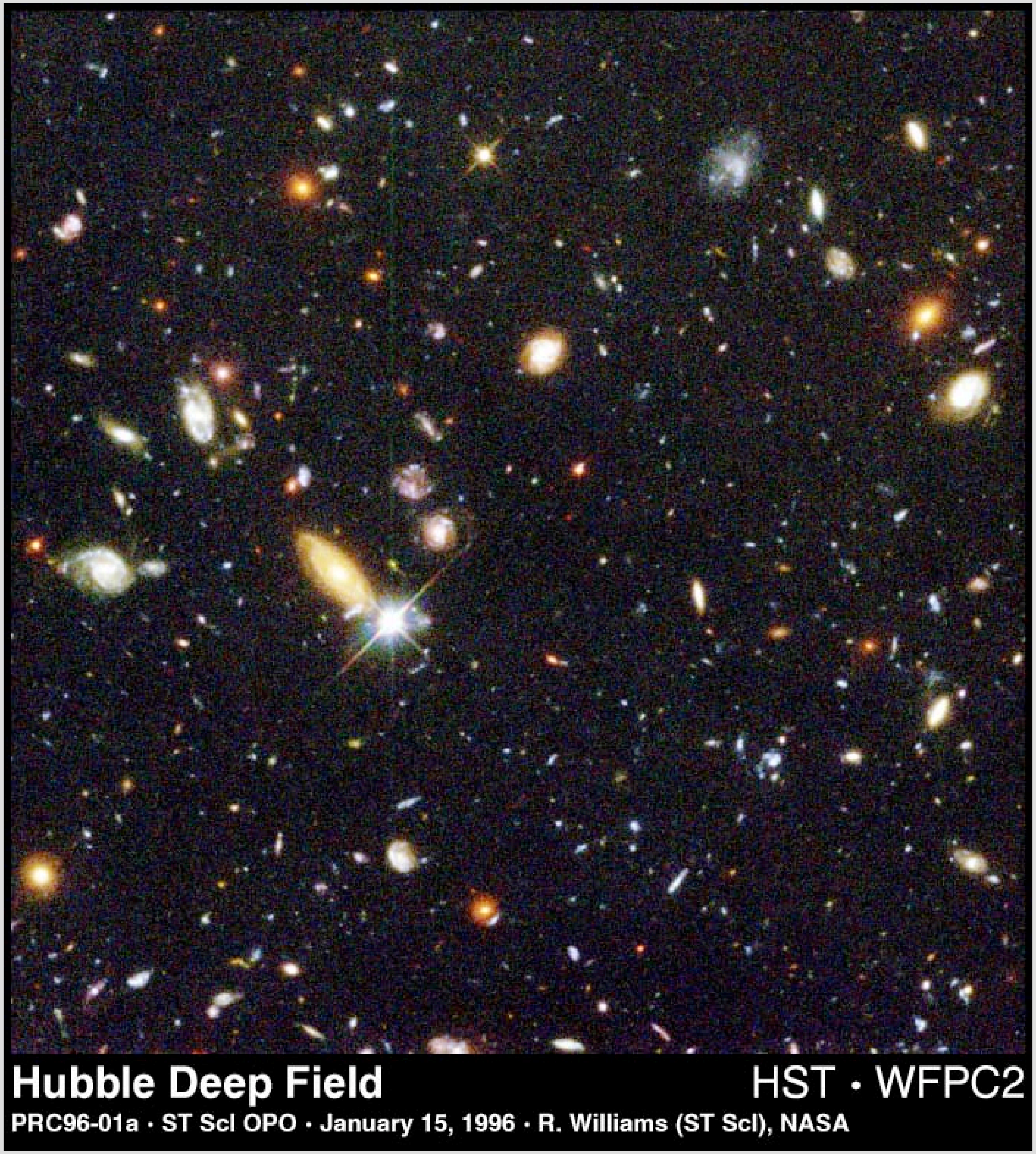
$$m_p - m_* = -2.5 \log F_p + 2.5 \log F_*$$

