AS3012: Exoplanetary Science

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Room 226

AS3012: Exoplanetary Science
Detection Techniques

- How can we discover extrasolar planets?
- Characteristics of the exoplanet population
- Planet formation
- Explaining the properties of exoplanets

Rapidly developing subject - first extrasolar planet around an ordinary star only discovered in 1995 by Mayor & Queloz. Observations are secure, but theory is still developing ...

`http://star-www.st-and.ac.uk/~srk1/as3012/`

Resources

No textbooks that I'm aware of

Observations: good starting point is the California & Carnegie Planet Search homepage

`http://exoplanets.org/`

Theory: Annual Reviews article by Lissauer (1993) is a good summary of the state of theory prior to the discovery of extrasolar planets

Links to these on the course webpage

Currently Known exoplanets

Global statistics (15^{th} February 2005):

Planets around main sequence stars

- 134 planetary systems
- 153 planets
- 15 multiple planetary systems

Pulsar planets

- 6 planets

Free-floating planets

- 1 planet

New planets are being found at a rate of around 1 per month

Definition of a planet

Simplest definition is based solely on mass

- Stars: burn hydrogen
- Brown dwarfs: burn deuterium
- Planets: do not burn deuterium

Deuterium burning limit occurs at around 13 Jupiter masses

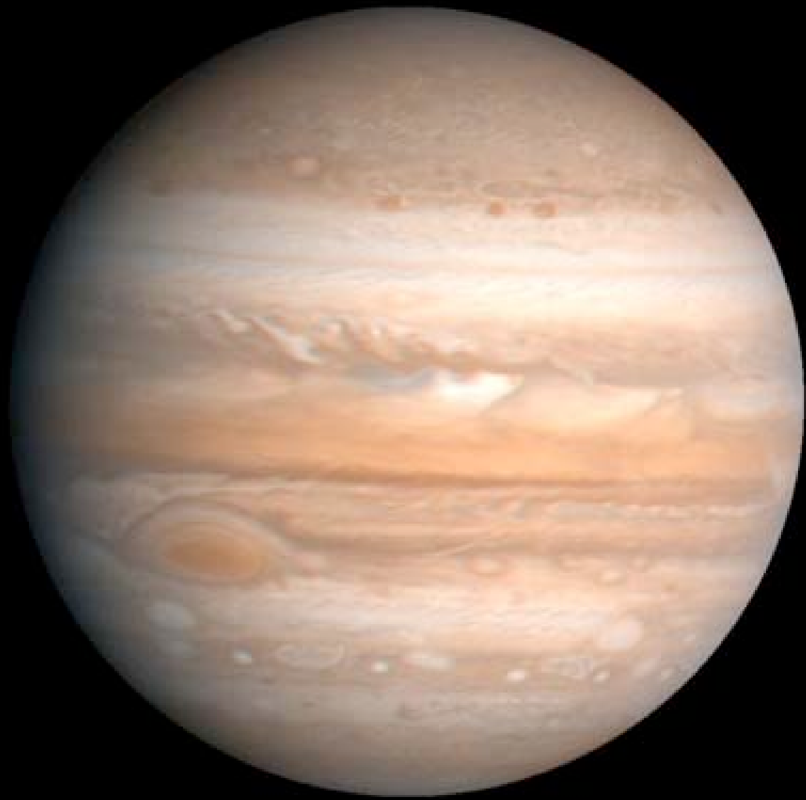
$$1M_J = 1.9 \times 10^{27}\, kg \approx 10^{-3} M_{sun}$$

Important to realise that for young objects, there is no large change in properties at the deuterium burning limit. ALL young stars / brown dwarfs / planets liberate gravitational potential energy as they contract

