Chapter 15 The Formation of Planetary Systems

Modeling Planet Formation

The process of forming the planets and moons in our solar system is a very complex thing. Our ideas have come from looking at interstellar gas clouds, the other planets and our own moon. The Earth is no help because it has undergone so many changes in its history. Until the 1990's the study was limited to our solar system, but now we are looking at *extrasolar planets* and using them to help explain what may have happened.

Model Requirements

Any model that we make must adhere to known facts. Here are 10 properties of our solar system.

1. Each planet is relatively isolated in space.
2. The orbits of the planets are nearly circular.
3. The orbits of the planets lie in nearly the same plane.
4. The direction that the planets go around the Sun is the same as the direction that the Sun rotates.
5. Most of the planets rotate in the same direction as the Sun's rotation.
6. Most of the known moons rotate around their parent planet in the same direction as the planets rotation.
7. Our planetary system is highly differentiated.
8. The asteroids are very old and exhibit a range of properties not characteristic of either the inner or outer planets or moons.
9. The Kuiper Belt is a collection of asteroid sized icy bodies beyond Neptune.
10. The Oort Cloud comets are primitive, icy fragments that do not orbit in the plane of the ecliptic and reside primarily at great distances from the Sun.

All of these facts suggest a high degree of order in the solar system. A convincing theory that explains all of the above facts has been the goal of astronomers for a long time.

Planetary Irregularities

There are many irregularities in the solar system that our theory doesn't have to explain, such as Venus' runaway greenhouse effect. Our theory doesn't have to explain everything, but it does need to be flexible enough to allow for and explain the deviations.

Planets in the Solar System

To discuss our formation, we are going to take a look at the condensation theory from chapter 6.

Condensation and Accretion

The original dusty cloud fragment that we formed from may have been 100,000 AU across (roughly a light year). The cloud would have been comprised mainly of hydrogen and helium, just like everything else. Intermingled with the H and He would have been microscopic dust grains made up of heavier elements such as nitrogen, carbon, silicon and iron. Some incident must have occurred and the cloud fragment started to collapse. Due to angular momentum, as the cloud contracted, it began to spin faster. This would have caused a flattened disk to form. By this time it has shrunk to a diameter of about

100 AU and is known as a solar nebula. As it continued to collapse, dust grains formed *condensation nuclei*. This provided the means by which the first solid clumps in the solar nebula formed. These clumps inherit the spinning motion of the cloud and orbit around the center of the cloud. They grow rapidly by *accretion*, the particles sticking together. In as little as 100,000 years these bodies have grown to the size of small moons. Now their gravity is affecting their neighbors and they are called *planetesimals*. Gravity caused the planetesimals to merge and form larger bodies. The larger bodies have more gravity, so the rich became richer. These would have evolved into the planets we know today. The condensation theory is an evolutionary theory. It describes the formation of our solar system as a series of natural and gradual steps.

Making Terrestrial Planets

Down in closer to the Sun the temperatures were very high and so only the heavier material could accrete. These heavy materials would have also accreted in the outer solar system, but out there the lighter gases were much more prevalent. There would have been a large number of bodies in the beginning, but over probably 100 million years many of these would have accreted to make larger bodies. The fact that it formed 4 planets was strictly chance. Regardless of the number of planets formed, computer simulations show the formation of terrestrial bodies that orbit in nearly circular orbits. It also shows that as you move out from the Sun the distances between the planets increases. As the collisions continued, many small bodies were shattered and led to the early bombardment of the solar system.

Making Jovian Planets

The making of the Jovian planets is less clear than the terrestrial worlds. There are 2 main ideas for the formation of the jovian worlds.

First, is the more conventional theory. In the outer solar system the colder temperatures gave rise to icy grains from which the protoplanets would have formed. They became large enough to capture gas from the nebula itself. This is called the *core-accretion theory*. Now there seems to be a problem for this theory; there may not have been enough time for this to have produced the planets we see out there. Young stars go through what is called the T Tauri phase where they have a very intense radiation and solar wind. This wind would have blown away most of the gases. The nebular disk was probably only a few million years old at this time. That would have left very little for the jovian worlds to capture.