$$m_p - m_* = -2.5 \log \left(\frac{F_p}{F_*} \right)$$

↑
f

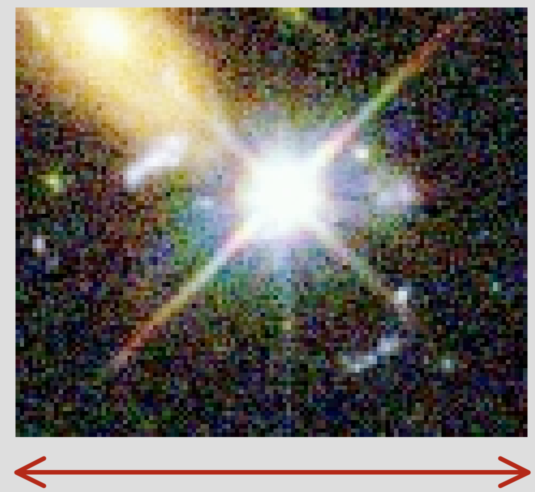
Find Δm ~ 22 magnitudes for Jupiter, 23 magnitudes for Earth.

Implied apparent magnitude is not too bad, e.g. for Earth orbiting a 5th magnitude G star (Solar type) would need to reach V ~ 27 - requires 5800 s of exposure using *HST's* Advanced Camera for Surveys.



Contrast between star and planet is the main problem

e.g. **brightest** stars in this image are around 18th magnitude



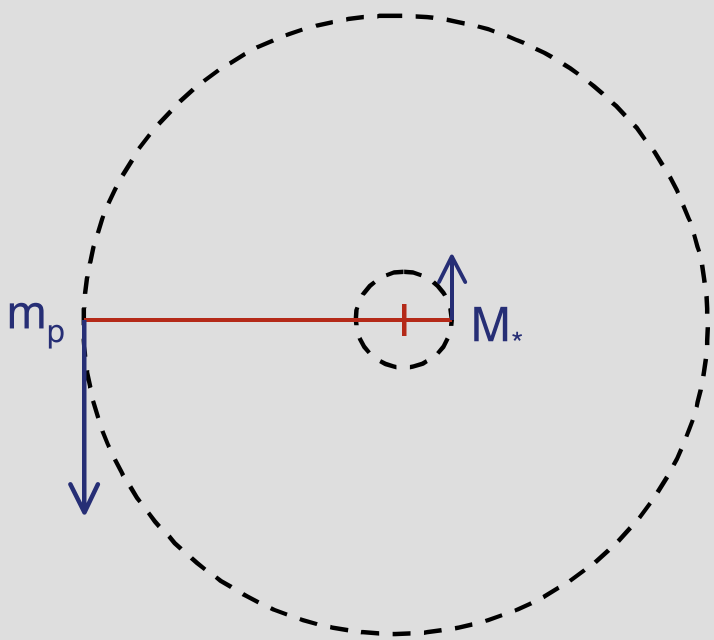
No direct detections of extrasolar planets…

Indirect detection of extrasolar planets

Radial velocity method

Star - planet system is a special case of a spectroscopic binary where:

- Only observe the radial velocity of one component
- Very large ratio of masses between components



For circular orbits, as previously:

Ratio of velocities of star and planet in orbit around center of mass

$$\frac{v_*}{v_p} = \frac{m_p}{M_*}$$

Kepler's laws give:

$$v_p = \sqrt{\frac{G\left(M_* + m_p\right)}{a}} \approx \sqrt{\frac{GM_*}{a}}$$

…for star-planet separation a

Velocity of the **star** due to presence of orbiting planet is:

$$v_* = \frac{m_p}{M_*}\sqrt{\frac{GM_*}{a}}$$

How large is this velocity?

