Chapter 15: The Formation of Planetary Systems
The Solar System and Beyond

Outline

15.1 Modeling Planet Formation
15.2 Planets in the Solar System
15.3 Interplanetary Debris
15.4 The Role of Catastrophes
15.5 Planets Beyond the Solar System
15.6 Is Our Solar System Unusual?

Summary

Not only does this chapter explain the formation of the solar system, it really ties up a lot of loose ends regarding why the solar system looks the way it does. The properties of the solar system overall do not happen by chance. The nebular theory is overviewed and the evidence supporting it is discussed.

Because the laws of physics are expected to be the same throughout the universe, the nebular theory is assumed to be correct for explaining the formation of stars and other planetary systems as well. The chapter continues with an overview of the search for extrasolar planets, the count of which is currently around 120! The chapter concludes with the question concerning the uniqueness of our solar system.

Major Concepts

- Concept of modeling
- Model requirements
- The solar nebula contraction
  - Conservation of angular momentum
  - Planet formation
  - Differentiation in the solar nebula
  - Formation of the jovian versus terrestrial planet
  - Accretion and condensation
- Fate of leftover planetesimals
- Importance of random events.
- Extrasolar planets

Teaching Suggestions and Demonstrations

Students are often confused by the actual sequence of steps in the formation of the solar system. Besides learning the new terminology it is necessary to know the order in the sequence of events. You will find that it is often very helpful to present an outline of the various steps prior to lecturing on the details. In this way the students see the process as a series of consecutive events. The following outline may be of help.

1. Interstellar gas and dust cloud: about 1 light-year in diameter, starts to gravitationally collapse.
2. Solar nebula: about 100 A.U. in diameter in the shape of a rotating disc.

3. Condensation and accretion: dust particles form condensation nuclei through collisions. Particles grow rapidly in size.
4. Gravitational accretion: planetesimals have sufficient gravity to attract material gravitationally; the largest bodies start to dominate and grow rapidly.
5. Gravitational accretion of gas: the largest protoplanets in the coolest parts of the solar nebula accrete gas; the smaller protoplanets in the inner solar nebula are unable to accrete gas due to its higher temperature.
6. Sweep of the debris: over about one billion years the material left over from the solar system formation is cleared.

Section 15.1

Before discussing the formation of the solar system directly, review some of the **major characteristics of the solar system** that must be explained by, or at least be compatible with, a theory of its origin. For instance, all the planets orbit in the same direction around the Sun, and most rotate in this same direction as well. Further, they lie (more or less) in the same plane. Look at the list of nine facts at the beginning of this section and remember to refer back to them as the specifics of the theory of the origin of the solar system are discussed.

Section 15.2

Outline the stages in the **formation of the solar system** for students. There are lots of new terms introduced in the text; go over them carefully. Define and discuss **angular momentum**; students will probably not be familiar with it unless they have taken physics. However, they will be familiar with the results of the law of conservation of angular momentum. Ask students to think of examples of the conservation of angular momentum such as a twirling ice skater. ➲ **DEMO** One classic demonstration involves a rotating stool and a pair of weights. Ask a student to sit on a rotatable stool and hold a weight in each hand, extended to arm's length. Give the student a very light push so that they start rotating slowly. Now ask them to bring in the weights slowly until they touch their body. A very obvious increase in rotation rate will result as angular momentum is conserved. Ask for several volunteers.

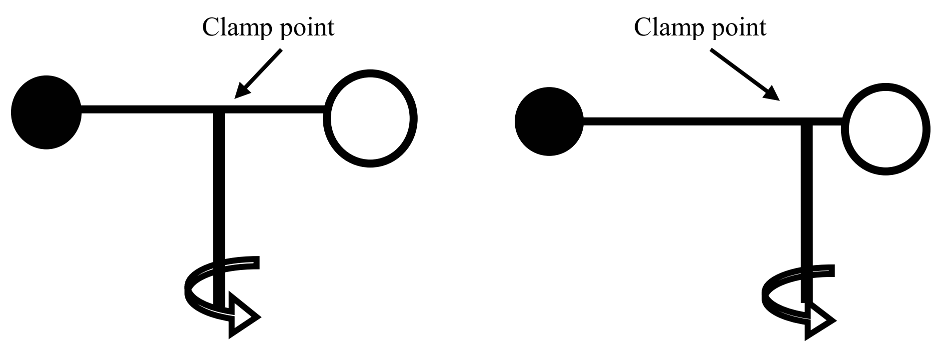
A computational approach may also be taken. Angular momentum, L, is rather easy to calculate. For a point mass, m, moving in a circle of radius r and velocity v, $L = mvr$. For a solid body, moment of inertia of I, that is rotating with angular velocity ω, $L = I\omega$. For a sphere, $I = 2/5\ mr^2$, where r is the radius of the sphere.