Most definitions also require that the object orbits a star to be a planet

Types of planet: giant planets

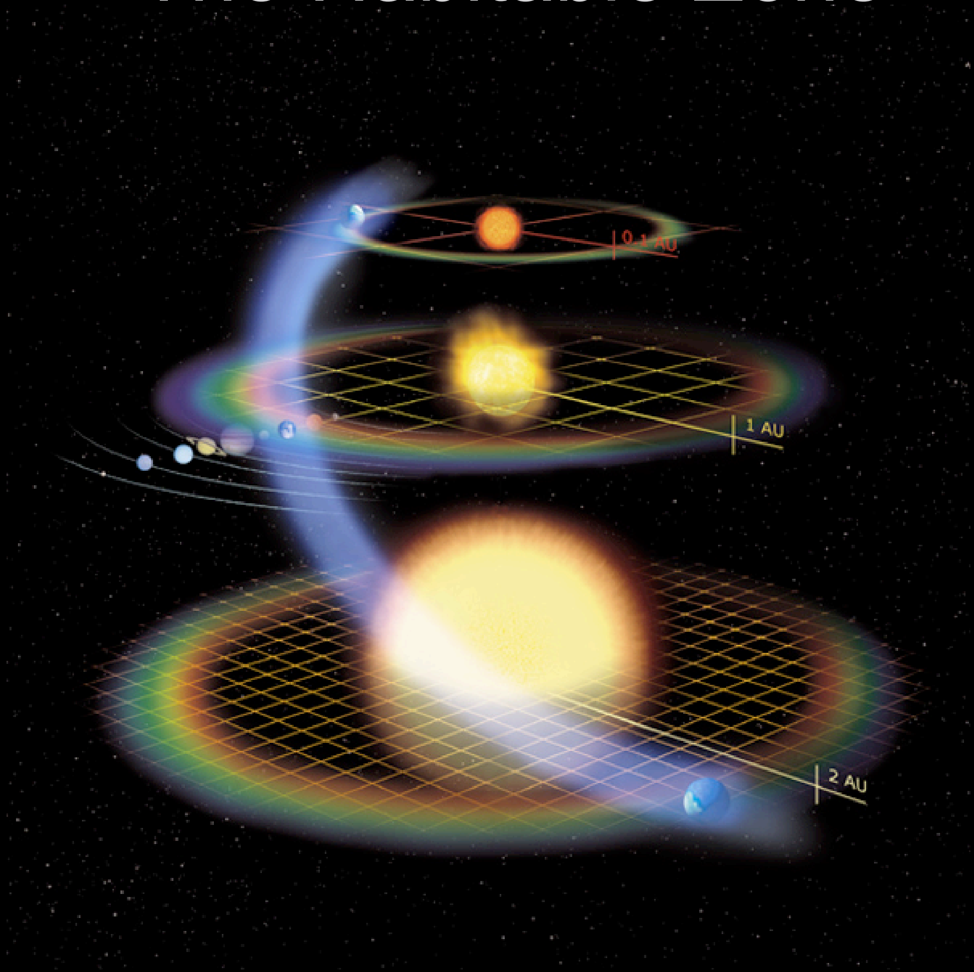
• Solar System prototypes: Jupiter, Saturn, Uranus, Neptune
• Substantial gaseous envelopes
• Masses of the order of Jupiter mass
• In the Solar System, NOT same composition as Sun
• Presence of gas implies formation while gas was still prevalent



Types of planet: terrestrial planets

- Solar System prototypes: Earth, Venus, Mars
- Primarily composed of rocks
- In the Solar System (ONLY) orbital radii is less than that for giant planets
- Much more massive terrestrial planets could exist (> 10 Earth masses), though none are present in the Solar System

The Habitable Zone



• The habitable zone is that region where liquid water is able to exist on the surface of a planet, but depends on the spectral type and age of the parent star

Detecting extrasolar planets

(1) Direct methods - difficult due to enormous star / planet flux ratio

(2) Astrometry

- Observable: stellar motion in plane of sky
- Very promising future method: Keck interferometer, GAIA, SIM

(3) Radial velocity

- Observable: line of sight velocity of star orbiting centre of mass of star - planet binary system
- Most successful method so far: >100 detections to date

(4) Transits

- Observable: drop in stellar flux as planet transits stellar disc
- Requires favourable orbital inclination
- Seven Jupiter mass exoplanets observed from ground
- Earth mass planets detectable from space (Kepler, Eddington)

(5) Gravitational lensing

- Observable: light curve of a background star lensed by the gravitational influence of a foreground star. The light curve shape is sensitive to whether the lensing star is a single star or a binary (star + planet is a special case of the binary)
- Rare - requires monitoring millions of background stars, and also unrepeatable
- Some sensitivity to Earth mass planets
- One detection so far