Jupiter: $m_p = 10^{-3}\ M_{sun}$, $a = 7.8 \times 10^{13}$ cm, $M_{sun} = 2 \times 10^{33}$ g

$$v_* \approx 1.3 \times 10^3 \text{ cm s}^{-1} = 13 \text{ m s}^{-1}$$

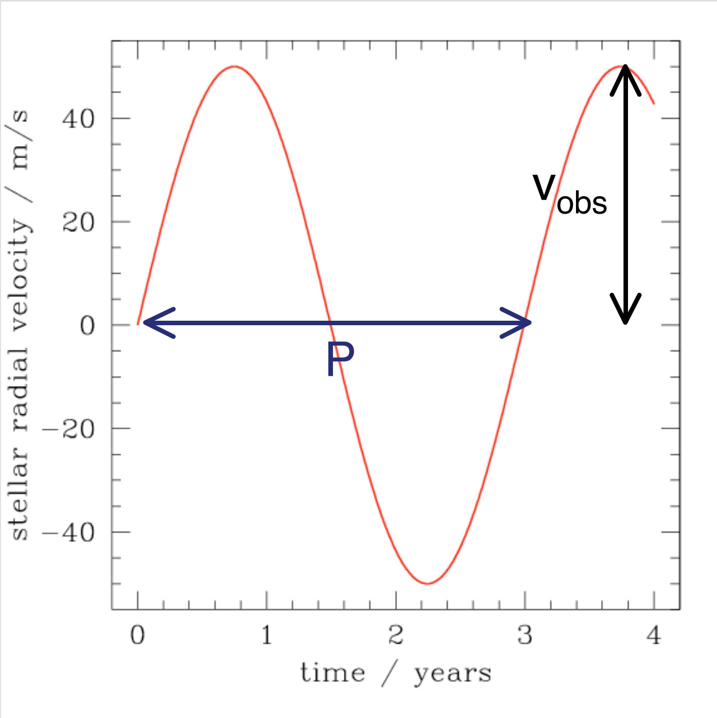
Earth: $m_p = 3 \times 10^{-6}\ M_{sun}$, $a = 1.5 \times 10^{13}$ cm

$$v_* \approx 10 \text{ cm s}^{-1}$$

Currently the best observations measure the stellar velocity to a precision of ~ 3 m s^{-1} (ultimate limit is not known, but is though to be ~ 1 m s^{-1}). **Can detect extrasolar `Jupiters', but not Earths.**

Radial velocity observables:

For a planet on a circular orbit, observables are the period and the amplitude of the radial velocity signal of the star:



Amplitude of the signal equals the velocity of the star around its orbit **only** if the inclination is 90 degrees (edge-on). Generally:

$$v_{obs} = v_* \sin i$$

Detect a smaller signal if the system is not edge-on, no signal at all if the system is face-on.

Planet masses from radial velocity measurements:

$$v_{obs} = v_* \sin i = \frac{m_p}{M_*}\sqrt{\frac{GM_*}{a}}\sin i$$

$$m_p = v_{obs} \times M_* \times \sqrt{\frac{a}{GM_*}} \times \frac{1}{\sin i}$$

Inclination factor is unknown unless we see eclipses (transits)

Observed amplitude of stellar `wobble' - measure this directly

Don't know stellar mass, but can get a good estimate from high signal to noise spectrum

Derive this from M_* and period P:

$$P = 2\pi\sqrt{\frac{a^3}{GM_*}}$$

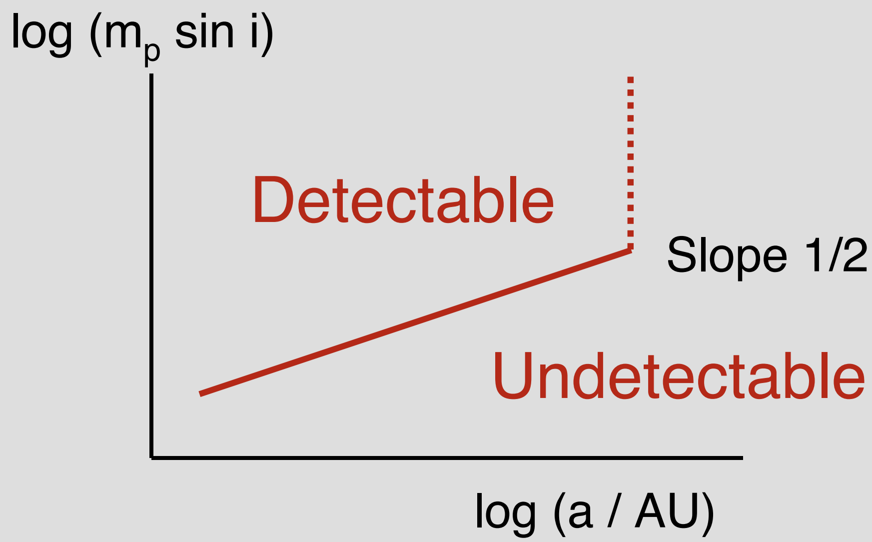
Radial velocity observables are:

- **Orbital period** (or semi-major axis)
- **m_p sin (i)** - i.e. a *lower* limit to the true planet mass
- **eccentricity of the orbit**

Selection effects:

$$v_* = \frac{m_p}{M_*}\sqrt{\frac{GM_*}{a}}$$

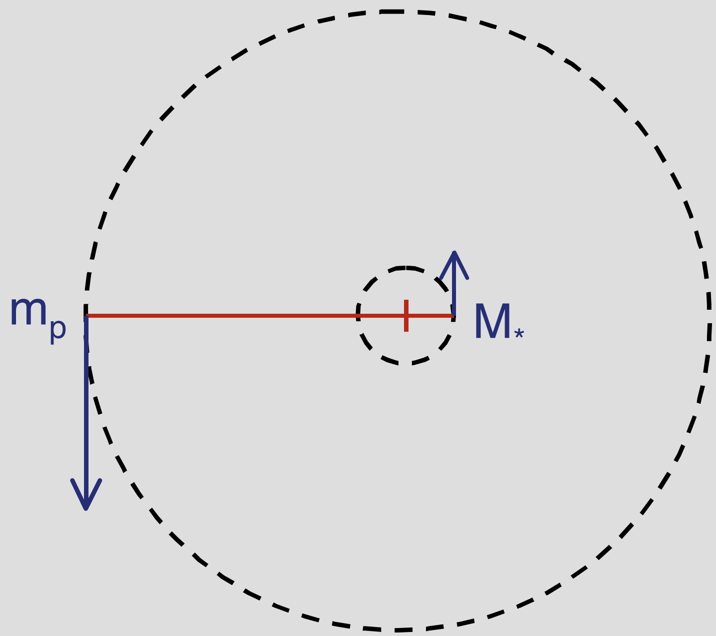
For fixed observational sensitivity, the minimum detectable planet mass scales as the square root of the orbital radius:



Also fail to detect very long period planets - won't (yet) have seen a complete orbit

Method favors detection of massive planets at small radii from the star…

Astrometry



Conceptually identical to radial velocity method - look for motion of star *in the plane of the sky* due to orbiting planet. Star moves in a circle radius a_*, where:

$$a_* M_* = a m_p$$

(definition of center of mass)

