Extrasolar Planets

- Detection Methods
  - Radial velocity variation
  - Astrometry
  - Direct imaging
  - Transients
Review

- **Kepler’s 3 Laws of Planetary Motion**
  - \( r = a(1-e^2)/(1 + e \cos(f)) \)
  - \( (dA/dt) = (1/2) \left( \mu a(1-e^2) \right)^{1/2} \)
  - \( \mu = G(M_1 + M_2) \)
  - \( T^2 = (4\pi^2/\mu)a^3 \)

- **3-body problem**
  - zero-velocity surfaces define included/excluded regions of orbital phase space
  - Lagrangian Equilibrium points – positions that are stationary in a frame with angular velocity, \( n \). There are 5 of them, three on the x-axis and two “triangular” Lagrangian points

---

Imaging

- Detection of “point source” image \( \rightarrow \) reflected stellar light
  - \( L_p/L_* = p(\lambda, \alpha)(R_p/a)^2 \)
    - \( \alpha \rightarrow \) angle between star and observer as seen from planet
    - \( p \rightarrow \) geometric albedo
    - Ratio \( \sim 10^{-9} \) for Jupiter (note numbers in Table 2.1)
  - Why is the ratio less in the infrared than in the optical?

- **Difficulties**
  - Planets are overwhelmed by starlight
  - Separations are tiny \( \rightarrow \) need space interferometry, adaptive optics
Dynamical Perturbation

- Motion of planet causes reflex circular motion in star about the center of mass of star/planet system
- Observables:
  - Radial velocity variations
  - Variations in position (astrometry)
  - Variation in the time of arrival of some reference signal (generally used for pulsars)
Radial Velocity Variations

- Just use Newton and Kepler….we’ll do this a bit later…

- For Jupiter-Sun system $\rightarrow K = 12.5 \text{ m s}^{-1}$ with a period of 11.9 years

- For Earth-Sun system $\rightarrow K = 0.1 \text{ m s}^{-1}$

- Only measure $M_p \sin i$, not $M_p$

- All extrasolar planets were initially detected using radial velocity variations
  - Resolution of a few m s$^{-1}$ are possible $\rightarrow$ but keep in mind the orbit times!
  - Might get down to 1 m s$^{-1}$
Astrometric Position

- Star moves a bit as it orbits about the center of mass
- Angular semi-major axis:
  
  \[ R(w) = a(1 - e^2)/(1 + e \cos(w)) \]
  
  \[ \alpha = (M_p/M_*) (a/d) \]
  
  Units: \( a \) (AU), \( d \) (pc)
  
  Jupiter-Sun system viewed from 10 pc away \( \rightarrow 500 \mu \text{as} \)
  
  Earth-Sun \( \rightarrow 0.3 \mu \text{as} \)

Need space interferometry \( \rightarrow \) impossible from the ground

Timing

- 1st “planet” detected was around a pulsar \( \rightarrow \) hard to believe!
- Planet causes a tiny wobble which would affect timing of pulsar
  
  \[ T_p = 1.2 \left( \frac{M_{\text{pulsar}}}{M_{\text{planet}}} \right) (P/\text{1 year})^{2/3} \text{ ms} \]
- Discovery of few Earth mass sized objects around pulsar PSR 1257+12
- Where did they come from?
  
  - Survived the SNe?
  - Captured
  - Formed after the formation of the neutron star
Transits/Reflections

- How does planetary motion affect the apparent brightness of the star?
- In suitable geometry, planet blocks out part of the star → 2% for a Sun-Jupiter system
  \[ \Delta L/L \sim \left( \frac{R_p}{R_*} \right)^2 \]
- Tiny fractions for terrestrial planets → $10^{-5}$
- Timing – transits are short!
  \[ T = \left( \frac{P}{\pi} \right) \left( R_\odot \cos \delta + R_p \right) / a = 13 (M_\odot)^{-1/2} (a)^{1/2} (R_*^4) \ h \]
  - In units of solar masses, solar radii, and AU
  - 25 hours for Jupiter
  - 13 hours for Earth

Maybe a large survey of large numbers of possible stars?
Direct Imaging

Extra-solar planets

Figure 2. Image of the brown dwarf Gliese 229 b, obtained with an adaptive-optics system at the Palomar Observatory 60-inch telescope (left) and with the Hubble Space Telescope (right). The brown dwarf is 7 arcsec to the lower right of the companion star, Gliese 229. The star/brown dwarf brightness ratio is < 1000:1, and the distance between the two objects corresponds roughly to the Sun-Pluto separation. A Jupiter mass planet, at a distance of 10 pc would be 14 times closer to its parent star, and much more than 100 times dimmer than Gliese 229 b (courtesy of Tatsuki Nakajima).

