CHAPTER III

SOLAR SYSTEM AND EXTRASOLAR PLANETS

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III.1 Origin of the Solar System

One of our goals in studying the Solar System is understanding how it formed. Any theory on the formation of the Solar System should be able to explain such things as the fact that the planets' orbits are approximately in the same plane, and the fact that the planets orbit in the same direction. In addition, it must be able to explain the distribution of angular momentum in the Solar System. Also, the different compositions and appearances of the planets must be explained.

Based of our present understanding of star formation, we now think that the Solar System is the remnant of the material that collapsed to form the Sun (see **Figure 3.1**). The original cloud might have been spherical. However, it must have been rotating, since we know that the Solar System has angular momentum. The result of the rotation is that collapse perpendicular to the axis of rotation is retarded, while that parallel to the axis of rotation continued. This means that the spherical cloud flattened to form a disk. It is the disk out of which the planets probably formed. Once the planets had formed, the debris not included in the planets was mostly cleared away by a very strong wind from the Sun. This would have been when the Sun was going through a *T Tauri phase*, and its wind would have been much stronger than it is today. The peak mass loss rate may have been 1 solar mass per a million year. The wind carried sufficient energy and momentum to sweep out the debris and stop the infall into the solar nebula.

In following the evolution of the solar nebula, we must keep track of three types of materials: gases, ices and rocks. Most of the mass was in the gas (as most of the mass of the interstellar medium is in gas). However, gas cannot be held to a growing planet by gravity, so it escapes from all but the largest objects. The ices are water (H_2O), carbon dioxide (CO_2) and nitrogen (N_2), along with some ammonia (NH_3) and methane (CH_4). These make up 1.4% of the mass of the Solar System. The rocks are iron oxides and silicates of magnesium, aluminum and calcium. Some of the iron was metallic and some of it was in iron sulfide (FeS). They can only be destroyed at high temperatures, in excess of 2,000 K. They make up 0.44% of the mass (not including the Sun) in the Solar System. They are particularly prominent in the inner planets, while the ices are prominent in the outer planets. Comets provide us with the best clues on the initial composition of the rocks and ices.

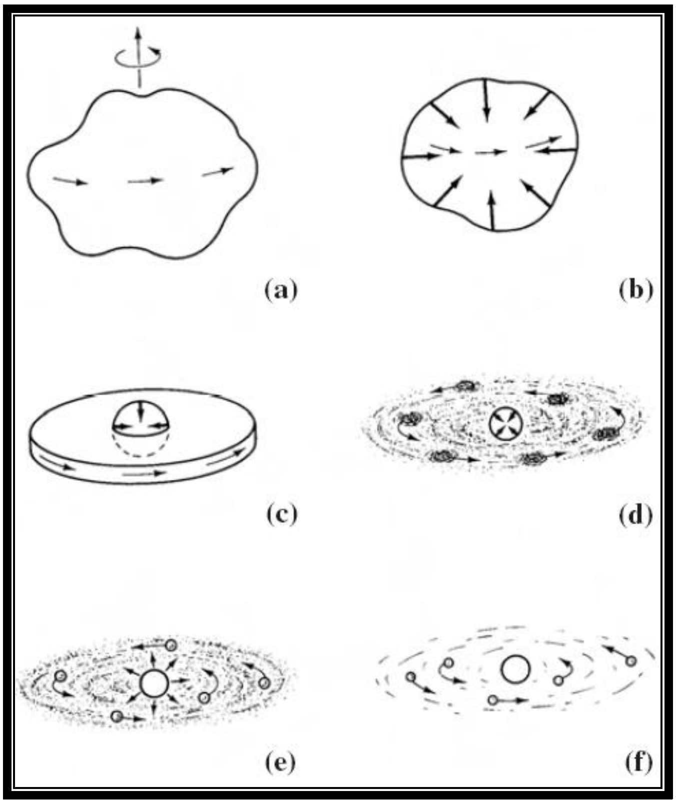

Figure 3.1 Formation of the Solar System. (a) A rotating interstellar cloud. (b) The cloud begins to contract. Since the angular momentum is conserved, the rotation becomes faster. (c) The rotation is fast enough to slow the collapse perpendicular to the axis of rotation, so a disk forms.The center is collapsing fastest, forming a denser concentration that will eventually become the Sun. (d) When the rotation prevents farther collapse of the disk, it breaks up into smaller clumps, so that some of the angular momentum is taken up by the orbital motion of the clumps.The clumps can then collapse. (e) Clumps of material gather together, forming planets, as the proto-Sun begins to radiate, and generate a large wind. (f) The wind clears debris from the Solar System.

The accretion of the nebula probably took place over 10,000 to 100,000 years. The first step in the process was for small grains to clump together. The grains collided, sometimes making larger ones, and sometimes breaking into smaller ones. The process produced many grains about 1 cm in size. These grains were large enough to settle through the gas in the plane of the nebula. This brought the clumps closer together, and allowed for even more collisions. Calculations indicate that the thin sheet of grains could then clump into objects with sizes of a few kilometers (essentially asteroid sized objects). About 1000 of these could then form a group held together by their own gravity. At that point, the groups were spinning too fast to collapse completely. Eventually these groups served as the cores for farther condensation of bodies orbiting at the same distance from the Sun.

Different parts of the Solar System then evolved differently because of the fall-off in solar radiation with distance from the Sun. The collapsing nebula had a higher temperature in the center (near the forming Sun) than at the edge. When the temperature was about 3,000 K near the center, it was a few hundred kelvin in the regions of planetary formation. It also falls by a factor of about five between the orbits of Venus and Neptune. Therefore, different materials condensed at different distances from the center.

Another factor affecting the nature of forming planets was a fall-off in the density of material as one goes farther from the Sun. When even a uniform interstellar cloud collapses, it develops a higher density in the center than at the outside. In fact, ultimately the highest density center becomes the star. In the higher density regions near the center, the material is also moving faster, as a result of infall, converting gravitational potential energy into kinetic energy. The higher density and higher speeds near the center meant that collisions also played an important role in shaping the gas. As a result of the temperature and density variations, we can think of planetary formation as occurring in three zones: *(1) the terrestrial planets, (2) the giant planets* and *(3) comets*.

Near the Sun, the temperature was too high for most of the gas (especially the H_2) to have survived the star formation process. So solid materials had to be involved. We think that the original building blocks for the terrestrial planets where chondrules. When they grew to sizes of about 1 km, we call them *planetesimals*.

Even though there were many planitesimals, they were distributed over a large volume of space, so encounters between planitesimals were rare, maybe once per thousand years. Computer simulations show that these collisions eventually made larger objects, and after about 20,000 years several Moon-sized objects should have appeared. After about ten million years, these objects collected to form most of the four terrestrial planets, though these planets probably continued to sweep up planitesimals for 100 million years.

The outer edge of the inner zone is the asteroid belt. There is a large gap between Mars and Jupiter suggesting that there was room for another planet to form. We don't expect a gap, since we expect that the material in the solar nebula would have been falling off gradually in abundance, and we know there was enough material farther out to form the giant planets. The most likely explanation is that the early formation of the very massive Jupiter prevented the formation of a planet. This could have been either by Jupiter somehow preventing the formation of the more massive planitesimals, or by Jupiter somehow removing them after they had formed.