Angular size of the circle on the sky: $\theta = \frac{a_*}{d}$

$$\theta = \frac{m_p}{M_*} \frac{a}{d}$$

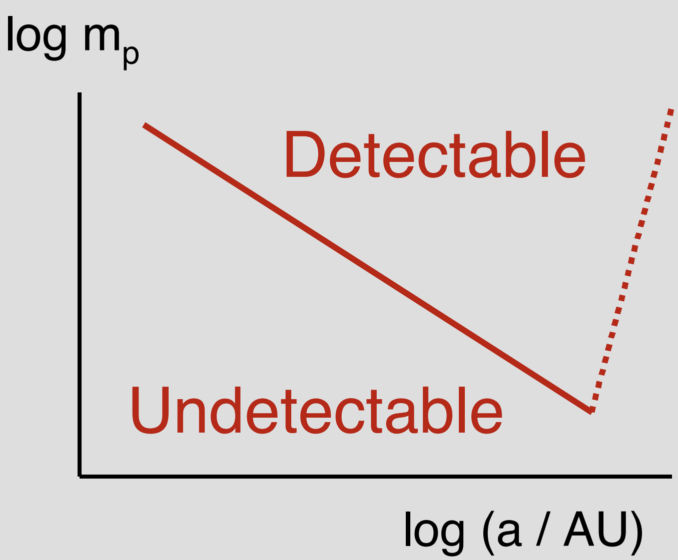
Units: if the star-planet separation a is in astronomical units, and d is in parsecs, then angle θ is in arcseconds e.g. for Jupiter mass planets:

$$\theta \approx 0.5 \left(\frac{m_p}{m_{Jupiter}} \right) \left(\frac{a}{5 \text{ au}} \right) \left(\frac{d}{10 \text{ pc}} \right)^{-1} \text{ mas}$$

← units, milli-arcseconds

Not achieved yet, but promising as fundamental limits do not preclude detection of even Earth-mass planets.

Sensitivity is complementary to radial velocity searches:

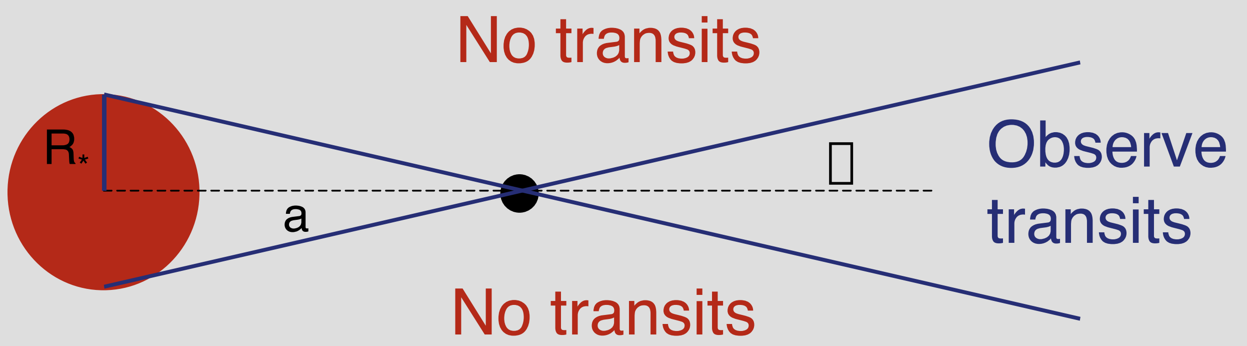


Easiest to find massive planets at large orbital radius, as long as the period isn't much longer than the duration of the search

Transits

Look for the periodic dimming of the star as the planet (seen from Earth) transits across the stellar disk.

Requires a favorable inclination (almost edge-on)

