Astro 205. Lecture 7, October 6, 2003
The Search For Planets: Radial Velocity Surveys

Introduction

A really major breakthrough in the last six years has been the detection of planetary systems around stars other than our own Sun. As it turns out, these systems look nothing like the Solar System.

Before we start, let's remember two simple physical principles. (a) the luminosity of a thermal body is proportional to T^4, so that even a small rise in temperature means a large increase in radiated energy, and (b) stars and planets are huge, and larger bodies have a smaller area to volume ratio than smaller bodies (it goes as radius^{-1} of course) so take a long time to lose their internal energy.

There are two main ways we can learn about planetary systems: by detection and measurement of planets orbiting other stars, and by the detection and measurement of the planetary disks of dust and gas around stars from which planets form.

Finding Planetary Systems

see:

http://exoplanets.org

There are various methods for detecting planets or planetary systems, which we will now begin to discuss. Here is a summary of these methods. We will deal with them one by one in the next several lectures.

1. Direct Detection

Last class, we saw that the reflected light from a planet is outshone by its Sun by factors like 10^8 or more, so that planets cannot at the present be seen by direct imaging. NASA is working on this, via a series of space missions leading to the Terrestrial Planet Finder TPF: see

http : //planetquest.jpl.nasa.gov/index.html

2. Debris Disks

There is a strong exception to the above. If there is a dust disk or cloud surrounding a star, it can be very easily seen. This is because dust is in tiny particles, and the surface area to mass ratio is large. For example, if you pulverise the Earth (6×10^{27} gm, radius 6.4 $\times10^8$ cm) into dust particles of radius 1 micron (10^{-4} cm) you increase the effective area by a factor of 6.4 $\times 10^{12}$!. Debris disks have been seen around many other stars, as you will hear in subsequent lectures, and were the first observational evidence that planetary systems might exist around other stars.

3. Transits

Jupiter's linear size (and that of objects from about 0.3 to 80 Jupiter masses) is about 1/10 that of the Sun. This means that if a planet passes in front of a star, the star's light dims by about 1%. This measurement is tough but doable.

4. Position Wobble

Detecting wobble in a planet's position requires precision position measurement, or astrometry: this will be the subject of Wednesday's lecture.

5. Microlensing

Light is bent by gravity: thus the light from a background object is bent when a foreground object passes in front of it. Potentially, this can allow the detection of planetary systems.

6. Pulsar Timing

Pulsars are very precise astronomical clocks, so measuring the pulse arrival times is a very good way to measure the masses etc. of any objects orbiting the pulsar.

7. Radial Velocity Wobble

This is, at present, the most important method for detecting planets (as opposed to planetary disks), and has found over 100 planets around other stars to date.

As we did last time, consider conservation of momentum: the planet and the star are moving in opposite directions with the same momentum, i.e.

$$\mathrm{M_\star V_\star} = \mathrm{M_p V_p}$$

The orbital speed round a 1 solar mass star at a distance of 1 A.U. is about 30 km/sec (the Earth's orbital speed), so

$$\mathrm{V_\star} = \frac{\mathrm{M_p}}{\mathrm{M_\star}}\mathrm{V_p}$$

For a 2 Jupiter mass planet, this is about $2\times10^{-3}\times$ 30 = 0.06 km/sec, 60 meters/sec (about 140 miles per hour). Thus if you see the star moving back and forth, you can find out:

that there's a planet in the system

its period

its mass (since we have some idea of the star's mass from the relationship between brightness and luminosity on the main sequence)

its distance from the star (by applying Kepler's laws)

the orbital eccentricity

The velocity of any object towards or away from you can be measured by the *Doppler shift*. This is a shift in the wavelength (and frequency) of light (or more generally electromagnetic radiation) due to the relative motion of the source of light and the observer.

$$\lambda_{\rm obs} \;=\; \lambda \left(1 \;+\; \frac{\rm V}{\rm c}\right)$$

If V is positive, i.e. the object is moving away from you, the wavelength is increased, while iv V is negative, i.e. the object is moving towards you, the wavelength is decreased.

What you actually measure is motion towards or away from you, i.e. the component along your line of sight. If the motion of the object is at an angle i to your line of sight, you measure $\rm V_z$ = V cosine (i).

So all we need is light (or more generally electromagnetic radiation) whose intrinsic wavelength we know. This is provided for us by absorption and emission by atoms and molecules.

The emission and absorption features from an atom are called *spectral lines*. Each atom, ion or molecule has a unique set of spectral lines.

Emission line spectra are produced by hot gas. In the atoms of this gas, the electrons are raised to high energy levels because the gas is hot, and spontaneously drop to lower energy levels, emitting a photon at the exact wavelength corresponding to that energy difference:

$$h\nu \;=\; E_1 - E_2$$

where ν, the frequency, = c/λ.