In the second zone, material was far enough out for water ice to exist. Since O is more abundant than the elements that are important in dust grains (e.g. Si, Mg, Fe), particles of water ice (essentially snowflakes) would have been more abundant than dust particles in the second zone. It is thought that Jupiter and Saturn formed initially from planitesimals made up primarily of water ice. These planitesimals would have formed in a manner similar to those for the rocky planitesimals that formed the terrestrial planets. However, once Jupiter and Saturn had enough material to exert strong gravitational forces, then they would have collected all of the interstellar material (mostly gas and a little dust) that was near them. This resulted in two very massive planets. Also, the planets had compositions reflected in the interstellar medium 4.5 billion years ago. So the compositions of Jupiter and Saturn are essentially the same as that of the Sun, meaning that they have primarily hydrogen.

Uranus and Neptune formed in the outer parts of the second zone. The icy planetesimals would have filled a larger volume of space, meaning fewer collisions, and less chance for growth than the ones that started Jupiter and Saturn. There would therefore have been less gravity to hold interstellar gas in. Furthermore, the density of interstellar gas was lower the farther one got from the center of the solar nebula. So, Uranus and Neptune are just the result of the buildup of icy planitesimals, and are dominated by ices. Their compositions are therefore different from those of Jupiter and Saturn. **Figure 3.2** illustrates some of the differences in composition between Jupiter and Saturn and Uranus and Neptune.

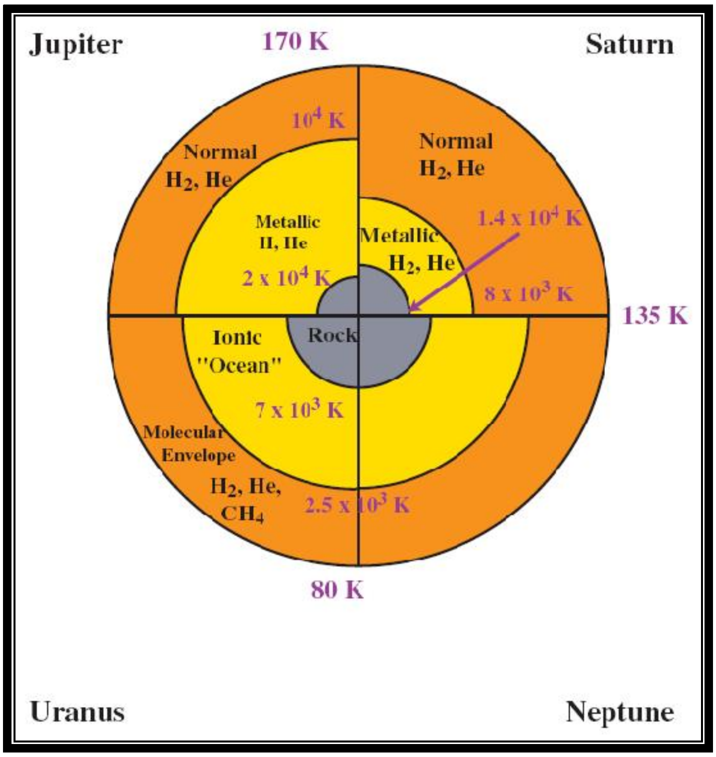

Figure 3.2 Interiors of Jupiter, Saturn, Uranus and Neptune.These are from model calculations, and are expressed relative to each planet's radius.The numbers at each boundary are estimated temperatures.

Most of the satellite systems probably grew from a disk forming around the planet. This process repeated the formation of the rocky planets on a smaller scale. The satellites whose orbits are close to the ecliptic and are not too eccentric were probably made in this way. Satellites with very inclined or eccentric orbits may have been captured.

In the third zone, beyond Neptune, ice/rock planitesimals were formed. However, they fill such a large volume of space that gravitational encounters are very rare. This means that they cannot collect into a planet. The ones from Neptune's orbit out to 50 AU formed the *Kuiper Belt*. Those farther out formed the *Oort cloud*.

III.1.1 Origin of life on earth

There may have been frequent lightning in the early Earth's atmosphere. The effects of such lightning were simulated in a laboratory at the University of Chicago, in the early 1950s, by a graduate student, *Stanley L. Miller*, under the supervision of his advisor *Harold Urey*. (Urey had won the 1934 Nobel Prize in Chemistry for his discovery of deuterium.) The *Miller–Urey experiments* helped chemists understand how the first prebiotic molecules may have formed in the Earth's atmosphere. Miller and Urey started with a mixture of methane, ammonia and hydrogen. The effects of evaporation and condensation of the early oceans were simulated by recycling water through the system. They ran the experiment for a few days at a time and then analyzed what had been produced. After some runs they found simple organic molecules important as building blocks of life, including amino acids.

Where did the molecules (methane, ammonia and hydrogen) come from? More recently, it has been suggested that molecules like those that came out of the Miller–Urey experiments could have been formed in the interstellar medium as part of the molecular cloud from which the Sun (and Solar System) formed. We know that some of this interstellar material has been preserved, as comets in the Oort cloud or the Kuiper belt. Some comets that passed close to the early Earth could have left some of this material behind, for it to sink into the atmosphere, and then eventually find its way to the surface.

Whether as a result of conditions like those simulated by the Miller–Urey experiments, or as a result of deposition from comets, it is possible that the early atmosphere was enhanced in these prebiotic organic molecules. Evidence suggests that there was a gap of almost 1 Gyr between the formation of the Earth and the appearance of the first multicell organisms. So, the question is, how do you go from a prebiotic soup to the complex DNA in less than 1 Gyr? How we go from these simple organic molecules to the life that is around us now?

There is a very close relationship between DNA and RNA. It is possible that historically RNA played a role in the development of DNA. The formation of RNA without making proteins first is quite difficult (given the complexity of RNA). Chemists working on the problem have focused on the idea of finding enzymes that might serve as catalysts for this process. Some catalytic reactions have been proposed which may have created RNA on a time scale of less than a year. Once the RNA formed, it could begin the process of replication.

Once the chemicals are available, the development of life requires the formation of cells. Cells are the basis of all life we know now, and one of the questions that is still being addressed is when the cells first developed. In the first RNA that developed, replications that directly produced surviving molecules were favored. With the development of cells, a replication (and some variation) could be favored because it produced something which could help the cell survive. However there are two different views on when cell walls began to appear. One is early in the process, and the other is late, about 3.8 giga years ago.

So how can Earth support life while other planets cannot? The first of Earth's feature that allow it to support life is **liquid water**. Water is essential for life on Earth, and presumably elsewhere in the universe. Even in the most extreme conditions on Earth, if water is present, life is too. Tube worms fl ourish in the dark, cold waters of the ocean floor alongside superheated volcanic vents; microbes have been recovered from ice cores near the South Pole; and bacteria and algae thrive in the scalding waters of the hot springs in Yellowstone National

Park. Water would evaporate on the blast furnace hot surface of Venus, where temperatures average 464^0C (867^0F), and water would freeze on Mars, where temperatures resemble those of Earth's polar ice caps (–63^0C, –81^0F). But on Earth, the average temperature is a pleasant, making it possible for water to exist as a liquid.

The second feature is **gravity and protective atmosphere**. Meteorites, moons, and planets are all held together by gravity. **Smaller planets have less gravity and thus thinner atmospheres; larger planets have stronger gravity fi elds and thus much thicker atmospheres.** Earth is large enough to have accumulated an atmosphere that protects the planet from all but the largest incoming space projectiles (comets, meteorites) and absorbs harmful radiation from the sun. Gravity holds Earth's layer of atmospheric gases close to the planet's surface. A fast-moving meteorite encounters gas molecules, mainly nitrogen and oxygen, as it plunges through Earth's atmosphere. Heat generated by the compression of the atmospheric gases is suffi cient to melt the surface of the meteorite. This process continues until the rocky object is destroyed or until it plows into Earth's surface. The atmosphere thus reduces all but the largest space objects to relatively harmless debris.

