Astro 205. Lecture 1. September 15 2003

Overview of the Course

The purpose of this new course, AST 205, "The Search for Planets", is to introduce you to one of the most exciting areas in modern astrophysics, the search for planets orbiting other stars in the Galaxy. Ever since the realization that the Earth is one of several planets orbiting the Sun, that the Sun is just an ordinary star, and that there are billions of stars in the Galaxy, we have searched for evidence of planets orbiting other stars. It turns to be very difficult to detect the observational signature of the presence of a planet against the enormous brightness of its star. In the past thirty years, as we have learned about how stars form, we have known that the formation of planets along with the formation of a star is likely to happen more often than not. In the last few years, we have finally found evidence of the existence of planetary systems around nearby stars. This course discusses the physical properties of stars and planets and the observational techniques we use to find planets and to measure their physical properties.

Several decades ago, we realized that we have the technology to communicate with technological civilizations similar to ours over interstellar distances. We will discuss this topic, generically known as SETI (the Search for Extraterrestrial Intelligence) later in the course. In the early days of SETI Frank Drake proposed the following equation to help determine the number of civilizations N with whom we might make contact:

$$\mathrm{N} = \mathrm{f(p)n(e)f(l)f(i)f(c)R_\star L}$$

here,

$R_\star$ is the average rate of star formation in the Galaxy

L is the average lifetime during which a civilization is technologically active

f(p) is the fraction of stars which have planets

n(e) is the average number of Earth-like planets per solar system

f(l) is the fraction of these earth-like planets which have life

f(i) is the fraction of these which have intelligent life

f(c) is the fraction of these which can communicate across interstellar distances

In precept, we will discuss two books, "Rare Earth" and "Life Everywhere" and compare and contrast these books.

Note that several of the quantities in the Drake equation are astronomical. As we go along, we'll begin to attach best-estimate numbers to these equations.

We will begin the astronomical discussion with:

Overview of the Solar System

The Solar System consists of the **Sun**, the **nine planets**, their **satellites**, and a host of minor planets and comets. The orbits of the major planets are fairly close to circular and lie roughly in the same plane;

further, the planets revolve around the Sun, and rotate about their axes, in the same direction, and most of the satellites orbit the planets in that same direction.

The **minor planets** fall into several categories: the **asteroid belt**, which lies between the orbits of Mars and Jupiter; the **Kuiper disk or belt**, which is a disk of minor planets lying beyond the orbit of Neptune and of which Pluto is likely to be a member; the **Centaurs**, asteroids whose orbits move between the distances of Jupiter and Neptune; and the **Trojans**, a group of asteroids bound to the orbit of Jupiter. In addition to these minor bodies (and other families or groups of asteroids) are the comets, the meteroids and the interplanetary dust. This debris provides a lot of information about the formation of the solar system, and its presence around other stars is often far easier to detect than are planets; so you will see a lot of discussion of circumstellar dust in this course.

The planets orbit the solar system *barycenter*, the center of mass. To first order, the barycenter is at the position of the Sun, the most massive member of the Solar System, but as we shall see, the orbit of a star around the barycenter of its planetary system provides an important means of detecting the planet(s) by observing the "wobbling" of the star. The basic unit of distance in the Solar System is the **astronomical unit**, (A.U.), the mean distance between the Earth and the Sun, or the semi-major axis of the Earth's orbit. 1 A.U. $= 1.5 \times 10^{13}$ cm. Note that at this sort of distance, light travel time is significant. The speed of light is 3×10^{10} cm s^{-1}, so that the light travel time between the Earth and the Sun is 500 seconds, or 8.3 minutes. The Earth is therefore *8.3 light-minutes* from the Sun.