Each method has different sensitivity to planets at various orbital radii - complete census of planets requires use of several different techniques

Direct Methods

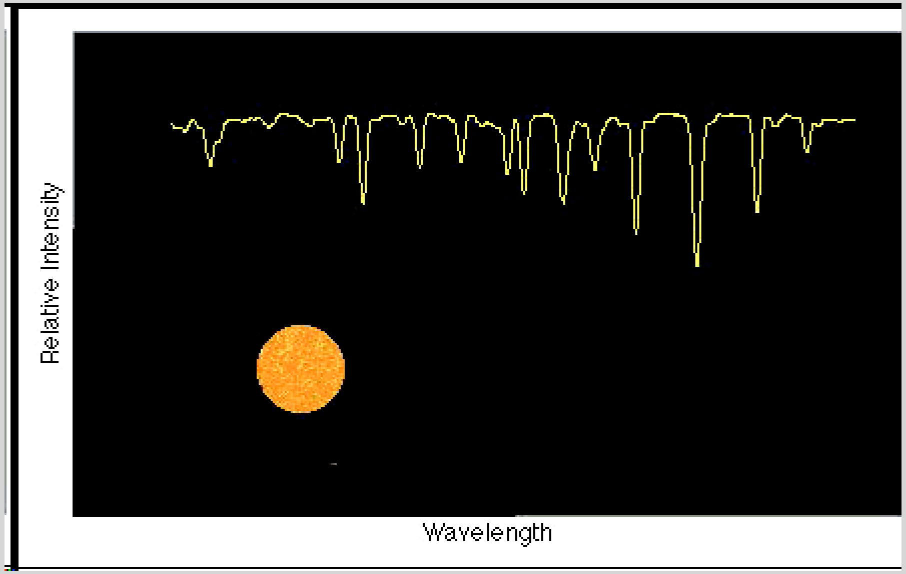
A *direct method* uses either starlight reflected from or thermal radiation emitted by the planet

An *indirect method* uses effects of the planet on the parent star or random background sources

What kind of things can we learn from direct detection?

- Radius, albedo, and temperature of planet
- Doppler imaging – planet's orbital velocity → orbital inclination
- Molecular tracers for probing planetary atmosphere

Reflected Light



- Hot Jupiters reflect only 10^{-5} to 10^{-4} of the incident starlight
- Reflected light has a Doppler shift of $\approx$ 100 km/s due to orbital motion of planet
- Take hundreds of high S/N spectra and subtract starlight spectrum
- A matched filter algorithm can then be used to extract the planet signature

$$F_{incident}(\lambda) = \frac{L_*(\lambda)}{4\pi a^2}$$

Geometric albedo p(λ) defined at α = 0

$$p(\lambda) = \frac{F_{reflected}(0,\lambda)}{F_{incident}(\lambda)}$$

Planetary flux received at Earth is then

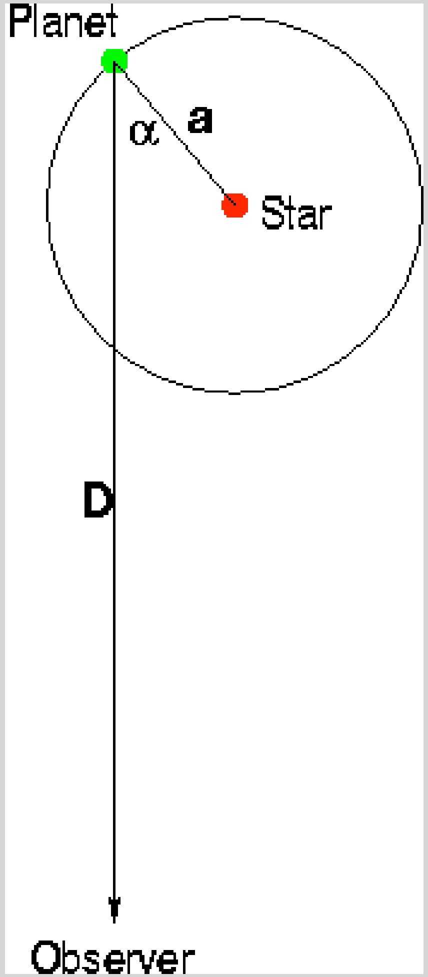
$$f_p(\alpha,\lambda) = p(\lambda) g(\alpha,\lambda) F_{incident}(\lambda) \frac{R_p^2}{D^2}$$