Short-wavelength solar radiation such as X-rays, gamma rays, and ultraviolet radiation would be extremely harmful to life on Earth, wiping out species and causing widespread mutations. Fortunately, our atmosphere intercepts and blocks these rays before they reach the planet's surface. Without a sufficiently thick atmosphere, life as we define it could not exist on land on Earth. Mars has a thin atmosphere that can do little to protect the planet's surface. In contrast, Venus has a thick, dense atmosphere that serves as a protective blanket and would destroy most incoming meteorites and absorb harmful solar rays. However, that carbon dioxide–rich atmosphere causes extreme global warming so that temperatures on Venus are too high to support life.

The third is **life-sustaining gases**. Earth's biosphere has moderated the composition of the atmosphere to make it more suitable for life. Vegetation absorbs carbon dioxide (a gas that is poisonous to humans in low concentrations) and produces oxygen, an essential gas for animal life. Earth's original atmosphere had higher concentrations of carbon dioxide, much like Venus, but much of that original carbon dioxide was removed by marine organisms and used to make rocks. Plant life gradually built up the store of oxygen in Earth's atmosphere to its current level (21 percent). The loss of oceans and the absence of a viable biosphere on Venus and Mars made it impossible to develop an oxygen-rich atmosphere. The land and oceans absorb solar radiation to warm Earth's surface (see **Figure 3.3**). Heat is radiated upward into the atmosphere where it is trapped by water vapor, carbon dioxide, and other gases to create a condition that has come to be known as the **greenhouse effect.** The greenhouse effect increases temperatures at Earth's surface by 33^0C, ensuring that we have a livable planet.

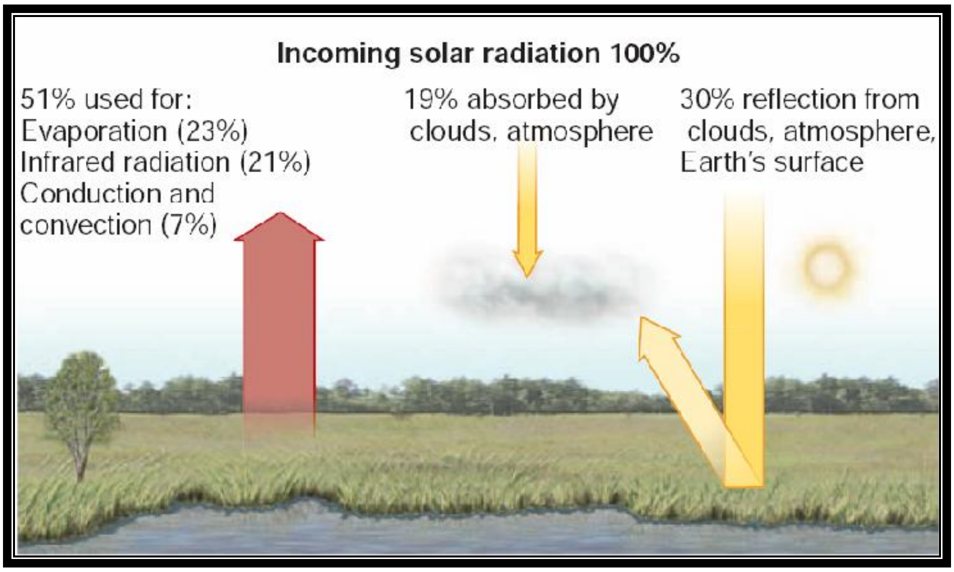

Figure 3.3 The solar energy budget. Approximately half of incoming solar radiation heats Earth's surface. Outgoing infrared radiation is absorbed by water vapor and carbon dioxide in the atmosphere.

The last feature of the Earth to support life on it is a **strong magnetic field**. Convection in Earth's outer core generates a planetary magnetic field. The magnetic field deflects the solar wind as shown in **Figure 3.4**. Were it not for the magnetic field, our outer atmosphere would have been steadily stripped away. A magnetic field is characteristic of planets that are large enough to still have hot interiors, such as Earth and Venus, and that rotate relatively quickly. Smaller planets with cool interiors (such as Mars) or larger planets that rotate slowly (e.g., Venus) may lack the currents in the core necessary to generate a strong magnetic field. The envelope of protective gases that once surrounded Mars was swept away by the solar wind relatively early in that planet's history. Mars has a localized magnetic field in some regions that is associated with specific rock types having weak magnetic properties. In these locations, Mars retains thin, isolated patches of its original atmosphere.

So here we are, third rock from the sun, with plenty of water and big enough to have sufficient gravity to hold onto our atmosphere. The gases that make up the atmosphere support life and absorb ample heat to sustain livable conditions near Earth's surface. Finally, the planet's magnetic field protects us from the worst of space weather.

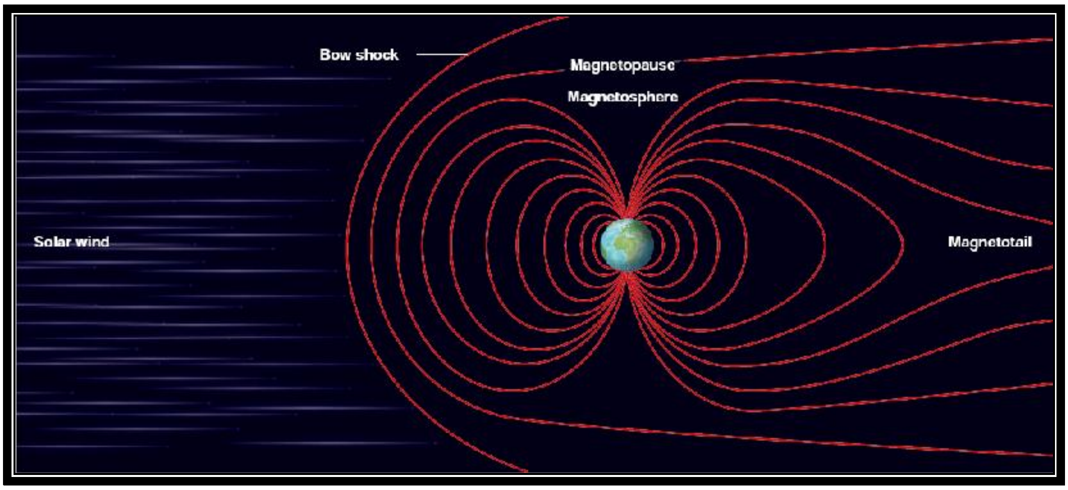

Figure 3.4 Deflection of Earth's magnetic field by the solar wind. Earth's magnetic field is compressed, meaning that the magnetic field lines are closer together.

III.1.2 Life in the rest of the solar system?

If the development of life on Earth did not require a special set of circumstances, then we expect life to have started elsewhere in the galaxy. It is therefore of interest to search for life elsewhere, and the obvious starting place is our Solar System. Finding even primitive life elsewhere in the Solar System would indicate that the Earth is not just one lucky case, and would give us hope of finding it widespread in the galaxy. Also, finding certain types of life elsewhere in the Solar System would give us insights into how life actually formed on the Earth. When we talk about searches for life, we generally mean *"life as we know it"*. That is, life based on carbon bearing (organic) molecules.