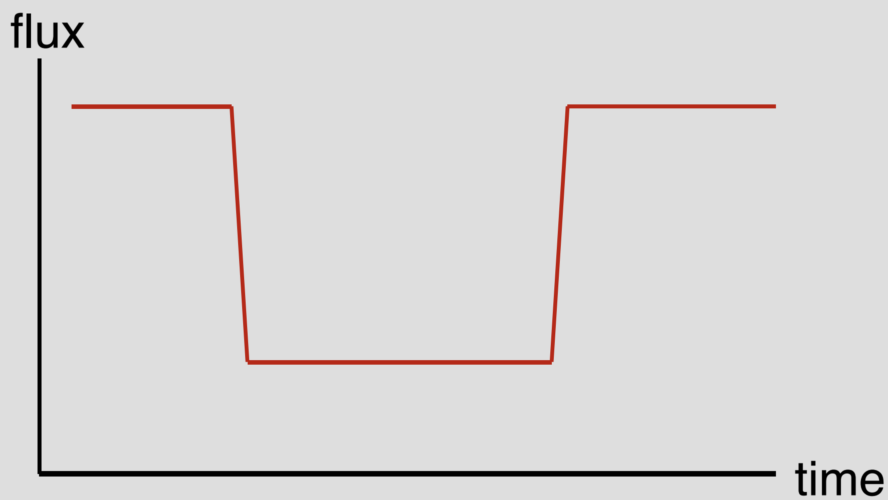


Probability of seeing transits: $P = \sin\theta \approx \frac{R_*}{a}$

At 1 au around Sun: P = 0.5%, at 5 au: P = 0.1%

Need to continuously monitor large number of stars

Schematic transit lightcurve:



Fraction of starlight absorbed (transit *depth*):

$$f = \left(\frac{R_p}{R_*} \right)^2$$

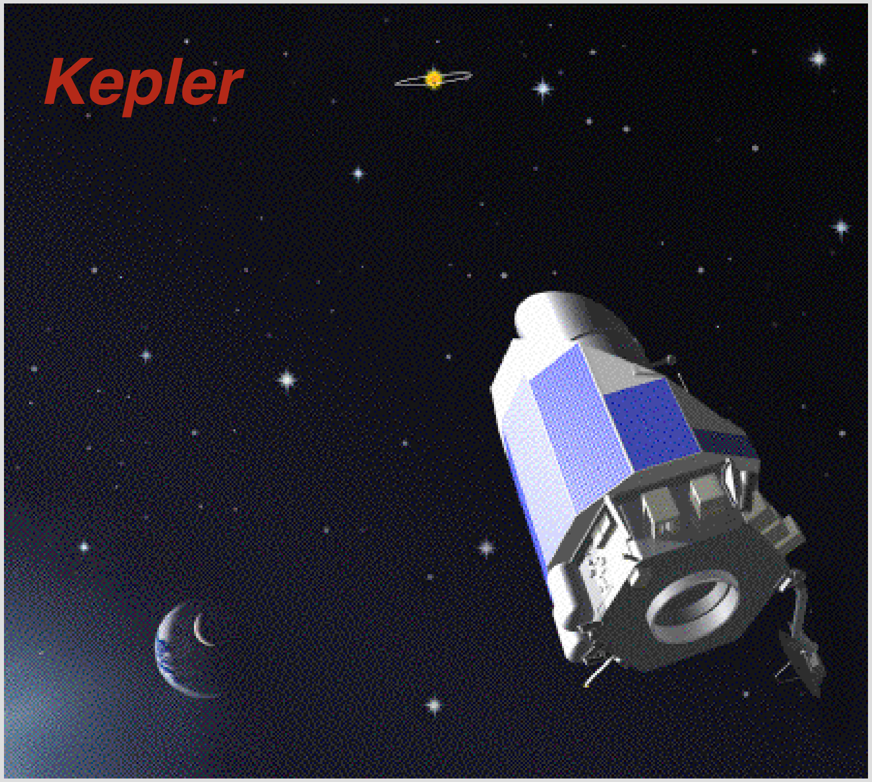
Giant planets all have very similar radii ~ 0.1 R_{sun}

Signal for Jupiter is ~ 1% drop in stellar flux during transit

For Earth, radius is ~ 0.01 R_{sun}

Signal for Earth is drop in flux by 1 part in 10^4

Photometry accurate to ~ 0.1% is possible (very difficult) from the ground, accuracy at 10^{-5} level thought achievable in space.



NASA has approved a Discovery class mission to search for transits by terrestrial planets:

- monitor 10^5 stars for 4 years
- 0.95 m telescope
- designed for a photometric precision of 10^{-5}
- planned launch in Fall 2007

Built by Ball aerospace

If all stars (in some mass range) have on average 2 planets with $R = R_{earth}$ orbiting between 0.5 au and 1.5 au, ~50 will be detected. Likely to provide first clue as to how common habitable planets are.

Possible that gravitational lensing (even less direct method, discussed next semester) will find Earth-mass planets first.