Where g(α, λ) is the "phase function" which is normalised to g(0, λ) = 1

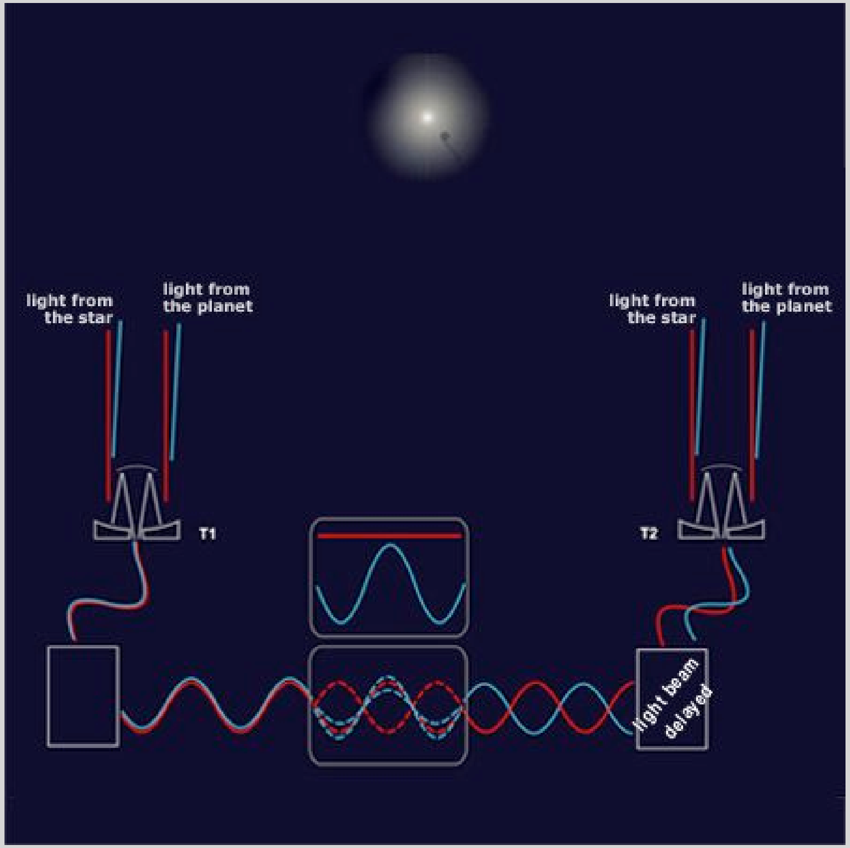
Stellar flux received at Earth is

$$f_*(\lambda) = \frac{L_*(\lambda)}{4\pi D^2}$$

$$\Rightarrow \varepsilon(\alpha,\lambda) \equiv \frac{f_p(\alpha,\lambda)}{f_*(\lambda)} = p(\lambda) g(\alpha,\lambda) \frac{R_p^2}{a^2} = \varepsilon_0(\lambda) g(\alpha,\lambda)$$



Nulling Interferometry



- Uses destructive interference to “cancel” the light of the parent star
- Foiled again by Earth’s atmosphere – must go to space!

  NASA – Terrestrial Planet Finder (TPF)

  ESA – Infrared Space Interferometer (IRSI)

Astrometry

- Conceptually identical to radial velocity searches
- Light from a planet-star binary is dominated by star
- Measure stellar motion in the plane of the sky due to presence of orbiting planet
- Must account for parallax, proper motion of star

Magnitude of effect: amplitude of stellar wobble (half peak displacement) for an orbit in the plane of the sky is $a_1 = (m_p / M_*)\ a$, and hence:

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

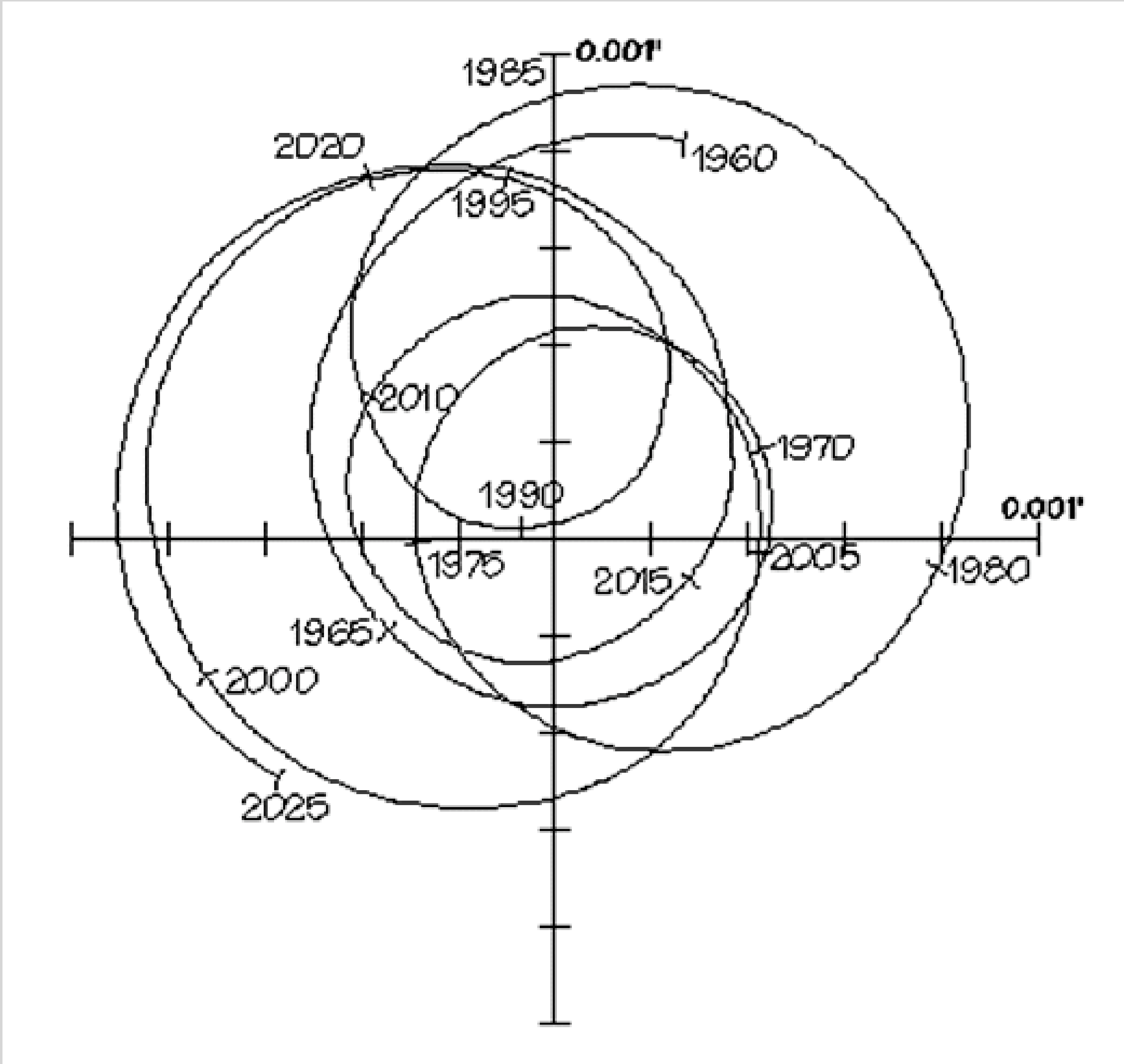
for a star at distance d. Note we have again used $m_p \ll M_*$

Writing the mass ratio $q = m_p / M_*$, this gives:

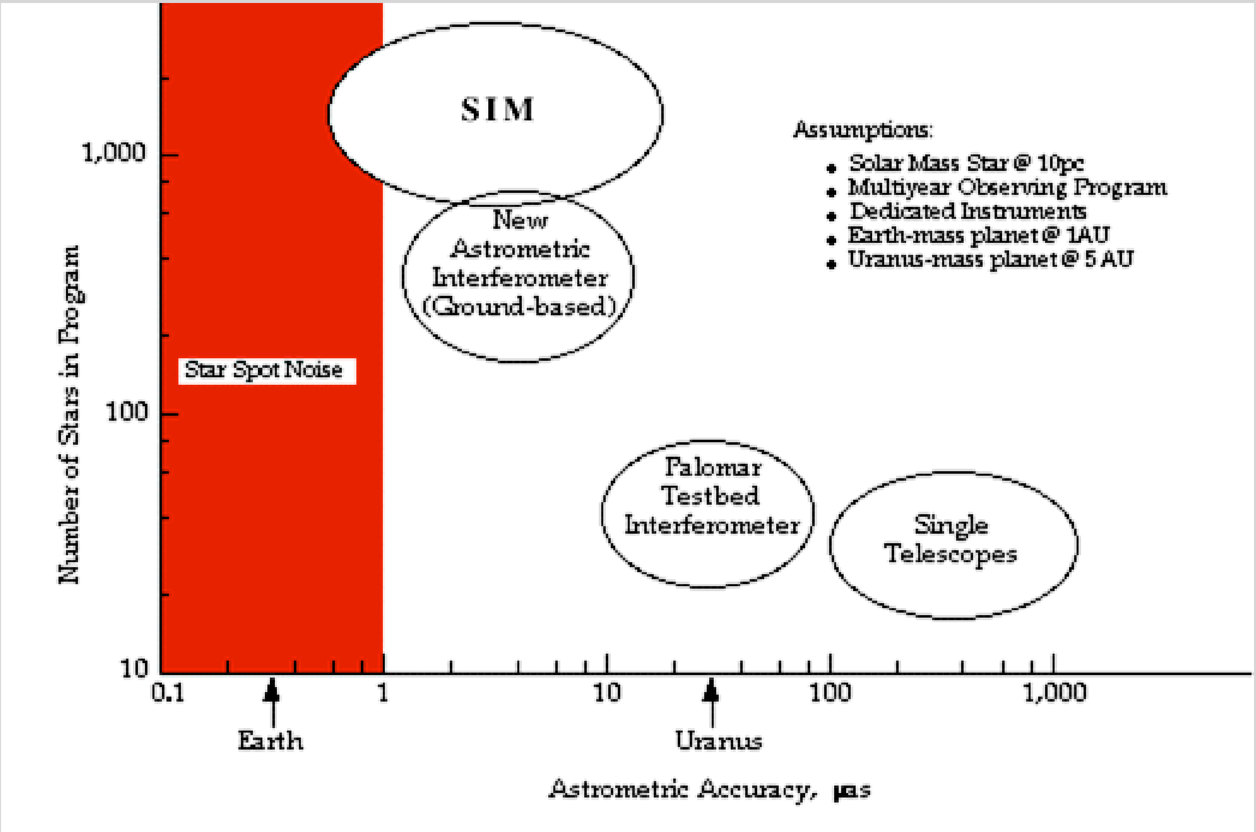
$$\Delta\theta = 0.5\left(\frac{q}{10^{-3}}\right)\left(\frac{a}{5\mathrm{AU}}\right)\left(\frac{d}{10\mathrm{pc}}\right)^{-1} \text{ mas}$$

Note:

- Units here are milliarcseconds - very small effect
- **Different dependence on a** than radial velocity method - astrometric planet searches are more sensitive at **large a**
- Explicit dependence on d (radial velocity measurements also less sensitive for distant stars due to lower S/N spectra)
- Detection of planets at large orbital radii still requires a search time comparable to the orbital period
- Has been used to detect the radial velocity planet GJ 876 b with a period of 61.0 days



The wobble of the Sun's projected position due to the influence of all the planets as seen from 10 pc



• Very promising future: *Keck interferometer, Space Interferometry Mission (SIM), ESA mission GAIA,* and others

• Planned astrometric errors at the ~10 microarcsecond level - good enough to detect planets of a few Earth masses at 1 AU around nearby stars