Let us think about how we might look for life elsewhere in the Solar System. Lunar soil samples, returned to Earth by Apollo astronauts, have been extensively studied in the laboratory, with no evidence for extraterrestrial life. For the first few missions, astronauts were kept in a quarantine for an extended period of time, because of the fear that they might carry some form of previously unknown contagion. That practice was limited when the first few missions revealed no signs of microbial life. Not finding life on the Moon should not be surprising, as the Moon lacks both an atmosphere and water.

Mars is potentially an interesting place to look for life, either current or fossil. That is because we think that prior to 3.5 giga years ago, when life was emerging on Earth, conditions on Mars were similar to those on Earth. There is evidence for abundant liquid water on Mars, in the form of rivers, lakes and possibly larger bodies, like oceans. We might ask how far the early, prebiotic, chemistry proceeded on Mars. Did such a chemistry develop so far as to lead to life–replicating molecules? If such early life started, how did it evolve? Is it still present or did it die off? If it is still present, we can look for it directly. If it died off, we can still look for fossil evidence.

The first attempts to answer these questions were made by the Viking landers. In designing experiments to look for chemical signs of life, e.g. respiration or photosynthesis, you have to make a decision about what chemicals you will look for. This requires making assumptions about the kind of life we are looking for. So, as a starting point, the Viking experiments were designed to look for microbial life with a chemistry similar to that on Earth. These experiments did not yield evidence for existing life "as we know it" at either site. A more extensive analysis of this data suggests that there is some evidence for organic chemical activity, but Martian life is not the only possible explanation. This shows some of the difficulties in designing and interpreting remote experiments to answer such subtle questions.

There is already a small source of Mars surface material on Earth. These are rocks that were thrown off the surface of Mars by meteoritic impact, and then happened to strike the Earth, like other meteors that the Earth encounters. The hard part is to distinguish rocks from Mars from those that come from normal meteor showers. If we can study them in the laboratory, we find that their chemistry is generally like that at the Viking lander site. This strongly suggests that they are from Mars. One meteor "observatory" on Earth is in Antarctica, as it is easy to pick out rocks against the white snow/ice background. One object found in 1984 was not classified as Martian until 1993 (see **Figure 3.5**). It was studied extensively for the next two years, and the researchers found microscopic fossils, which they concluded may have come from Mars. However, other groups studying this meteor suggested that these fossils may have been contamination from Earth. This shows how difficult these experiments can be.

Figure 3.5 Meteorite from Mars *(left)* and fossil inside it *(right)*.

III.2 The Sun and Planets

III.2.1 Characteristics of the sun

The sun is just one of billions of similar stars throughout the universe. The sun accounts for 99.8 percent of the mass of our solar system and dwarfs its orbiting planets. Even mighty Jupiter is just one-tenth the diameter of the sun.

Just as Earth rotates every day, the sun rotates about once a month. However, this big ball of gas experiences differential rotation; that is, its equator rotates more rapidly than its polar regions (25 versus 36 days). Scientists are still trying to fi gure out why this happens, but they do know that the differential rotation causes twisting of the sun's outer layers, **causing disruptions in the sun's magnetic field to produce sunspots and solar flares** (see **Figure 3.6** below).

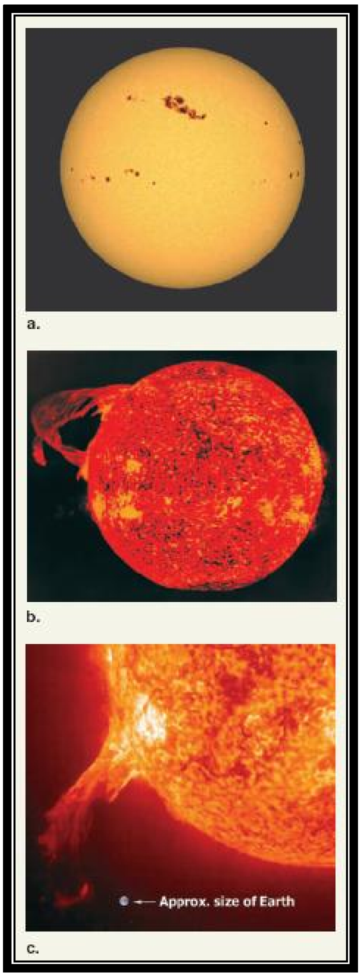

Figure 3.6. Sunspots and solar flares. (a) Dark splotches on the photo-sphere, the sun's outermost layer, are sunspots. Sunspots have been recognized on the surface of the sun for several centuries. Individual sun-spots may be as large as 50,000 kilometers in dia-meter, the approximate size of Neptune. (b, c) Prominen-ce and flare extend above the surface of the sun and are many times larger than Earth.

Sunspots are dark blotches on the sun's outermost layer. They represent slightly cooler areas of the sun's surface and are the source of intense lines of magnetic force. The apparent movement of sunspots across the sun's face can be used to measure the periodicity of the sun's rotation. The number of sunspots can vary considerably but shows a long-term trend recognized as the sunspot cycle as shown in **Figure 3.7**. The average number of sunspots varies over an 11-year cycle, from a handful of sunspots during a solar minimum to well over 100 during the peak time known as the solar maximum. According to **Figure 3.7**, a recent maximum occurred in the early months of 2001, and we reached the minimum of the cycle in 2006. Solar flares, intense pulses of X-rays and ultraviolet radiation, are often associated with sunspots. These eruptions from the sun's surface can affect activities on Earth.

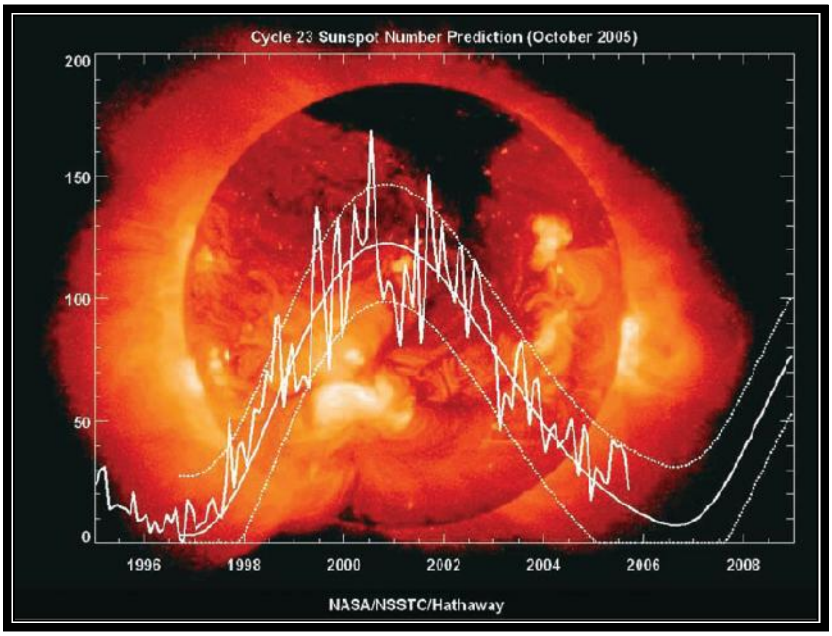

Figure 3.7 The current sunspot cycle. A record of sunspots has been kept since the middle of the eighteenth century, with each sunspot cycle numbered since then. The smooth lines on the graph represent the predicted range of sunspot activity; the jagged lines show the actual activity.

Space has its own weather system, but it doesn't have the moving air and clouds so familiar to us on Earth. Instead, **space weather is dominated by the solar wind, a constant stream of charged particles emitted from the sun's magnetic field.** These charged particles travel at an average speed of 450 kilometers per second. **The region of space affected by the solar wind is known as the heliosphere,** and represents the volume of space in which our sun is the dominant infl uence. The heliosphere extends far beyond the planets of our solar system and may be likened to a giant bubble that shields us from harmful cosmic rays from elsewhere in the universe.