The second theory says that the planets in the outer solar system formed because of instabilities in the nebula. It is called the *gravitational instability theory*. In this scenario, these bodies would have formed in a few thousand years while the protosun was still forming. When the Sun ignited, they were already well established in the outer solar system. The way to determine this is the study of their cores. The instability model says that the cores should be no more than 6 Earth masses while the core-accretion theory says the cores should be more like 20 Earth masses. We have guesses, but further missions to study the cores are necessary. Most of the moons formed up at the same time as their parent planets. These worlds would have looked like miniature solar systems in formation.

Giant Planet Migration

One of the more intriguing ideas today, which is not accepted by all scientists, is that the giant planets formed farter out from the Sun and migrated inward. This is thought to be due to the friction between the giant planets and the nebula they were moving through. As they slowed down, they moved inward. The Galileo spacecraft helped this idea when it discovered higher than expected levels of nitrogen, krypton, argon, and xenon. Where Jupiter is it is too warm for those gas concentrations. This says that it must have formed where it was cooler to have those gases in Jupiter. Either the nebula was cooler than thought or it formed out around the Kuiper Belt.

Interplanetary Debris

Regardless of the chain of events that occurred, we know that after the solar nebula was ejected all that was left was the planets and the planetary debris. These would have evolved to what we see today. TIMELINE

The Asteroid Belt

In the inner solar system, the planetary fragments that didn't collide with a planet would have received numerous gravity assists from the other bodies and would have been flung out beyond the orbit of Mars. Probably a billion years was necessary to sweep the inner solar system clean of this debris. This would have been a time of the heaviest bombardment in the solar system. These rocks found between Mars and Jupiter never accreted into a body, due probably to Jupiter's immense gravitational field.

Comets and the Kuiper Belt

In the outer solar system with the formation of the jovian planets, the remaining planetesimals would have been subject to the strong gravity of the planets, especially Uranus and Neptune. These bodies were flung outward from the Sun by the gravity of these worlds. Many of these icy bodies were flung out to the Oort Cloud. Some of these bodies were left behind just beyond Neptune in the Kuiper Belt. We now know about 900 Kuiper Belt Objects between 50 and 1000 km. Some of these bodies were kicked inward towards Jupiter and Saturn only to be kicked out into the Oort Cloud. By the time the outer solar system had been cleared of comets, the outer planets had moved inward. These movements occurred long after the inward migration that was discussed earlier. It has been found that about 15% of the KBO's orbit Neptune with a 3:2 resonance, just like Pluto. They are called *plutinos* because Pluto has a 3:2 orbital resonance with Neptune. It is thought that as Neptune moved outward this caused the plutinos to be swept outward with Neptune in the 3:2 resonances. It was slow enough that many planetesimals in a near resonance were swept up. While all this happened, many were swept into the inner solar system where they played an important role in the evolution of the inner planets. This may answer where the water and other volatiles came from on the inner planets.

The Role of Catastrophes

The condensation theory accounts for the 10 characteristics listed at the beginning of this chapter. A good theory allows for imperfections. This would have been taken care of by the randomness of what happened as the planetesimals became protoplanets. As the number of bodies decreased and their masses increased, each collision acquired a greater importance. Now we can look at 8 irregularities in the solar system.

1. Mercury's large iron-nickel core may be due to a collision between 2 planets that were partially differentiated and merged together. The outer material was lost in the collision.
2. Two large bodies could have merged to form Venus with its unusual rotation.
3. The Earth Moon system may have been formed by a collision with a Mars sized object.
4. A late collision may have caused Mars curious north-south asymmetry and the loss of its atmosphere.
5. The unusual tilted rotational axis may have been caused by a grazing impact or the merger of 2 smaller bodies.
6. Uranus' moon Miranda may have been almost destroyed by a planetesimals collision, accounting for its bizarre surface features.
7. Interactions between the jovian protoplanets and one or more of the planetesimals may account for the irregular moons of those planets, especially Triton's retrograde motion.
8. Pluto may simply be a large representative of the Kuiper Belt. The Pluto-Charon system may be the result of a near miss between 2 planetesimals.