Assuming the Sun rotates as a solid body (it doesn't, but it is hard to do the problem otherwise) with a rotational period of 25.38 days, $\omega = 2.86\times10^{-6}\ \text{sec}^{-1}$. The moment of inertia is $I = 3.86\times10^{47}\ \text{kg m}^2$. Then $L = 1.1\times10^{42}\ \text{kg m}^2/\text{sec}$. Calculate the *orbital* angular momentum for Jupiter but use mvr, which is easier. Its orbital velocity is 13,100 m/sec and $L = 1.9\times10^{43}\ \text{kg m}^2/\text{sec}$. Comparing these two angular momenta, we see that Jupiter has about 17 more angular momentum than the Sun. It is actually more than this because we have overestimated the angular velocity of the Sun by using its highest rotation rate.

Could a large amount of angular momentum have been transferred to comets in the Oort Cloud? The same can be tried for a 1–km–diameter body at 1,000 A.U. $L \approx 10^{28}\ \text{kg m}^2/\text{sec}$. For this you can see that it would take an enormous number of such objects to carry away a significant amount of angular momentum. They would all have to be orbiting in the same direction too, which comets do not do. Even over the lifetime of the solar system, there have likely not been this many comets in the Oort Cloud.

Section 15.5

Extrasolar planets are being discovered at an ever increasing rate as the technology and methods improve. ➲ **DEMO** The technique itself can be demonstrated fairly easily by assembling a simple device. Take a wood rod and two styrofoam balls about 4 inches or so in diameter. Paint the rod and one ball black and the other ball white. Attach one ball to one end of the rod and the other ball to the other end. The white ball will represent a star and the black ball will represent a massive planet orbiting the star. Now, you will need to be able to rotate this rod horizontally so that the balls orbit each other. The easiest thing to do here would be to simply clamp the rod to another rod, perpendicular to the second rod's axis and then rotate the second rod in your hand. A motorized version of this works even better. You can easily simulate varying center of mass by choosing different locations on the horizontal rod as the clamp point on the rotating rod as shown:



Turn off the lights and leave only enough light so that the students can see the white "star," but not the black "planet." From the wobble of the star, the presence of the planet is deduced. The mass of the planet can be determined by the amount of wobble simulated by the choice of the clamp point. This same demonstration can be used when discussing binary star systems as well.

Section 15.6

The **selection effect** is a very important concept for students to understand as it relates not only to Astronomy but to science as a whole. Remember, the answers that nature provides for our questions are dependent on the questions themselves. We see fewer Earth-sized planets simply because the techniques utilized in the search for Extrasolar planets favor more massive planets. It is no wonder, then, that most of the extrasolar planets known to date are Jupiter-like rather than Earth-like.

Student Writing Questions

1. In carnival-type rides, give some examples that demonstrate angular momentum and conservation of angular momentum. Explain what occurs and the significance of angular momentum to each.

2. Is it possible that planets could have formed without the presence of dust? When the universe was very young, there would have been little if any dust. Could planets have formed then? How? Do you think planet formation is something that has only been happening rather recently in the universe?

3. About half of all stars are binary. How does the scenario change if another star is formed during the process? Could planets still form? Where could planets exist in reasonably stable orbits?

4. Assume a binary star system has formed. What would it be like to live on one of these planets, with two suns instead of one? What would be different from living on the Earth with one Sun?

5. When Jupiter formed it was a much hotter (brighter) planet than it is today. Speculate on what the Galilean moons might have been like back at that time, when they too were newly formed. What would their surface environment have been like? Would they have been icy, with no atmospheres?

Answers to End of Chapter Exercises

Review and Discussion

1. Properties of the solar system that models must explain:
   isolation and positions of planets,
   nearly circular planetary orbits,
   planetary orbits in nearly the same plane,
   planets' direction of revolution the same and same as Sun's rotation,
   most planets' rotation in same direction as Sun's rotation,
   most moons have revolutions in same direction as planet's rotation,
   highly differentiated planetary system,
   asteroids are very old and unlike planets and moons, and
   comets are primitive, icy fragments that do not orbit in ecliptic plane.

2. After the formation of the solar system the planets continued to evolve. The theory of the formation of the planets does not have to account for subsequent evolution for each planet. Three examples of this would be the Moon's synchronous rotation, Venus's runaway greenhouse effect and the presence of ring systems around the jovians. Each of these is based on the planets' individual predicaments. Earth's tidal forces and the fact that the Moon still possessed a molten interior after major impacts produced the conditions favorable to the formation of the maria resulted in the Moon's synchronous rotation. Venus's outgassing, proximity to the Sun and a possible major collision producing a very slow rotation rate may all have contributed to its greenhouse effect, while Earth and Mars did not experience similar activity once the overall structure of the solar system was determined. The ring systems of the jovians came about by continual fragmentation of a relatively large number of moons and other debris that collected around the giants due to their enormous gravity.

3. An evolutionary theory is one in which the solar system develops as a series of gradual and natural events that conform to physical law. A catastrophic theory invokes an accidental or rare event to explain the formation of the solar system.

4. The nebular theory has the solar system forming out of a large, spinning cloud of gas. As it spins, it flattens into a pancake shape and forms a series of concentric rings. Each of these rings eventually forms a planet; the central condensation forms the Sun.