Figure 3.8 Aurora formed by the interaction of the solar wind with Earth's magnetic fi eld. (a) Aurora seen from Earth; (b) aurora seen from space. These spectacular visual displays can be best observed at high latitudes, i.e., closer to the poles.

Earth has its own magnetic field that deflects the solar wind around our planet, **protecting our atmosphere.** But, although Earth's magnetic fi eld keeps our protective atmosphere from eroding, we are still vulnerable to the harmful effects of occasional solar eruptions that hurl intense pulses of dangerous X-rays, ultraviolet radiation, and charged particles toward Earth. **Intense streams of charged particles can disrupt Earth's magnetic field, generating electrical currents that result in power surges** and leading to blackout conditions as electrical systems shut down. Over 6 million people in eastern Canada and the northeastern United States lost power for 9 hours in March 1989 because of a powerful solar storm that coincided with a solar maximum. The economic costs of power outages are measured in billions of dollars. Disruptions in Earth's magnetic fi eld caused by solar wind can also result in spectacular effects such as the dramatic light displays known as *aurora* in the upper atmosphere (**Figure 3.8**).

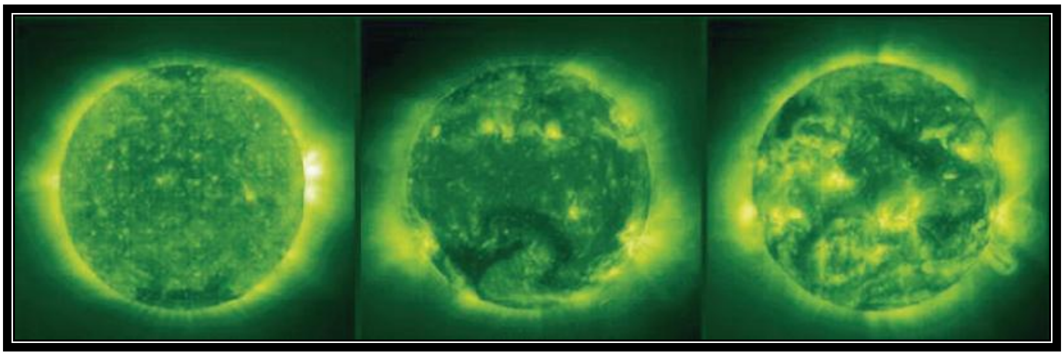

Figure 3.9 Satellite monitoring of solar activity. These three views of the sun were taken by the SOHO (Solar and Heliospheric Observatory) satellite in successive years using the Extreme Ultraviolet Imaging Telescope. The far right image shows increased solar activity approaching a peak in the sunspot cycle, which could lead to damaging bursts of energy headed toward Earth.

Every day, we depend on over 600 operational satellites to provide information for a host of needs on Earth, including communications, navigation, and weather forecasting. Many of these satellites could be knocked out of action by concentrated streams of solar radiation. NASA has launched specific satellites to monitor solar activity and provide notice of potentially damaging bursts of energy heading for Earth (**Figure 3.9**). Such warnings will be vital to future space exploration that could expose astronauts to the dangerous radiation generated by these solar emissions. People living outside the protection of Earth's magnetic field and atmosphere would be exposed to much higher levels of harmful radiation from the sun than the rest of us on Earth's surface.

III.2.2 Radar mapping of planets

Spacecraft which is sent into orbit can use radar to map the surface features. A raised surface feature may show up as a stronger than average radar echo. However, the problem is to determine where on the surface the feature is. There are two effects that help us locate the feature. One is the time delay for the signal returning to Earth, and the other is the Doppler shift. These are illustrated in **Figure 3.10**.

We first look at the time delay. Since the surface is round, different parts of the surface are different distances from our radio telescope. These different distances mean that the light (or radio wave) travel times will be different for waves bouncing off different parts of the surface. We can express time delays relative to that of a wave bouncing off the closest point. According to **Figure 3.10a**, the extra distance that the signal has to travel is $2x$, so the time delay is

$$\Delta t = 2x/c$$

We can see that

$$\begin{aligned} x &= R - y \\ &= R - R\cos\theta \\ &= R(1 - \cos\theta) \end{aligned}$$

This means that the time delay is

$$\Delta t = \left(\frac{2R}{c}\right)(1 - \cos\theta) \quad \ldots\ldots\ldots(3.1)$$

If we measure the time delay, and we know the planet's radius, R, then we can solve equation (3.1) for θ. This does not give a point uniquely. There is a whole ring of points that all have the same θ. As viewed from the radio telescope, lines of constant time delay appear as concentric rings about the closest point.

We now look at the Doppler shift. If a point on the equator moves with a speed v_0, then a point at latitude φ moves with speed

$$v(\varphi) = v_0 \cos\varphi$$

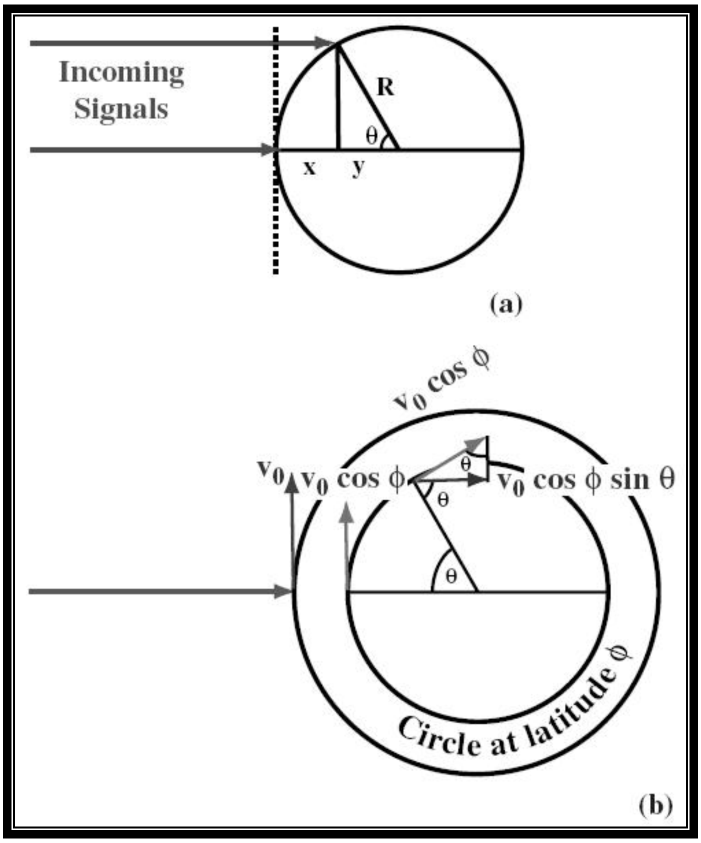

Figure 3.10 Radar mapping of a planet: (a) time delay; (b) Doppler shift.

Now we view this point from above the pole, assuming the line from the point to the pole makes an angle θ with the line from the pole to the telescope. The Doppler shift depends on the radial velocity, $v_r(\theta,\varphi)$, which is given by

$$\begin{aligned} v(\theta,\varphi) &= v(\varphi)\sin\theta \\ &= v_0 \cos\varphi \sin\theta \end{aligned} \quad \text{..........(3.2)}$$

As seen from the telescope, lines of constant Doppler shift form concentric rings about the point on the equator that is just appearing from the back side, and the point on the equator that is just about to disappear.