To first order, the planets orbit the Sun in a plane on an ellipse, with the Sun at one focus. An ellipse has 2 foci, and its definition is:

$$r' + r = 2a$$

2a is the largest diameter, or *major axis*, and 2b the smallest, or *minor axis*. The equation of an ellipse in Cartesian coordinates is

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

and

$$b^2 = a^2(1 - e^2)$$

where the quantity e is the *orbital eccentricity*. If $e = 0$, then $a = b$ and the ellipse becomes a circle with both foci at the same place, the center of a circle. If $e = 1$, the curve becomes a straight line with the planet moving back and forth along the line. The point of closest approach of a planet to the Sun is called the *perihelion*: the perihelion distance is

$$r = a(1 - e)$$

Table 1 gives some properties of the nine solar system planets. The distance from the Sun is in A.U., the mass is given either in grams or in Earth masses, the year is the time it takes the planet to go around the Sun once, e is the orbital eccentricity (see above), i is the orbital inclination to the ecliptic (the *ecliptic* is the plane of the Earth's orbit), and $< \rho >$ is the mean density (the density of water is 1 gm cm^{-3}).

The Solar System does not stop at the orbit of Pluto, 40 A.U. from the Sun, but is considerably larger. The **Kuiper Belt** of planets extends from about 30 - 50 A.U., while the cloud of comets orbiting the Solar System, the **Oort Cloud**, lies at about 10^4 A.U.

Several interesting things can be gleaned right away from Table 1. First, the Sun contains almost all of the mass in the Solar System: the next largest body, Jupiter, has a mass of 0.001 $M_\odot$. The Sun's radius is $R_\odot = 7 \times 10^{10}$ cm - this is almost twice the mean distance between the Earth and the Moon (3.8×10^{10} cm), so that if the Earth were located at the center of the Sun, the Moon's orbit would be well inside the Sun.

Second, the orbits of the planets are very regular; they are close to being circular (small eccentricities) and are very close to lying in the same plane. The interesting exceptions to this are the innermost and

Table 1. Major Bodies in the Solar System

Body	D(A.U.)	Mass	Year	e	i	$<\rho>$ gm cm^{-3}
Sun	–	2×10^{33} gm	–	–	–	1.4
Mercury	0.39	0.055 $M_\oplus$	88^d	0.206	7^o	5.4
Venus	0.72	0.815 $M_\oplus$	224^d	0.007	3^o	5.2
Earth	1.00	6×10^{27} gm	365^d	0.017	–	5.5
Mars	1.52	0.108$M_\oplus$	1.88 yr	0.093	2^o	4.0
Jupiter	5.20	318$M_\oplus$	11.9 yr	0.048	1^o	1.3
Saturn	9.54	95.1$M_\oplus$	29.5 yr	0.055	2^o	0.7
Uranus	19.2	14.5$M_\oplus$	84.0 yr	0.047	1^o	1.6
Neptune	30.1	17.2$M_\oplus$	164.7 yr	0.009	2^o	2.3
Pluto	39.3	0.17 $M_\oplus$	247.7 yr	0.250	17^o	2.0

outermost planets, Mercury and Pluto, and thereby hang several interesting tales. The planets orbit the Sun and are bound to it by the force of gravity, and since the direction of this force is along the line joining the planet to the Sun (gravity is an example of a *central force*) it has no preferred orientation, in other words gravity does not cause all of the planets to orbit in the same plane or in the same direction (nor to have almost-circular orbits) and so we must search elsewhere for the explanation for these regularities. The answer lies in *initial conditions*, i.e. the Solar System was formed this way; in turn, this regularity traces the history of formation of the Solar System.

One last interesting regularity should be noted; the four inner planets have roughly the mean density of rock, while the outer planets have roughly the density of water, and close to the mean density of the Sun. This tells us that the *composition* of the four outer planets is close to that of the Sun while the composition of the inner planets is different. Since the regularity of the planetary orbits strongly shows that the Solar system formed as a unit, how did this come to be? The answer lies in the *evolution* of the Solar system.

We've thus identified three things we need to understand about the Solar system:

1. The *force of gravity* which holds it together.

2. The *initial conditions*, i.e. how the Solar system formed.

3. The *evolution* of the Solar system. This has two aspects: *dynamical evolution*, i.e. how the motions of the bodies have changed over time, and how they are influenced by the distribution of mass in the Solar system (e.g. the capture of asteroids by Jupiter); and *chemical evolution*, how and why the composition of the Solar System has changed over time.