Planets Beyond the Solar System

Now that we are starting to discover planetary systems around other stars, we can test our ideas and see how well they stand up to scrutiny.

The Discovery of Extra Solar Planets

Since the mid 1990's we have seen the discovery of many extra solar planets. We still have not been able to image the planets themselves. They have been discovered by indirect methods. We looked at Sun-like stars to look for planets and look for the stars to wobble. The more massive the planet, the greater the wobble. This lets us see the Doppler shift of the stars light. You can see the wobble of the first one found, 51 Pegasi. This star lays 40 LY from us. These 50 km/sec fluctuations have been confirmed by several other groups. The other graph shows Upsilon Andromedae, one of the most complex systems of planets discovered. It is a triple planet system. The masses here are .7, 2.1 and 4.3 Jupiters. For those stars whose wobble is perpendicular to our line of sight, we can detect a slight change in the stars position in the sky. We currently have over 100 extrasolar planets catalogued. We have one case where the light from the star drops significantly as the planet transits the star. The planet is .6 Jupiter masses and .05 AU from its Sun.

Planetary Properties

We have over 120 planets orbiting more than 100 stars. Only about 5% of the stars observed have yielded any planets.

1. All of the planets found so far are about Jupiter sized, from 1/3 Jupiter to 10 Jupiters. Most have been in the low range.
2. The observed orbits are much smaller than Jupiter or Saturn.
3. The observed orbits are much more eccentric than Jupiter or Saturns.

So far we have been discovering only singleton planets around the stars. The numerous Jupiter sized planets orbiting close to their star are called *hot Jupiters*. Most of these bodies are in very circular orbits caused by their stars close proximity. Spectroscopic studies have shown that stars similar to the Sun are more likely to have planets around them.

Are They Really Planets?
These systems are very alien when you compare them to our solar system. The mass measurements are the big problem. Eccentric orbits are known to be common in binary star systems. Also, the masses of these objects could make them actually brown dwarfs, or failed stars. The dividing line between Jupiter sized planets and brown dwarfs is thought to be somewhere around 15 Jupiter masses. This is about the size of the largest known extra solar planet. Believers say that this is no coincidence that we have found only 1 big planet. Detractors say that we are seeing it almost face on which greatly reduces the radial velocity. The problem here is that for every low mass planet we find, this would mean that we would have to see it face on. The odds that we are seeing every one face on are very slim.

Is Our Solar System Unusual?
Early on it was argued that solar systems should be out there and that they should be like ours. Well we are seeing other solar systems, but they are nothing like ours. So are we really unusual in the universe?

Observational Limitations
Are the planets we see really representative of all the extrasolar planets? We don't see Earth mass planets or large planets farther out from their star. This is easily explained because neither one of those would cause significant motion in the star fort us to see. This is called the *selection effect*. Our methods are biased towards finding the larger bodies close to the star. Most of our discoveries show radial velocities of 12 m/s. We need to refine our techniques and our technology to look for lower radial velocities. More recently we are finding more Jupiter sized and lower mass bodies.

Making Eccentric Jupiters
Is the method of formation of these planets inconsistent with our condensation theory? Probably not. Current theory provides ways for short period or eccentric orbits. These planets could have been knocked into eccentric orbits by interactions with other Jupiter sized bodies. If they formed from gravitational instabilities they would have had eccentric orbits from the beginning. As mentioned earlier, as the gas giant moves through the nebula, it slows down and spirals inward. Having a Jupiter sized planet plow through the inner parts of the system would have dire consequences for Earth sized planets.

Searching For Earth-like Planets
The big question is how do we look for Earth sized bodies? Looking for a wobble in the position of the star won't do it. Radial velocities won't be large enough to measure and find these planets. Right now probably the best way to find them is by watching for

transits across the face of the parent star and measuring the light drop. Everything has to be right to see it, but we have the technology to see the drop. An Earth sized planet would cause a drop in the light of less than 1 part in 10,000. WE are looking at 100,000 stars for a brightness drop and we hope to find as many as 100 terrestrial planets.