By combining time delay and Doppler shift data, we limit the source of the echo to two possible points. These are the two points where the time delay circle intersects the Doppler shift circle. The remaining ambiguity in the location of the feature can be removed by observing at a different time where the feature's location and Doppler shift have changed. More recently, orbiting spacecraft have also been used for higher resolution radar mapping on Venus and Mars.

III.2.3 Temperature of planets

The temperature of the Earth is determined by a balance between the energy absorbed from the Sun and the energy given off by the planet. For planets like the Earth, heat from the inside does not have much effect on the surface temperature. The planetary temperature for which these balance is called the *equilibrium temperature* of the planet. The actual energy transport might be complicated by the presence of an atmosphere, but we will first calculate the equilibrium temperature,ignoring atmospheric effects.

We start by calculating the energy received per second. The energy per second given off by the Sun is its luminosity, L⊙ (we could leave this in terms of the luminosity, or rewrite the luminosity as $4\pi R_{\odot}^2 \sigma T_{\odot}^4$). At the distance *d* of the planet from the Sun, the luminosity is spread out over a surface area of $4\pi d^2$. This means that the luminosity per surface area is $L_{\odot}/4\pi d^2$. As seen from the Sun, the projected area of the planet is πR_p^2. The planet therefore intercepts a power equal to this area multiplied by the power per surface area. Finally, not all of the sunlight is absorbed by the planet. A fraction *a*, the albedo, is reflected. The amount absorbed is equal to (1 – *a*) multiplied by the amount that actually strikes. In this calculation, we are assuming that the albedo is the same at all wavelengths. Therefore the power absorbed by the planet is

$$P_{absorbed} = \frac{L_{\odot}(1-a)R_p^2}{4d^2} \quad \text{.........(3.3)}$$

We now look at the power radiated. We assume that the planet rotates fast enough that there is no great difference between day and night temperatures so we can treat the temperature of the planet as being the same everywhere (this is a good approximation for the Earth but not for the Moon). The power radiated per unit surface area is $e\sigma T_p^4$, where *e* is the *emissivity*. The emissivity can range from zero to one, and is one for a perfect blackbody. Multiplying this by the planet's surface area $4\pi R_p^2$, we obtain the total power radiated:

$$P_{radiated} = 4\pi R_p^2 e\sigma T_p^4 \quad \text{.........(3.4)}$$

If we equate the power absorbed with the power radiated, we solve for the equilibrium temperature of the planet, giving

$$T_p = \left[\frac{L\odot(1-a)}{16\pi d^2 \sigma e}\right]^{\frac{1}{4}} \quad \text{.........(3.5)}$$

This calculation doesn't account for the fact that the albedo and emissivity vary with wavelength. We must integrate the energy received over the spectral energy distribution of the Sun, and integrate the energy radiated over the spectral energy distribution of the planet.

On the Earth, the albedos are different for the oceans and for land. They are also different for cloud cover. When we take these into account, the equilibrium temperature is 246 K. However, this is still not the temperature we measure at the ground. We have not yet considered the important effects of radiative transfer in the atmosphere.

We can also do this calculation for planets at any distance from the Sun, and we obtain the results shown in **Figure 3.11**. Here we present a graph, in which we show the equilibrium temperature at different distances, and note the locations of the planets. Notice how this temperature decreases with increasing distance.

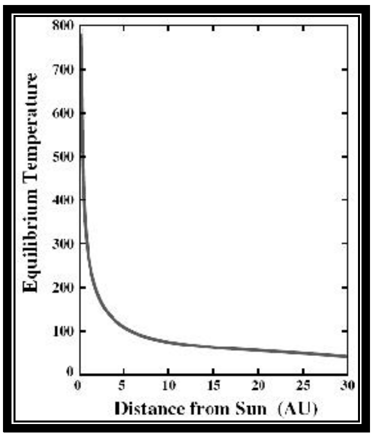

Figure 3.11 Diagram showing graph of the equilibrium temperature vs. distance from the Sun.

III.2.4 Density of planets

Since we cannot directly observe the interior of a planet, we must come up with indirect methods for determining the interior structure. We briefly go over some types of evidence that we can use for studying planetary interiors.

The average density of a planet can give us information. For example, consider the simple structure shown in **Figure 3.12**. The planet has a core with density ρ_C and radius R_C, and a mantle with density ρ_M and radius R_M, the radius of the planet. In this case the mass of the planet is

$$\mathbf{M_p} = \left(\frac{4\pi}{3}\right)\left[\mathbf{R_C^3}\rho_C + \left(\mathbf{R_p^3} - \mathbf{R_C^3}\right)\rho_M\right] \text{……….(3.6)}$$

The average density of the planet is its mass, divided by its volume,

$$\begin{aligned}\bar{\rho} &= \frac{\mathbf{M_p}}{\left(\frac{4\pi}{3}\right)\mathbf{R_p^3}} \\ &= \rho_C\left(\frac{\mathbf{R_C}}{\mathbf{R_p}}\right)^3 + \rho_M\left[1 - \left(\frac{\mathbf{R_C}}{\mathbf{R_p}}\right)^3\right]\end{aligned} \text{……….(3.7)}$$

If we know the material that is likely to make up the mantle and the core, we can estimate ρ_M and ρ_C. The average density is easily determined, so we can find (R_C/R_P).

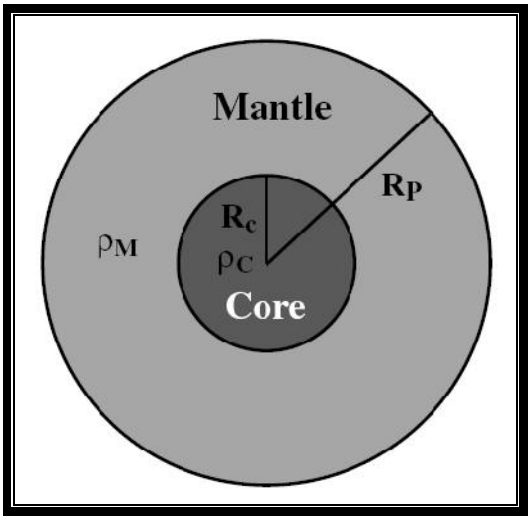

Figure 3.12 Planet with core and mantle.

III.3 Minor Bodies in the Solar System

The solar system consists of a central star, called *the sun*, eight *planets*, several *dwarf planets*, dozens of *moons* or *satellites*, millions of *asteroids* and *Trans-Neptunian Objects* (TNOs), and myriads of *comets* and *meteoroids*. Borders between the categories are not clear. Discoveries of new Solar System bodies caused that in 2006 the *International Astronomical Union* (IAU) in its General Assembly defined three distinct categories to clarify the situation:

(1) **A *planet*** is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighbourhood around its orbit.

(2) **A *dwarf planet*** or a *planetoid* is a celestial body that: (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighbourhood around its orbit, and (d) is not a satellite.

(3) All other objects orbiting the sun shall be referred to collectively as ***Small Solar System Bodies***. These include most of the asteroids, Trans-Neptunian Objects, comets, and other small bodies.

According to the IAU 2006 definition, *Pluto* is a *dwarf planet* and the prototype of a new category of Trans-Neptunian objects. Gravitation controls the motion of the solar system bodies. The planetary orbits around the sun are almost coplanar ellipses which deviate only slightly from circles. The orbital planes of *asteroids*, minor bodies that circle the sun mainly between the orbits of Mars and Jupiter, are often more tilted than the planes of the planetary orbits.