Gravity

Kepler's analysis of the observed planetary motions led to the formulation of his three *empirical* laws (a rough definition of "empirical" is that the laws work but you don't understand why):

1. The orbits of the planets are ellipses with the Sun at one focus.

2. The radius vector between the planet and the Sun sweeps out equal areas in equal time.

3. The period ("year") P of the planet and its mean distance from the Sun a are related by:

$$\frac{P^2}{a^3} = \text{constant}$$

Newton's enormous intellectual leap of realizing that the force which causes objects to fall is the same as that which keeps the planets orbiting the Sun led to his formulation of the *laws of gravity*, and as we shall see in the next lecture, Kepler's laws can be derived from Newton's gravity.

The Inner Planets

The inner planets have roughly the density of rock, and their atmospheres contribute relatively little of their total mass. By contrast, the outer planets are gaseous. We think that the inner planets originally had the same composition as the outer planets but lost most of their gas early in the history of the solar system, because they are closer to the Sun and warmer. We will discuss the Earth's temperature, composition and evolution in later lectures.

Where did the Earth's atmosphere, with its very different composition, come from? To the best of our ability to tell, the Earth's composition at the formation of the Solar System was similar to that of the Sun, i.e. mostly H and He, with small amounts of heavier species. The Earth is close enough to the Sun that during the initial stages of its life, the primordial Sun, which was of higher luminosity and much more active than it is now, heated the Earth's atmosphere above its escape velocity, leaving the Earth and the other inner Solar System planets as naked rock. The hot Earth, however, released gases during its volcanic activity, creating a new atmosphere. This atmosphere consisted of gases like H_2O, CO_2, N_2, NH_3, CH_4, etc and has been altered to its present composition by the action of life. The Moon, having a smaller mass, was unable to hold on to an atmosphere and is a dead, rocky world today.

The Earth has a solid inner core, a molten outer core, a solid mantle and a surface crust. This is revealed by tracking disturbances caused by earthquakes via a worlwide seismic network. P waves, which can travel through both liquids and solids, are propagated across the whole earth, while S waves, that can travel only through solids, can travel only through the solid mantle and do not pass through the center of the Earth. P waves are longitudinal waves, while S waves are transverse waves. The existence of the solid core is not confirmed by observations, but is inferred from the huge pressures at the center of the Earth. The central core of the Earth is mostly iron and nickel, shown both by the wave propagation properties and by the mean density of the Earth.

Heat transfer from the center of the Earth to the outside takes place partly by convection in the mantle. The convection cells carry the lithosphere as large plates, the *continental plates*. Where the plates meet, mountains are built and earthquakes happen. Where they separate, molten magma can reach the surface and there is volcanic activity. Because of this continental drift, most of the Earth's surface is much younger than the age of the solar system.

The Moon is solid throughout. As a much smaller body, it has mostly cooled down (it is still losing a little heat). The Apollo missions left seismographs on the Moon, which can pick up the waves propagated by small moonquakes (mostly due to the shifting of the crust due to libration) and meteor impacts. These show that the Moon has no liquid core. The Moon is very heavily cratered and its surface is mostly old: study of Moon rocks therefore tells us about the early solar system. The *maria* are younger. They are the result of bombardment by very large meteors early in the solar system. The orbits of spacecraft around the Moon reveal internal structure indicating the presence of dense masses (the remains of the meteors) under the surfaces of the maria. Most of the maria are on the Earth-facing side of the Moon. The explanation is that the Earth's tidal distortion means that the lunar crust is thinner on the side facing the Earth, so that big meteor impacts could penetrate the crust and allow molten rock to flow to the surface.

Life on Earth

There is only one life on Earth. This is one of the most profound recent discoveries of biology. All life forms on Earth have the same biochemistry. Life is based on a common set of some 20 amino acids. Both left-handed and right-handed (laevo- and dextro-rotary) isomers of these acids exist in the laboratory, *but life uses only left-handed amino acids.* When you die, the amino acids in your body will gradually convert to 50% left-handed and 50% right handed by quantum processes. This racemerization can be used to date organic remains. All life shares the same genetic code: RNA and DNA. Thus life shares a common ancestor.