Stellar Spectroscopy

Since we will be measuring the spectra of stars, we need to know a bit about them. The spectrum of electromagnetic radiation is the observed intensity versus wavelength (energy, frequency) and can be measured by passing the radiation through a dispersing element. In the case of light, the dispersive element is a prism or a diffraction grating. The prism spreads the light out into its component colors by using the fact that the path of blue light through glass or a similar medium is effectively longer than that of red light, so the path of blue light through a prism is more deviated than that of red light, and the spectrum can thereby be observed.

Frauenhofer observed the spectrum of the Sun in 1814, and found that it is crossed by numerous dark lines, some darker than others - look at the picture of the Solar spectrum in CO page 127 - it's highly complicated! These dark lines are images of the spectrograph slit. They show that the intensity of the sunlight has many dips over small ranges of wavelength. Frauenhofer noted that two of the darkest spectral lines in the Sun are at exactly the same wavelengths as the bright sodium 'D' lines at 5886 and 5890 Å (Å is short for Ångstrom unit, a unit of wavelength used in optical spectroscopy, with 1 Å = 10^{-8} cm. Visible light covers the range about 4000 to 9000 Å), which are seen from hot glowing sodium gas, and deduced that there is sodium in the Sun. Bunsen and Kirchoff had shown that each element produces a set of spectral lines which is unique to that element, and found the following laws:

1. A hot solid body radiates a *continuum* spectrum with no gaps.

2. A hot gas produces emission only at specific wavelengths - this is an *emission line spectrum.*

3. A cool gas in front of a hot glowing body produces dark *absorption lines*, in the spectrum. For the same gas, the absorption and emission lines are at the same wavelengths.

Absorption lines are produced in the spectrum when light from the hot body is absorbed at certain wavelengths by cool gas in front of the body. The fact that absorption lines are seen in the Sun and stars tells you that there is a *temperature gradient* - the interior is hotter than the outside.

Thus spectroscopy tells you what elements/compounds are present in a body, including bodies you can't analyze directly, like stars. Further, you can measure many more things:

1. *How much of an element is present.* If two stars have the same temperature, but one has, say, sodium lines which are twice as strong as those in the other star, it's a reasonable inference that the first star contains twice as much sodium.

2. *The stellar temperature.* Let's take a simple example here. Suppose you have a pure hydrogen star. The *absorption lines* of hydrogen will appear strongly in the spectrum of a star whose atmosphere has a temperature of about 10,000 K because the hydrogen is mostly atomic (and because the higher energy levels are significantly excited, see below). A very hot star (T> 20,000 K) will not have hydrogen lines in its spectrum because the hydrogen is all *ionized*, while a cool star (T < 4000 K) will not have atomic hydrogen absorption lines because the hydrogen is all in *molecular* form. You can extend this argu-

ment to include lots of different kinds of atoms and molecules, and see that the patterns of spectral lines are strongly related to the gas temperature.

3. The *radial velocity* of the star. This is the radial component of the velocity towards or away from you, and is measured by the *Doppler effect*.

Stars are classified by spectral type. These are, in order of decreasing temperature:

OBAFGKMLT

and are still much in use. There are subdivisions of 0-9: thus the Sun is a G2 star.

CO chapter 8 have a graph of how the strengths of various important spectral lines change with stellar temperature - see p 240. With the theory of atomic structure came an understanding of spectra - the wavelengths of the transitions can be derived from this theory. See CO ch 5.

Spectrographs

Spectra are measured by *spectrographs*. These instruments *disperse* the light passing through them, ordering the light by wavelength. Light passing through a prism, for example, may enter as a parallel beam but is spread out by wavelength as it leaves the prism, because the speed of light in glass or whatever the prism is made of is wavelength dependent. Measurements of the tiny radial velocities produced by planets need the light to be studied in exquisite detail, which means that it needs to be measured in very small wavelength intervals. We need a lot of light to analyze: hence the use of large telescopes, which collect light from astronomical objects in proportion to their area. So stellar spectra are measured by spectrographs fed by a beam of light from a large telescope. The spectrograph itself needs a device which can spread the light out in great detail (this is called *dispersing* the light, so you need *high dispersion*. This is done by diffraction gratings rather than prisms, but we won't discuss how these work here).

You look for wobbling back and forth in the star's radial velocity. The Sun's reflex wobble due to Jupiter, for example, is 13 meters per second. This is also very hard to measure, because the stellar spectral lines have widths of tens or hundreds of kilometers per second and because the spectrographs have a resolution of about 50,000, even at their best (resolution means how finely you can split the light up into wavelengths. A resolution of 50,000 means that $\lambda/\Delta\lambda$ is 50,000, so that at 5000 Å you are splitting the light up into slices of thickness 0.1 Å). Here is what we are up against: the shift you are looking for is a few parts in 10^7 (V/c), while the resolution of the spectrograph is about 1 part in 50,000. So you are trying to measure a shift of 0.005 of the spectrograph resolution. A very sensitive technique which has finally succeeded is to pass the starlight through a gas cell - as the star's spectrum moves with the doppler shift, the signal getting through the gas cell, with its absorption lines, changes slightly. The planet searches by Marcy and Butler use an iodine gas cell and observe the wavelength range 5000 - 6000 Å.

