PHY2003 ASTROPHYSICS I

Lecture 14. Finding Extrasolar Planets

The first planet orbiting another star was found in 1995. As of October 2018, astronomers have confirmed $4,201$ *extrasolar planets or exoplanets* orbiting stars beyond our Solar System. 3214 of the known exoplanets were detected via the transit method.

Imaging Searches

Large telescopes are sensitive enough to detect Jupiters around nearby stars.

Example: Jupiter has $V = -2.2$ at its brightest as seen from Earth. What would be the apparent magnitude of a similar planet with the same orbit around the solar-type star Alpha Centauri, 1.3 parsecs away? (Assume: $m_V = -2.5 \log f_{\rm V} - 18.74$)

Nearest stars are $\sim 10^6$ au from Earth.

At this distance 1 au $\equiv 10^{-6}$ radians $= 0.2$ arcsec.

So a Jupiter at 5 au would appear ~ 1 arcsec from parent star.

Planet of radius R_p at a distance R_h intercepts amount of light given by

$$L_P = \frac{L_*}{4\pi R_h^2} A\pi R_P^2 = \frac{L_* A}{4} \left(\frac{R_P}{R_h}\right)^2$$

$$\boxed{\frac{L_P}{L_*} = \frac{A}{4} \left(\frac{R_P}{R_h}\right)^2}$$

For Jupiter-size, $A \simeq 0.5$ and $R_P \simeq 5 \times 10^{-4}$ au $\Rightarrow L_P/L_* \simeq 3 \times 10^{-8}$

Hence the problem is trying to see a very faint object that is close to a very bright object. This contrast problem currently prevents direct imaging of *small* planets around other stars.

50 nearby stars have now had planets directly seen orbiting them. All detections have used adoptive optics for high angular resolution, near-infrared wavelengths where the contrast is smaller, plus advanced image processing to remove light from the central star.

The star HR8799 has *four* exoplanets imaged around it, clearly showing Kelperian orbital motions over 6 years.

Astrometric Searches

As the planets move around the Sun, it also moves in response around the center of gravity. The distances of the star and planet to the centre of gravity is given by,

$$M_* r_* = M_P r_P$$

For the Sun-Jupiter system:

$$r_* = (M_J/M_\odot) r_J \simeq 7 \times 10^5 \text{km} \simeq R_\odot$$

The nearest star is $\simeq 270,000$ au distant, so from that star $R_\odot \equiv 0.004$ arcsec. This is impossible from ground-based telescopes, but is possible using the GAIA astrometric spacecraft that is currently gathering data. Currently, 1 planet has been discovered with this technique.

Radial Velocity Searches

A star will move towards and away from us around the centre of gravity of the system with the same period as the planet. We can detect this spectroscopically via Doppler shifts of the stellar lines.

From Kepler's 3rd law:

$$a^3 = \frac{G(M_* + M_P)}{4\pi^2} P^2 \simeq \frac{GM_*}{4\pi^2} P^2$$

Can get M_* from the spectrum of the star, so this gives the orbital distance of the planet. Then knowing this, can calculate the orbital velocity of the planet.

$$V_P = \sqrt{\frac{G(M_* + M_P)}{a}} \simeq \sqrt{\frac{GM_*}{a}}$$

For a balanced system the resultant linear momentum must be zero relative to the center of gravity. The Doppler shifts give the velocity of the star.

$$\sum_i M_i V_i = 0, \quad \text{so } M_* V_* = M_P V_P$$

So we can then calculate the mass of the planet. But the spectroscopic Doppler shift of the parent star is expected to be very small!

Astronomers don't directly measure the velocity of the star, but instead its doppler shift. The v of the star relative to the observer through will be visible through the *Doppler shift* of its spectroscopic lines.

$$\frac{\lambda' - \lambda_0}{\lambda_0} = \frac{d\lambda}{\lambda_0} = \frac{v}{c}$$

With the Doppler shift, we can estimate V_* and measure the mass of the orbiting planet.

Example: Calculate the Doppler accuracy required to discover Jupiter by looking at the reflex motion of the Sun.

Another problem is that the orbit is inclined by some unknown angle i to the sky, so the radial velocity will rarely be the total velocity of the parent star around the center of mass.

We measure some velocity given by $K = V_* \times \sin i$. So planet mass measured is given by

$$M_P \sin i = \frac{V_* \sin i}{V_P} M_*$$

$$\boxed{M_P \sin i = \frac{K}{V_P} M_*}$$

So this technique then gives a lower limit to the mass, and
as $i \to 0^\circ$, the value of M_P increases.

The first planet orbiting a normal solar-type star was discovered in 1995, planet 51 Peg b.

810 confirmed exoplanets have been discovered to date via the radial velocity technique. From surveys of nearby stars over past decade,
> 5**% of Sun-like stars have gas giant planets.**

Transiting Planets

For gas giants relatively close to their star, stand a chance of the planet passing in front of the star once per orbit - a *transit*.

Stars are unresolved from Earth, so would detect the transit by part of the starlight being blocked from reaching earth by the planet during the transit.

The light seen from the star is proportional to the amount of visible surface. Therefore the ratio of brightness of the star with a planet in transit to outside transit is

$$\frac{I'}{I_0} \simeq \frac{\pi R_*^2 - \pi R_p^2}{\pi R_*^2} \simeq 1 - \left(\frac{R_p}{R_*}\right)^2$$

For Jupiter, $R_p \simeq 0.1 R_*$. So to see Jupiter-sized planets crossing their stars, need to look for a decrease in light from stars of $\simeq 1\%$.

First transiting system discovered in 1999 - HD209458b, now $> 75\%$ of exoplanets have been found using this method.

This is possibly the most important type of planet discovered - transit depth gives true radius, and $\sin i \simeq 1$. So if doppler measurements can be made, mass can be measured and we can derive the planet density.

In the Plato-11 system, a transiting planet causes 0.01$\%$ drop in light when it moves in front of its parent star. The Plato-11 hot star is a Solar-type main sequence star with a mass of 0.95$M_\odot$ and a radius of 1.1$R_\odot$. Estimate the planet's radius.