The fossil record shows that life has been on the Earth for at least 3.5 billion years. Already by that time sophisticated microbial life had evolved, producing oxygen by photosynthesis and radically altering the composition of the Earth's atmosphere. While simple amino acids can be synthesized in the laboratory, suggesting that the chemistry of life is part of cosmic organic chemistry, it is a very long way from the simple compounds found in interstellar space, in comets and in meteorites to DNA, and we do not yet have any real glimmering of the origin of life.

Microbial life is still the largest part of the biomass (thank goodness) - responsible for the oxygen level in the atmosphere and the temperature regulation of the Earth. Microbial life is found in ocean vents (at temperatures, note, not much lower than those in the atmospheres of brown dwarfs!), in ice covered lakes in Antarctica, and pretty well everywhere in between. We are descended from and related to this life by a process of evolution, affected by both slow (e.g. ice ages) and catastrophic (e.g. large meteor impacts) changes. Our species has produces the largest changes in the Earth's environment since the microbes (changes produced by life that is).

The Outer Planets

The outer planets, Jupiter, Saturn, Uranus and Neptune contain 99.9% of the mass of the Solar System outside the Sun.

The dynamical facts about the planets were summarized in Table 1. Here are some statistics about the four gas giants:

<u>Jupiter:</u> Mass = 318 $M_\oplus$; density = 1.34 gm s^{-1}; atmosphere 90%H, 10% He
<u>Saturn:</u> Mass = 95 $M_\oplus$; density = 0.70 gm cm^{-3}; atmosphere 97%H, 3% He
<u>Uranus:</u> Mass = 14.5 $M_\oplus$; density = 1.6 gm cm^{-3}; atmosphere 83% H and 15% He
<u>Neptune:</u> Mass = 17.2 $M_\oplus$; density = 2.3 gm cm^{-3}

Notice the density minimum at Saturn, which is less dense than water. What seems to be going on is that the inner planets have the density of rock, Jupiter and Saturn the density of gas, and Uranus and Neptune the density of ice. These two planets, which are farther from the Sun, are beginning to freeze. Jupiter's density is higher than Saturn's because its mass is greater and, because of this higher pressure, it is partly *degenerate.* While Jupiter is only 1/1000 the mass of the Sun, it is only three times less massive than the lowest mass "brown dwarf", as we shall see shortly. It therefore does not quite obey the expected mass-radius relationship (the larger the mass, the larger the radius) for normal matter.

The giant planets probably have slushy, rocky cores.

Only Jupiter shows a composition like that of the Sun, though we believe that this is the original composition of all the planets in the Solar System.

Both Jupiter and Saturn radiate energy at about twice the rate they receive it from the Sun. In Jupiter's case, this is probably due to the energy released in gravitational collapse and the fact that Jupiter, being massive, cannot radiate as efficiently as the other planets (the surface area to mass ratio effect coming into play again).

Flybys by the Voyager probes produced a suite of fabulous pictures of the gas planets. The four large moons of Jupiter show a progression away from the planet. Io has no ice, Europa thin water ice, Ganymede thick ice with many craters and Callisto thick ice and dust. Further, the moons have decreasing density with increasing density from Jupiter. The inference is that the ratio of ice to rock increases with distance from Jupiter, showing that Jupiter was once considerably hotter and evaporated much of the gas and volatiles from the moons closer to it.

Io is a very special case. Long before the Voyager flybys, Io was known to be a strange satellite, with a peculiar color and albedo. Jupiter has a very strong *magnetic field*, due to its rapid rotation (Jupiter's rotation period is about 10 hours - we think the Earth's used to be also, but the Earth's rotation has slowed because of tidal interaction with the Moon to its present 24 hours). This magnetic field, like ours, captures charged particles from the solar wind (Jupiter, and Saturn, have pretty spectacular *aurora*). A peculiarity of Jupiter's *ionosphere*, as this layer of charged particles is known, is that it contains a roughly equatorial torus of ionized sulfur and sodium. Io's slightly eccentric orbit lies within Jupiter's magnetosphere, causing ferocious bursts of radio energy at long wavelengths - at radio wavelengths of meters and longer, Jupiter is far and away the brightest object in the Solar System, including the Sun. Just days before the first Voyager flyby, a group of planetary astronomers (S. Peale, P. Cassen and R. Reynolds, Science 203, 892) calculated that Io's orbital eccentricity, coupled with its closeness to Jupiter and that planet's huge mass, caused variable tidal stresses in Io which are sufficient to melt its interior. Io would then be very volcanic, and the sulfur/sodium torus has a natural origin in gas ejected during volcanic activity. The Voyagers indeed saw huge volcanos on Io - it has the most active volcanic activity in the Solar System, and at any given time something like half a dozen volcanos are erupting. Io's surface has its odd color because it is covered with sulfur in several of its allotropic forms. These volcanos have been named for the fire gods of various terrestrial mythologies - Loki, Pele etc.

