ExtraSolar Planets
Our **solar system** consists of

- 1 Star
- 4 Jovian planets (+ icy moons)
- 4 Terrestrial planets
- The asteroid belt (minor planets)
- The Kuiper belt (dwarf planets, plutinos and TNOs)
- The Oort cloud and the comets

There are $4 \times 10^{11}$ stars in the Galaxy
Finding Extrasolar Planets. I

Direct Searches

Direct searches are difficult because stars are so bright.
How Bright are Planets?

Planets shine by reflected light.

The amount reflected is

• the amount received (the solar constant)
• times the projected area of the planet
• times the albedo (fraction reflected)

\[ L_p = \frac{L_*}{4\pi d^2} \times \text{albedo} \times \pi R_p^2 \sim L_* (R_p/d)^2 \]

For the Earth, \((R_p/d)^2 \sim 5 \times 10^8\)

For Jupiter, \((R_p/d)^2 \sim 10^8\)
How Bright are Planets?

You gain by going to long wavelengths, where the Sun is relatively faint, and the planet is relatively bright.

Planets also re-radiate sunlight at long wavelengths.
How do you detect extra-solar planets?

- Remember – planets orbit stars
Finding Extrasolar Planets. I.

Direct imaging

(there is no planet in this image!)
How Far are Planets from Stars?

1 au = 1“ at 1 pc (definition of the parsec)
- 1 pc (parsec) = 3.26 light years
- 1“ (arcsec) = 1/3600 degree

As seen from α Centauri (4.3 ly):
- Earth is 0.75” from Sol
- Jupiter is 4” from Sol

Can we see this?
Yes, but it takes special techniques, and is not easy.
HR 8799 (A5V)

Near-IR Coronography
Direct Imaging

Best for planets that are
- Large
- Hot (self-luminous)
- Far from their star
Aside: Orbits

**Orbit**: the trajectory followed by a mass under the influence of the gravity of another mass.

Gravity + Newton's laws explain orbits.

In circular motion the acceleration is \( a = \frac{V^2}{r} \)
where \( V \) is the velocity and \( r \) is the radius of the orbit.

The acceleration in orbit is due to gravity, so
\[
\frac{V^2}{r} = \frac{GM}{r^2}
\]
or
\[
V = \sqrt{\frac{GM}{r}}
\]

Since \( V = \frac{2\pi r}{P} \), we know \( r \) and can estimate \( M \).
Orbits

\[ V = \sqrt{\frac{GM}{r}} \]

Observables:

- orbital velocity \( V \) (actually \( V \sin i \))
- orbital period \( P \).

In a circular orbit, \( V = \frac{2\pi r}{P} \), so we know \( r \) and can estimate \( M \).

Does this help?
Center of Mass Motions

The star and the planet orbit the common center of mass.

The planet is invisible.

- \( r = r_* + r_p \)
- \( r_* = \frac{m_p}{m_*} r_p \) (astrometric wobble)
- \( v_* = \frac{m_p}{m_*} v_p \) (radial velocity wobble)
Kepler’s Laws

**Empirical** laws describing planetary orbits

1. Orbits are ellipses, with the Sun at one focus of the ellipse
2. The line connecting the planet to the Sun traces out equal areas in equal times
3. $a^3 = P^2$
Types of Orbits

K+U > 0

K+U = 0

K+U < 0
Finding Extrasolar Planets.

II. Transits

Transits require an edge-on orbit.

- Light occulted = \( \left( \frac{r_p}{r_*} \right)^2 \)
  (area of planet / area of star)

Jupiter blocks 2% of the Sun's light
Earth blocks 0.01% of the Sun’s light
How Transits Work
Transits

Best for planets that are
  – Large relative to their star,
  – Near their star

Due to the Kepler mission, about \( \frac{3}{4} \) of all exoplanets have been discovered with this method.
Finding Extrasolar Planets. III.

Astrometric Wobble
Reflex Motion

Planets do not orbit the Sun - they both orbit the center of mass.

The radius of the orbit is inversely proportional to the mass.

\[ a_1 M_1 = r_2 M_2 \quad (r = r_1 + r_2) \]

This is Newton’s law of equal and opposite reactions.