Asteroids and distant Trans-Neptunian Objects revolve in the same direction as the major planets; comets, however, may move in the opposite direction. Cometary orbits can be very elongated, even hyperbolic. Most of the satellites circle their parent planets in the same direction as the planet moves around the sun. Only the motions of the smallest particles, gas and dust are affected by the *solar wind*, *radiation pressure* and *magnetic fields*.

The planets can be divided into physically different groups. Mercury, Venus, Earth, and Mars are called *terrestrial* (earth-like) planets; they have a solid surface, are of almost equal size (diameters from 5,000 to 12,000 km), and have quite a high mean density (4,000−5,000 kgm^{-3}; the density of water is 1,000 kgm^{-3}). The planets from Jupiter to Neptune are called *Jovian* (Jupiter-like) or *giant planets*. The densities of the giant planets are about 1,000−2,000 kgm^{-3}, and most of their volume is liquid. Diameters are ten times greater than those of the terrestrial planets.

Dwarf planet Pluto is falling outside this classification. Pluto is the prototype to the family of icy bodies orbiting the sun at the outer edges of the solar system. The discovery of large objects since early 1990's beyond the orbit of Neptune raised the question of the status of Pluto. The discussion culminated in the General Assembly of the IAU in 2006 when a new planetary definition was accepted. This reduced the number of major planets to eight.

III.4 Other Planetary Systems

III.4.1 Methods and techniques of detection

The notion that the Solar System formed as a byproduct of the formation of the Sun has a number of interesting consequences. One is that, if planetary systems are a natural by-product of star formation, we should be able to find many other planetary systems in our galaxy. As you might suspect, looking for planets around a distant star is a formidable observational challenge for a number of reasons. Any radiation given off by the planets (either by reflected starlight or emitted far infrared and radio emission) would be very weak, especially at large distances. This is complicated by the fact that it is much weaker than the radiation from the star in that system. The linear separation between a planet and the star it orbits is not very large, so the angular separation is small, even for relatively nearby systems (a few parsec away). The masses of the planets are much less than the stars they orbit, so the recoil motion of the star is also very small. To illustrate the problem, consider an example below.

Example:

<u>Problem</u> *Assume we are observing the Solar System from a distance of 10 pc. (a) What is the angular separation between Jupiter and the Sun? (b) What is the angular amplitude of the Sun's motion in response to the gravitational force exerted on it by Jupiter?*

<u>Answer</u> *If an object is a distance D (pc) from us, and has a linear separation R (AU), then its angular separation (in arc sec) is:*

$$\Delta\theta \text{ (arc sec)} = R \text{ (AU)} / D \text{ (pc)}$$

So for Jupiter (5.2 AU from the Sun), $\Delta\theta = 0.5$ *arc sec*

The ratio of the radii of the orbit of the Sun and that of Jupiter about the Sun–Jupiter center of mass is just the ratio of the masses:

$$r_{Sun}/r_{Jup} = M_{Jup}/M_{Sun}$$
$$= 1.9\text{x}10^{27} \text{ kg} / 2.0\text{x}10^{30} \text{ kg}$$
$$= 10^{-3}$$

So the radius of the Sun's orbit about the center of mass is:

$$r_{Sun} = r_{Jup} \text{ x } 10^{-3} = 5.2\text{x}10^{-3} \text{ AU}$$

At a distance of 10 pc, the angular size is:

$$\Delta\theta \text{ (arc sec)} = R \text{ (AU)} / D \text{ (pc)}$$
$$= 5.2\text{x}10^{-3} \text{ AU} / 10$$
$$= 5.2\text{x}10^{-4} \text{ arc sec}$$

The above example illustrates the difficulty of detecting planets around other stars. Shining by reflected sunlight, Jupiter would appear just at our detection threshold, even if it wasn't swamped by the direct light from the Sun which would be less than an arc second away. This does suggest, however, that if you were going to detect direct radiation from a planet, you might do better in the infrared where the blackbody radiation from the planet peaks. The Sun still gives off much more radiation, but the imbalance is less.

Directly seeing the motion of the Sun about the center of mass would also be very difficult. The best hope is to look for the Doppler shift (as an indirect method) caused by that motion. That motion is best observed if we are in the plane of the orbit. We would observe a variation in the star's Doppler shift that looked like a sine wave with a period equal to the orbital period of the planet. Just as for binary stars, if the orbit is inclined, you still see periodic motion, but the range of Doppler shifts is reduced by the sine of the inclination angle. If more than one planet is present (e.g. Jupiter and Saturn) you would see a more complicated pattern that comes from adding two sine waves with different periods, amplitudes and phases.

The technique which has proved most successful has been looking for the variations in the Doppler shifts of nearby stars. A group headed by *Geoffrey Marcy* and *R. Paul Butler* has studied a large number of potential systems. Other groups have also made independent measurements, giving more confidence, as the measurements are difficult. These groups have studied more than 1,000 stars. This comprises a nearly complete sample of Sun-like stars within 30 pc of us. They have found evidence for a planet in more than 90 systems (so far). More recently, they have found a few systems with evidence for more than one planet.

Sample data is shown in **Figure 3.13** The dots show the data points, with error bars to indicate the uncertainties in the measurements. The dashed lines show the best fit to the data. The masses are expressed as $M_{\mathrm{JUP}}/\sin(i)$, since we don't know the inclination angle, i. So, these numbers are lower limits to the true mass. They are expressed as M_{JUP}, since that is a convenient reference.

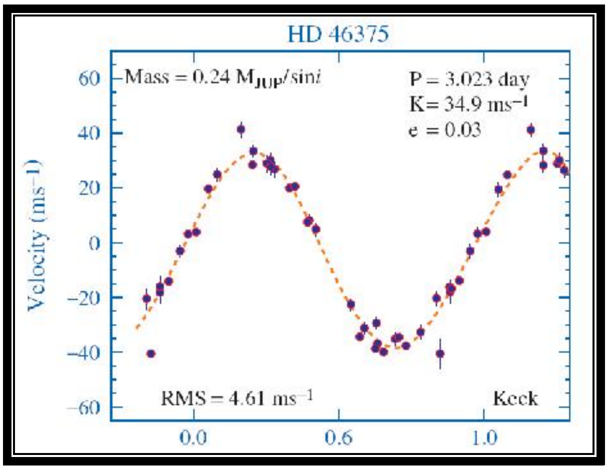

Figure 3.13 Radial velocity variations of star with evidence for planet.The horizontal axis is phase within the orbit, relative the listed period. [Geoffrey Marcy, University of California at Berkeley]

More than 400 planets have been found so far with various techniques. There is also another way to look for systems that might be forming planets. We saw earlier in this chapter that we think that planetary systems form from the disks that are a by-product of the star formation process. The disks that will form planets around a solar mass star are even smaller. For example, a 1,000 AU disk at the 500 pc distance of the Orion Nebula, the nearest extensive star forming region, would subtend an angle of 2 arc sec. Of course, this is large compared to the size of Jupiter, so it would be much easier to see than even a giant planet.

These disks are best seen in the infrared for a number of reasons. They are cooler than the protostars they surround, so they give off relatively more radiation in the infrared than in the visible. Also, since they are often deep inside molecular clouds, with tens of magnitudes of visual extinction, they are hard to see in the visual. Of course, since they are small, we must use infrared observations with very good angular resolution. Hubble Space Telescope (HST) has provided the opportunity to carry out these observations, and a few samples are shown in **Figure 3.14**.