Saturn also has many moons, including the moon long thought to be the largest in the Solar System - Titan. Titan's atmospheric pressure is 1.5 times that of our atmosphere at sea level! Its surface temperature is 94 K (work out from the tables of planetary distances how this compares with the temperature expected for a bare rock, i.e. a moon with no atmosphere and hence no greenhouse effect, at Saturn's distance). The atmosphere is a methane/nitrogen mixture. At this temperature, some heavier organic compounds, like ethane, are liquid and under all that ice there may be ethane oceans. One of Saturn's other moons, Mimas, has a huge impact crater - the satellite only just escaped being smashed.

Uranus had five moons, Ariel, Umbriel, Oberon, Titania and Miranda (you can tell that British science was pre-eminent when Uranus and its moons were discovered) and has the peculiarity that the system's angular momentum vector lies almost in the plane of the planet's orbit - the planet's rotation and the revolution of the moons are almost perpendicular to the planet's revolution - it rolls around its orbit. This leads to peculiar seasons!

Neptune, the third largest planet, has two moons, both with peculiar orbits. The smaller, Nereid, is in a very eccentric but prograde orbit, while the larger, Triton, is in a retrograde orbit (*prograde* angular momentum means roughly parallel to that of most of the large bodies in the Solar System, *retrograde* means antiparallel). Triton's surface is covered with pinkish nitrogen frost, and there are occasional plumes of gas which fountain up from this moon. No-one has yet come up with a widely accepted explanation for this.

All of the gas giants have *rings*. Saturn's are particularly prominent and have been known since telescopes were used. The origin of these rings is fairly easy to understand - they are all within the *Roche limit* of their planets, i.e. the closest point of approach for a gravitationally bound body before it is torn apart by tides. The rings around the giant planets are small rock-ice pebbles each in orbit around the planet and probably originate in the ramains of a satellite that got too close or material close to the planet which could not condense into a satellite because of the tidal force. The ring particles collide frequently and the rings would have dissipated long ago were it not for the action of *shepherd moons*, small satellites within the ring system (small enough that they are held together by local molecular forces like you and me) whose orbital resonances with the ring particles keep them in their orbits and cause the amazing radial structure seen in the rings. Take a look at the fabulous pictures at
http://voyager.jpl.nasa.gov/image/index.html

How old is the Solar System?

Examination of the abundances of radioactive elements in terrestrial rocks gives an age for the oldest rocks of about 3.5 billion years. Cometary debris fallen to earth as meteors gives an age since the formation of the solar system of about 4.5 billion years.

How would you detect the solar system?

What are the markers?

The Sun wobbles back and forth as it orbits the solar system barycenter. *Jupiter*, having the greatest mass, would be the most detectable planet. You'd need observations over a good fraction of the 11 year period of Jupiter to detect these.

The *zodiacal light*, the dust in the solar system, is best detectable at infrared wavelengths and is the brightest component of the solar system by far. Because the solar system is old, there is no longer much dust and this emission is weak, but it is quite bright in much younger stars.

The *Earth* has by far the most unusual composition in the Solar system, and its spectrum would show the greatest difference from that of the Sun.

At radio wavelengths, *Jupiter* is far brighter than the Sun because of radio bursts emitted by Io's interaction with its magnetic fields. In very narrow frequency ranges, the *Earth* is the brightest object in the Solar System because of radio broadcasting.