The radius of the Sun’s orbit with respect to

- **Earth**: 1 / 300,000 au, or **500 km**.
- **Jupiter**: 5.2 / 1,000 au, or about **1 R_☉**
Barnard’s Star

**M4V star**

V mag: 9.5

**Distance:** 6 ly (4th closest)

**Rotation:** 130 days

**Age:** 7-12 Gyr

**Proper motion:**

RA: -0.8 arcsec/yr

DEC: 10.3 arcsec/yr

(90 km/s)

**Parallax:**

0.55 arcsec

**RV:**

-110 km/s
A Planet Orbiting Barnard’s Star?

P. Van der Kamp, 1963 - 1972, Sproul Observatory
Van der Kamp’s Planet

- 1.6 $M_J$ at 4.4 au
- Never confirmed
- Attributed to calibration/maintenance of the telescope
Astrometric Wobble

Best for planets that are

- Massive relative to their star,
- Far from their star
Many planets have been found by Doppler Wobble (radial velocity variations).
Finding Extrasolar Planets. IV.
Orbital Velocity

\[ V = \frac{2\pi r}{P} \]
- \( r \): radius of the orbit
- \( P \): orbital period
- \( V \): orbital velocity

How fast does the star “wobble”?

Kepler’s 3rd law: \( P^2 \propto M a^3 \) (a: semi-major axis of orbit)
- \( a \sim r_p \) (\( M_* \gg M_p \))
- \( r_* = \frac{m_p}{m_*} r_p \) (center of mass)

\[ V_* = 2\pi \frac{m_p}{m_*} / r_p^{1/2} \]

\[ V_{\odot \odot} = 2 \text{ cm/s}; \ V_{\odot J} = 3 \text{ m/s} \]
Doppler Shifts

Laboratory spectrum
Lines at rest wavelengths.

Object 1
Lines redshifted: Object is moving away from us.

Object 2
Greater redshift: Object is moving away faster than Object 1.

Object 3
Lines blueshifted: Object is moving toward us.

Object 4
Greater blueshift: Object is moving toward us faster than Object 3.

Copyright © Addison Wesley
Doppler Wobble

Best for planets that are

- Massive relative to their star
- Near their star
Finding Extrasolar Planets. V.

Timing

The Doppler Effect applied to pulse arrival times. Applicable to pulsar planets.
Pulse Timing

Equivalent to doppler wobble and astrometric wobble

- $\Delta t = ca \sin i$ (light travel time across orbit)
- Requires a stable clock (e.g., a pulsar)
- Best for edge-on orbits
Finding Extrasolar Planets. VI.

Gravitational Lensing

Foreground objects focus (and magnify) light because they distort space.
Gravitational Lensing

Best for planets that are
  – Fortuitously located in space
Astrometric Method

\[ \theta^* = \left( \frac{M_p}{M_\star} \right) \left( \frac{a}{r} \right) \approx 10^{-3} \left( \frac{P(\text{yr})}{M_\star(\odot)} \right)^{2/3} \]

\[ V_c (m/s) \approx \frac{30}{[P(\text{yr})]^{1/3}} \left[ \frac{M_p(\odot)}{M_\star(\odot)} \right]^{2/3} \]

Microlensing Method

\[ R_g^2 = \frac{4GM}{c^2} \]

\[ D = \frac{D_o D_i}{D_s} \]

\[ t_0 = \frac{2D_i \theta_g}{V_L} = \frac{2D_i}{V_L} \sqrt{ \frac{4GM (1 - D_i/D_s)}{c^2 D_i} } \]

\[ A = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}} \]

Radial Velocity Method

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

Microlensing Method

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

Direct Detection

\[ B \geq \frac{4D}{r} \left( \frac{\lambda}{10 \mu m} \right) \left( \frac{D}{10 \text{pc}} \right) \left( \frac{r}{1 \text{AU}} \right)^{-1} \]

Effective Temperature

\[ T_p = \frac{(1 - A)^{1/4}}{\sqrt{2}} \left( \frac{R_p}{r} \right)^{1/2} T_i \]

Transit Method

\[ \frac{\Delta F}{F} = \left( \frac{R_p}{R_\star} \right)^2 \]

\[ t = \frac{P_p}{\pi} \left( \frac{R_\star \cos \delta + R_p}{a_p} \right) \]

\[ i_{\text{min}} = \cos^{-1} \left( \frac{R_\star}{a_p} \right) \]

\[ \cos i = \frac{R_\star \sin \delta}{a_p} \]