Astro 205. Lecture 8, October 8, 2003
Planetary Systems and Astrometry

Planetary Systems

The radial velocity techniques we talked about last time have allowed the detection of over 100 planetary systems, which gives a good sampling of systems. The precision of the radial velocity technique is about 3 meters/second, which is sufficient to detect the reflex motion of the Sun due to Jupiter (13 meters per second), but not that of the Earth. For suppose the Earth were the only planet in the Solar System: then

$$\mathrm{M}_\odot \mathrm{V}_\odot \quad = \quad \mathrm{M}_\oplus \mathrm{V}_\oplus$$

by conservation of momentum, so the maximum reflex velocity of the Sun due to its orbiting the Sun-Earth barycenter would be

$$\begin{aligned} \mathrm{V}_\odot \quad &= \quad \frac{\mathrm{M}_\oplus}{\mathrm{M}_\odot} \mathrm{V}_\oplus \\ &= \quad \frac{6 \times 10^{27}}{2 \times 10^{33}} \times 30 \times 10^3 \quad \text{meters/second} \end{aligned}$$

(the Earth's orbital speed is 30 km/sec) or 0.09 meters/sec, which is far below current levels of detectability.

So keep this in mind. The instrumental accuracy, and the time scale over which observations can be made, preferentially detect massive, close-in planets:

−−the more massive the planet, the larger the reflex velocity

−−the closer the planet is to the star, the larger its orbital velocity and the larger the reflex velocity of the star

−−the closer the planet is to the star, the shorter its period, and so the less time passes before the signature of the orbital motion can be detected.

The detection limit at present is close to a Jupiter mass. With these caveats in mind, what has been found to date?

1. Of about 1000 nearby stars surveyed, about 100 have detectable planets. The detection rate of planetary systems is thus currently about 10%.

2. The more metal-rich a star is, the more likely it is to have planets. Remember that we define the heavy-element content of a star as the abundance ratio of the heavy elements to hydrogen. Since the abundances of the heavy elements more or less correspond to each other - the more calcium a star has, the more oxygen, iron etc. etc. - we can use the abundance of one element (usually iron) as a proxy. Figure 1 shows the percentage of stars with planets versus iron abundance relative to that of the Sun. The higher the iron abundance, the more likely it is that the star has planets. Remember that the iron abundance of a star can be measured by observing and measuring *spectral lines* in the star's *spectrum.*

3. There are about 115 planets known, with 8 systems with two or more planets. The plot of orbital semi-major axis (in AU) for these systems is shown in Figure 2.

4. Remember that the observations give only a lower limit to the planet's mass. The orbits of the planet and star about each other are in a plane, which can be tipped at an arbitrary angle to the line of sight. You actually measure V sin(i), where i is the inclination of the plane of the orbit to the plane of the sky. If the orbit is edge-on as seen from Earth, $i = 90^o$ and $\sin(i)=1$. The planet's mass is gotten as a fraction of the star's mass if the planet's period can be measured. The star's mass is inferred from its *spectral type* (OBAFGKM–) which locates it on the *main sequence* of the Herzsprung-Russell diagram, and we have pretty good theoretical and observational understanding of the relationship between spectral type and stellar mass. Figure 3 shows a nice reflex velocity curve, for the star HD 70642 (this is a catalogue number). Figure 4 shows another, for HD 73256 (from the European team of Mayor and Queloz). As it happens, both of these planets have close to circular orbits.

5. Most planets are found to be in very eccentric orbits. This is completely unlike the Solar System, for which the eccentricities of the planet orbits are small (i.e. the orbits are close to circular). The radial velocity curve for the planet around HD 3651 is shown in Figure 5. The eccentricity is 0.63.

6. Planet masses in the range 0.1 to about 13 Jupiter masses are found (see Figure 6), but most of the planets are 1-2 Jupiter masses.