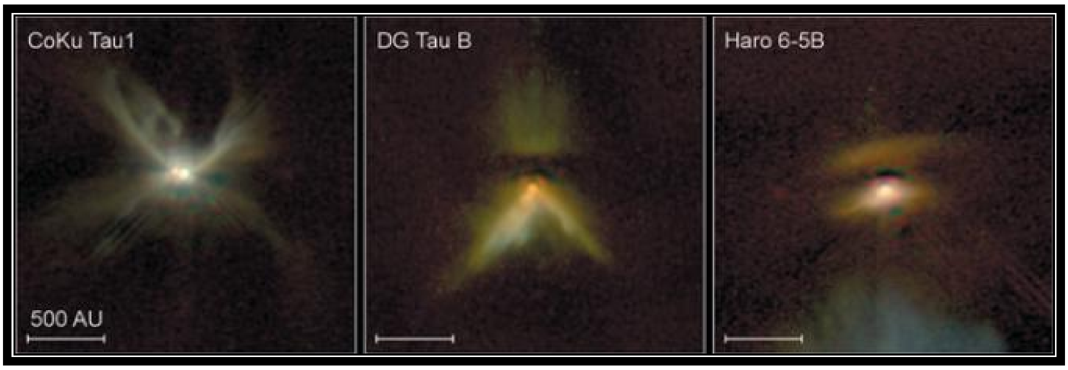

Figure 3.14 HST images of infrared emission from selected disks around forming stars. All six objects are in Taurus, at a distance of 150 pc. [STScI/NASA]

These disks are important because they allow us to study the stage between the collapse of a molecular cloud to form a star and the formation of a planetary system. Of course, in order to study these disks in detail, we would like to be able to do high resolution spectral line observations, so we can trace the velocity structure of the disks.

III.4.2 Searches for extraterrestrial intelligence

A number of recent discoveries suggest that life may be more common in the galaxy than many had thought. It appears that organic molecules can form and survive in even the hostile environment of interstellar space. It also appears that planetary systems form as a natural by-product of star formation, so there might be a large number of potential hosts to life. It is natural to suggest that if life has had sufficient time to evolve on a planet, then it might lead to intelligent life at some point. Such intelligent life might, knowingly or accidentally, give off evidence of its existence. These thoughts have fueled the push for *searches for extraterrestrial intelligence (SETI)*.

The important issues in SETI are **(1)** *what is the likelihood that detectable extraterrestrial civilizations exist (or how many exist)*, and **(2)** *what is the best strategy for detecting them*. We look briefly at both issues. The development (and survival) of a detectable extraterrestrial civilization depends on a number of factors. The important factors were first put down by *Frank Drake* in the famous

Drake equation, which gives the number of civilizations in our galaxy that would be able to contact each other as

$$\mathbf{N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L} \quad \text{.........(3.8)}$$

where R_* = the rate at which stars are forming, f_p = the fraction of stars that have planets, n_e = the number of planets per planetary system with conditions suitable for life to develop, f_l = the fraction on which life actually exists, f_i = the fraction of life forms that develop intelligence, f_c = the fraction of intelligent species that choose to communicate and L = the average lifetime of the civilization after they reach a technological state. We can estimate some of these quantities and make guesses at others.

One strategy of SETI projects has been to look in great detail in the directions of nearby stars that may have planetary systems and have environments like our Solar System. Less time per location could be expended in looking systematically over large parts of the sky. So this is one of the great technological problems of SETI. We must search over two spatial dimensions (on the sky) and frequency. Sensitive searches are being carried out at Aricebo, taking advantage of the large surface (now upgraded), and the ability to use a number of receivers simultaneously, so we can cover more frequency ranges. More continuous coverage is being done using smaller telescopes. Another problem is how to recognize a signal from an extraterrestrial intelligent source. The recent development of fast relatively inexpensive computers has made it possible to search signals for regular patterns or variations that could not be natural.

Astronomy Laboratory

THE PERIOD OF ROTATION OF THE SUN

Procedure:

You are going to use software from CLEA Project: Period of Rotation of the Sun to do this laboratory activity.

1. ***Start-up***
   Run the CLEA Period of Rotation of the Sun software. Log in. Choose **File**…**run** and the main data window will appear. Choose **File..image database..image directory..load** and the times of available images of the Sun will appear in the image database window (the right half of the window.) Scroll down the window to see what dates are available.

2. Select 6 or 7 images by double-clicking the left mouse button. The dates of the images will appear in the **loaded images** window (the left half of the main window). An **image display** window will also open, showing you one of the loaded images of the Sun. Animate the images by choosing **Animation..start** on this image display window. You can stop the animation by choosing **Animation**…**stop** from the menu.

3. Choose a sunspot to measure, call it sunspot A. Choose a sunspot that has just rotated into view, then load all of the images for 4 or 5 days following the image in which the sunspot first appears (see step #2 for loading images). Anything listed in the **loaded images** window can be displayed by double-clicking on the listing. If the listing gets cluttered with images you don't intend to measure (because they contain no suitable spots), you can clean it up by choosing **Images**…**cut** or **Images**….**clear all images** on the menu bar.

4. Measure and record the heliographic coordinates of sunspot A on each of your chosen images using the cursor and the mouse.

5. Plot and analyze the coordinate data for sunspot A. Choose **Analysis..plot fit data** from the main window menu. The **Solar Rotation Analysis** window will appear. Choose **File..dataset..load..longitude values** from the Solar Rotation Analysis menu bar and select the values for spot A. The data will be plotted (time on the x axis and heliographic longitude on the y axis.) Depending on how your instructor has set up the software, the program will either compute a best fit line through the data or allow you to fit the line yourself using two sliders. If you are fitting the line with the sliders, try to get the lowest "error of fit"

Lab Skills and Objectives

- **Be able to determine how fast the longitude and latitude of spots on the Sun change**
- **Obtain the sidereal period of rotation of the Sun**

as displayed in the digital readout labled "fit (RMS Degrees)" in the lower left of the Analysis window.

When you are satisfied with your data, write your results for the slope and the intercept of the graph in ANALYSIS TABLE 1 below. Also, record the slope and intercept you have measured in a data file by choosing **File..record** results from the Analysis window menu bar. Print the graph showing the line and your fit by choosing **File..print** on the Analysis window menu bar and submit it with this report.

Analysis table 1: Rate of motion of selected sunspots		
SPOT IDENTIFIER	***Slope (Degrees per Day)***	***Intercept (Julian Day)***
A		
B		
C		

6. Measure the rotation rate of two other spots, following the steps above, and write the results in **Analysis Table 1** above.

7. You can now calculate the synodic rotation rate and the sidereal rotation rate of the Sun.

   - The slope of the sunspot longitude versus time line is the number of degrees per day a sunspot moves on average. If you divide this number into 360, you get the number of days it takes for the spot to rotate through 360 degrees---which is the synodic rotation rate of the Sun. If we let S equal the synodic rotation rate of the Sun,

   S[days] = 360 [degrees] / Slope[degrees per day]

   - Once you have the synodic period, use the formula below to calculate the sidereal rotation period of the Sun. Average your results for the three spots, and record the average value on the table, too. Fill in **Analysis Table 2**.

   P= (S × 365.25) / (S + 365.25)

Analysis Table 2: Sidereal and Synodic Rotation Rate Calculations		
SPOT IDENTIFIER	***Synodic Rotation Rate(days)***	***Sidereal Rotation Rate (days)***
A		
B		
C		
AVERAGE SIDEREAL ROTATION RATE (days)		

8. Try opening the analysis window and plotting latitude data for one of the spots. What can you say about how the latitude of a sunspot changes with time?