Fig. 10. Adaptive-optics image of a brown dwarf and its companion. The two stars in the system have masses of 25 and 5 times the mass of Jupiter. Although the companion has a mass within the giant planet range, the small mass of the primary and the large separation of the two objects seems to imply that it is not a planet; we are rather observing a binary brown-dwarf. From Chauvin et al. (2004).
Radial Velocity Variation

Radial Velocity Variations

\[ K = \left( \frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_p + M_\star)^{1/2}} \frac{1}{(1 - e^2)^{1/2}} \]  

(2)

In a circular orbit the velocity variations are sinusoidal, and for \( M_p \ll M_\star \) the amplitude reduces to:

\[ K = 28.4 \left( \frac{P}{1 \text{ year}} \right)^{-1/3} \left( \frac{M_p \sin i}{M_\star} \right)^{1/2} \left( \frac{M_\star}{M_\odot} \right)^{-3/2} \text{ ms}^{-1} \]  

(3)

where \( P \) and \( a \) are related by Kepler's Third Law:

\[ P = \left( \frac{a}{1 \text{ AU}} \right)^{3/2} \left( \frac{M_\star}{M_\odot} \right)^{-1/2} \text{ year} \]  

(4)

Figure 4. Examples of radial velocity measurements: HD 219277 (left) and HD 188753 (right), from Marc et al. (1999), obtained with the HIRES spectrometer on the Keck telescope. The solid lines show the best-fit Keplerian models. The non-sinusoidal variations result from the eccentric orbits, and the derived \( M \sin \iota \) values are 1.28 and 4.01 \( M_\odot \) respectively. The fit for HD 188753 is improved further by a linear velocity trend, suggestive of an additional nearby, long-period stellar or brown dwarf companion (courtesy of Geoffrey Marcy).
Exoplanets circa 2000

Figure 11. Left: eccentricity versus orbital radius for the known planetary systems listed in Table 1. Diameters of the solid circles are proportional to the measured values of \(M_p\) \(^{1/2}\). Right: schematic of the resulting orbits. The systems are shown with their relevant values of \(a\) and \(e\), again showing masses by the size of the relevant solid circle. The Earth's orbit at 1 AU is shown as a solid line for reference. Orbits with the largest \(a\) (14 B ce) and largest \(e\) (HD 22562, HD 8778 and 16 Cyg B) are labeled.

Fig. 5. Period–mass distribution of known extra-solar planets orbiting dwarf stars. Black dots are for planets around single stars, red squares for planets in binaries, and starred symbols for “solid” planets. Dashed lines are limits a 2.25 \(M_{\text{Earth}}\) and 100 days. The dotted line connects the 2 “massive” components orbiting the star HD 188433. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Figure 6. Detection domain for methods exploiting planet orbital motion, as a function of planet mass and orbital radius, assuming $\Delta v_c = \Delta v_\pi$. Lines from top left to bottom right show the limits of non-detectability for periods of 10 and 100 years and eccentricities of 0.6 and 1.0, respectively. Distances of 50 and 100 pc from Jupiter and distances of 100 and 1000 pc are 100 times higher. A measure of accuracy 3–4 times better would be needed to detect a given value of $\Delta v_c$. Very short and very long period planets cannot be detected by planned astrometric space missions: vertical lines show limits corresponding to orbital periods of 0.1 and 100 years. Lines from top right to bottom left show radial velocities corresponding to $K = 10$ and $K = 1$m/s (equations 3 and 4), a measurement accuracy 3-4 times better would be needed to detect a value of $K$.

Horizontal lines indicate photometric detection thresholds for planetary masses, of 1.5 and 0.01, corresponding to Jupiter and Earth-mass planets, respectively (neglecting the effects of orbital inclination, which will diminish the probability of observing a transit as a function). The positions of Earth (E), Jupiter (J), Saturn (S) and Uranus (U) are shown, as are the lower limits on the masses of known planetary systems (triangles) from Table 1.

Figure 7. Period–recency diagram for the sample of known exoplanets (red open pentagons) in comparison with stellar binaries (black dots). The Earth and giant planets of the Solar System are also indicated as well. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Extrasolar Planets

- Population $\rightarrow$ 150 “exoplanets”
- Most with masses: 100-5000 $M_{\text{Earth}}$
- 6 transits
- Orbital periods 1.21-4.02 days
- Planet radii: 1.0-1.35 $R_{\text{J}}$
- Planet masses: 0.53-1.45 $M_{\text{J}}$
- Mass-radius relation $\rightarrow \rho = 0.4-1.0$

Santos, Benz, Mayor 2005

Figure T: The first detected transit of an extrasolar planet, HD 209458 b (T. C. Charbonneau et al. 2003). The figure shows the measured relative intensity versus time. Shown are two transits in the right (top to bottom) at 4.5 days. The planet transit is not periodic ($\tau$ is the time of central transits) and the planet orbit is inferred (courtesy of D. Charbonneau).
**Extrasolar Planets**

- **Population → 150 “exoplanets”**
  - Most with masses: 100-5000 M$_{\text{Earth}}$
- **6 transits**
  - Orbital periods: 1.21-4.02 days
  - Planet radii: 1.0-1.35 R$_{\text{J}}$
  - Planet masses: 0.53-1.45 M$_{\text{J}}$
  - Mass-radius relation $\rho = 0.4-1.0$
- **Metallicity → correspondence** between composition and presence of planets

Detection of 589.3 nm feature from Na

Looking for deeper transit
- Variation with time $\rightarrow$ “limb darkening”
- “Deeper” relative to other bands

(Charbonneau et al. 2002)