Theory

(see Shu P 179)

This introduction to measuring planet masses is based on a brief discussion of binary stars. Binary stars probably form about half the time when stars are formed, but they are quite difficult to study: only in a small number of cases do we actually observe two separate stars orbiting each other. Most of the time, the stars are so close together that their light is blended, or one is much brighter than the other and its light overwhelms that of its companion.

The orbits of binary stars are a pair of similar ellipses: the larger the mass ratio of the star, the larger the ratio of the semi-major axes of the ellipses. If one of the stars has a relatively low luminosity, the knowledge that it is there at all is gained indirectly, by observing that a star's radial velocity wobbles. Spectra of binary stars show spectral lines belonging to both stars, if they are of comparable brightness. The two sets of spectral lines move with time: as one is redshifted, the other is blueshifted, tracing out a pair of periodic velocity curves of opposite phase. If the companion is much less luminous than the primary, you see one set of spectral lines tracing out a periodic velocity curve. This of course is the case for planets.

Binary stars orbit in a plane: their angular momentum is conserved, and since angular momentum is a vector, both its direction and amplitude are invariant. Suppose the two members of a binary system have masses m_1 and m_2, and r is the relative separation. The distances of the stars from the center of mass are then:

$$\begin{aligned} r_1 &= \frac{m_2}{m_1 + m_2} r \\ r_2 &= \frac{m_1}{m_1 + m_2} r \end{aligned}$$

Suppose the orbits are circular about the center of mass. The orbital speeds

$$\begin{aligned} v_1 &= \frac{2\pi}{P} r_1 \\ v_2 &= \frac{2\pi}{P} r_2 \end{aligned}$$

Kepler's third law is

$$\frac{4\pi^2}{p^2} = \frac{G(m_1 + m_2)}{r^3}$$

The maximum Doppler velocities observed are then $v_1 \sin(i)$ and $v_2 \sin(i)$, where i is the inclination angle of the orbit, with $i = 90^o$ being edge-on.

By conservation of momentum:

$$m_1 v_1 \sin(i) \;=\; m_2 v_2 \sin(i)$$

or

$$\frac{m_1}{m_2} \;=\; \frac{v_1 \sin(i)}{v_2 \sin(i)} \tag{1}$$

From Kepler's Third Law

$$m_1 + m_2 \;=\; \frac{4\pi^2 r^3}{G P^2} \tag{2}$$

Now

$$v_1 \;=\; \frac{2\pi r_1}{P}$$

$$v_2 \;=\; \frac{2\pi r_2}{P}$$

so

$$(r_1 + r_2)\frac{2\pi}{P} \;=\; v_1 + v_2$$

or

$$r \;=\; \frac{P}{2\pi}(v_1 + v_2)\sin(i) \tag{3}$$

What can you measure? The *period*, P, and the projected maximum velocities v_1 and v_2. You don't know i, unless you can see both stars and observe the orbit, or unless the binary is eclipsing, in which case you know that $i = 90^0$. If you don't know i, you *can* measure the mass ratio. If you do know i, you can measure the sum of the masses (and hence get both masses) and r.

Finding Planets: Doppler Wobble

For a planet, $m_2 << m_1$. If you know the mass of the star (say from the mass-luminosity relationship) a measure of the *period* gives r (equation 2). Then equation (3) gives v_2 (since $v_2 >> v_1$). However, note that since you cannot see the planet you can't measure its velocity directly, and you end up with M sin(i).

You can see that looking for Doppler wobbles favors short-period, massive planets: the shorter the period, the faster the planet is orbiting the star and the higher the reflex speed. Short period phenomena are also easier to measure: Jupiter's period is 11 years, for example, so you'd need to observe for more than 20 years to find it.

Two groups (Michel Mayor and colleagues in Geneva and Butler and Marcy at Berkeley) have finally succeeded in detecting other planetary systems, and have found some real surprises - all the systems so far have Jupiter-mass planets very near the primary star. Now at last we can begin to understand what is 'typical' in planetary system formation.

To date some 110 planets have been detected around other stars, including some multiple systems. Most of the planets are much more massive than Jupiter (note that apart from the one pulsar, the detection of Earth-like planets is still out of reach) and with short periods (see the exoplanets web site). These systems are thus very unlike our solar system.

Are all the orbits face on, so that the companions are really brown dwarfs or low-mass stars? (v sin(i) gives a lower limit to the planet's mass). This is statistically very unlikely!

A most interesting result is that the more metal-rich the star, the more likely it is to have planets; this tells us a lot about how they form.

Please read the exoplanet wb page carefully.