7. In complete contrast to the Solar System, most of these "Jupiters" are close to their stars. Figure 7 shows a histogram of the semi-major axes of the planets' orbits (remember that although you cannot directly measure these distances, you can calculate them by applying Kepler's laws). There are selection effects - it's hard to find planets at large distance - but the prevalence of massive planets well within 1 AU is very different from the Solar System. Figure 8 shows the orbits of these planets compared with that of the Earth. Note that if there were such massive planets in the Solar System in orbits like these, the Earth would long ago have been ejected from the Solar System.

Figure 9 shows a plot of orbital eccentricity versus semi-major axis for known planets. There are about 90 planets beyond 0.15 AU, and their mean eccentricity is 0.32. Within 0.1 AU, however, the orbits are close to circular. This is likely due to the influence of *tides* - the pull of gravity on the distorted shape of the planet. Jupiter's eccentricity is very close to zero, and its almost-circular orbit may have a stabilising effect on the orbits of planets in the solar system.

Multiple Systems

Figure 10 shows the radial velocity curve of a system with two planets: one with a period of 263 days and an eccentric orbit, and the second with a period of 1550 days and a close to circular orbit. You can see the signatures of both orbits in these figures. Figures 11 and 12 show two resonant planetary systems.

Brown Dwarfs

Remember our "physical" definition of stars, brown dwarfs and planets. Marcy's group defines planets as "objects with masses between those of Pluto and the deuterium burning threshold, which form in orbit around an object which can generate nuclear reactions" (in a word, a star). Brown dwarfs are objects of too low a mass to burn hydrogen (the limit is about 70- 80 Jupiter masses) but can burn deuterium. Note from Figure 6 that the number of planets detected drops with mass, *even though it is easier to detect high mass planets.* The highest mass planet so far is about 12 Jupiter masses, fortuitously (?) close to the brown dwarf limit. While 10% of solar type stars have close in planets, fewer than 1% have close-in brown dwarf companions. So perhaps brown dwarfs do not form the same way as do planets? This is an area of very active research right now.

Astrometry and Reflex Position Wobble

Can the back and forth wobble of a star orbited by a planet be detected by seeing its position change? Before we discuss this we have to realize that the positions of stars on the sky, especially nearby stars, change because of *parallax* and *proper motion.* Parallax we have already discussed. Proper motion is the motion across the sky due to the star's orbit in the Galaxy (or more correctly the slight difference between its motion and that of the Sun). The star thus appears to follow a corkscrew path on the sky, with the back and forth parallax motion smaller for more distant stars.

What about reflex motion? Here, the further apart the planet and the star the better (except you have to observe for a long time). The center of mass of the star-planet system is at

$$\mathrm{r} \;=\; \frac{\mathrm{M_p}}{\mathrm{M_\star}}\mathrm{D}$$

if the planet's mass $\mathrm{M_p}$ is much less than that of the star $\mathrm{M_\star}$, where D is the distance between the planet and the star. The distance between the center of mass and the center of the star in the Solar System is about 8×10^{10} cm, and the star wiggles back and forth by this amount with the period of the planet's orbit. Note also that whatever the inclination of the orbit you observe the full amplitude of this wiggle. But it's very hard to observe, because even for a nearby star (say 5 light years, where a light year is $9.5\ \times 10^{17}$ cm) the amplitude of the wiggle is only about 0.004 arcseconds in the above example, compared with the image blurring due to the atmosphere of 1 arcsecond. Even if you can escape this, by orbiting a spacecraft for example, you are still limited by *diffraction*, caused by the wavelength of light, which adds uncertainty to the location of the light beam. Further, to remove instrumental problems, you have to compare the position of your target star with that of other (non-moving) stars, each of which is also uncertainly measured. 0.004 arcseconds (or 4 milliarseconds) is just within the reach of current techniques, which use electronic imaging devices called CCDs (charge-couple devices) which, unlike photographic plates, are quite rigid. CCD astrometry has been used to firm up planet parameters from radial velocity measurements.

Finding lots of planets by position wobble must await the technological advance of space interferometry, about which you will be hearing a lot. The Space Interferometry Mission SIM is designed to measure positions to a few *micro*arcseconds. Since all the star are moving (proper motion) SIM ties its positions to those of the most distant objects, *quasars*, which are far to far away to have detectable proper motions.