5. In the solar nebula where the jovian planets are now found, the temperatures were sufficiently low for ices of water, ammonia, and methane to form. This provided much more material for the early accretion that occurred and it proceeded rapidly. The planetesimals that formed could then also attract hydrogen and helium, and the jovian planets grew to a large size. In the region of the inner solar nebula, temperatures were sufficiently high that time had to pass before the first rocky particles could condense and start the accretion process. There was less material to accrete because it was too hot for the icy material to exist. Finally, hydrogen and helium could not be accreted because of the planets' low gravity and high temperatures.

6. In the first scenario, the jovian protoplanets grow large enough to accrete large amounts of gas from the solar nebula. In the second scenario, the jovian protoplanets grow directly and quickly from instabilities in the nebula, like mini-solar systems.

7. The Sun's heat was less intense in the outer regions of the solar system, which allowed the cooler gases to condense into the jovian atmospheres. Since the dominant constituents of the solar nebula were hydrogen and helium gas, the jovians had much more material from which to form.

8. The voluminous jovians would have experienced "drag" in traversing the outer regions of the early solar nebula. This drag would have resulted in decreased orbital speed, and, therefore, a reduced orbital radius.

9. Basically, the "debris" that we have been discussing resulted from the process of fragmentation. These objects include the asteroids and the Kuiper Belt and Oort Cloud objects.

10. Earth's composition was heavily influenced by its location in the solar system. The temperatures were such that the accretion process could continue to gather heavier fragments, but the lighter gases, which were too hot to condense, did not become a significant ingredient. However, Earth's distance from the Sun was also far enough so that liquid water could exist once the region of the solar system had cooled enough and water had become available in larger quantities. This balance has provided Earth with not only a solid surface, but liquid water oceans and an atmosphere that was not too dense and yet dense enough to maintain a reasonable, relatively constant temperature.

11. Earth would not have been able to condense enough water in the early period of formation due to the high temperatures. However, once the planet cooled sufficiently, the temperatures became acceptable for the condensation of water. Now, at this point, there was no longer enough water ice in the vicinity of Earth to account for the amount of water that we see today. Therefore, the water must have been brought in by objects originating in the far regions of the solar system. These objects would be comets.

12. The jovians, due to their high gravitational influence, gave energy to and extracted energy from the large numbers of icy planetesimals as they threw these objects around. In effect, they produced a sort of gravity-assist in speeding up or slowing down these many planetesimals. Because energy is conserved, the planets that gave energy to icy planetesimals were slowed in their orbits and subsequently fell closer to the Sun, while those planets acquiring energy in slowing icy planetesimals were sped up and moved to higher orbits. In short, the orbits themselves of the jovians were influenced by the ejection of icy planetesimals.

13. Plutinos are large, icy bodies left over from the formation of the jovian planets. Mostly larger than comets, they gravitationally interacted with the jovian planets and were moved outward. Neptune captured them into orbits with a 3:2 resonance with its orbit.

Conceptual Self-Test

1. F
2. T
3. F
4. F
5. F
6. T
7. F
8. T
9. F
10. F
11. A
12. D
13. A
14. A
15. C
16. A
17. C
18. C
19. D
20. B

Problems

1. Orbital angular momentum can be expressed as *MVR*, where *M* is the mass of the planet, *V* is its orbital velocity, and *R* is the radius of its orbit. But in Chapter 2, the orbital velocity was found to depend on the square root of *M/R*. Putting this all together gives

$$\text{Ang. Mom.} \propto MR\sqrt{\frac{M}{R}}$$

$$\text{Ang. Mom.} \propto M^{3/2}R^{1/2}$$

(a) This now makes it easy to compare the angular momentum of Jupiter and Saturn to that of the Earth. Using Earth units for mass and A.U. for *R* gives:

$$\text{Jupiter Ang. Mom.} = 318^{3/2}5.2^{1/2}$$
$$= 12{,}900 \text{ Ang. Mom. of Earth}$$

$$\text{Saturn Ang. Mom.} = 95^{3/2} 9.5^{1/2}$$
$$= 2{,}850 \text{ Ang. Mom. of Earth}$$

(b) 10^{13} kg compared to the Earth's mass of 6×10^{24} kg is 1.7×10^{-12}.

$$\text{comet Ang. Mom.} = (1.7\text{x}10^{-12})^{3/2}(50{,}000)^{1/2}$$
$$= 5 \times 10^{-16} \text{ Ang. Mom. of Earth}$$

2. A 1-km-diameter body has an area of πr^2 that will intercept other bodies. This gives 0.8 km^2. 500 m/s is 0.5 km/s. This 1-km body will sweep out a volume of space equal to its area × its speed × time. The number density of such bodies is 10^{-10}; it will hit one other body after it has swept out this volume × the density.

$$0.8 \text{ km}^2 \times 0.5 \text{ km/s} \times t \times 10^{-10} = 1$$

$$t = 2.5 \times 10^{10} \text{ s} = 800 \text{ yrs.}$$

3. From Kepler's 3rd law we have $P^2 = a^3 = 25^3$, so P=125 Earth years per revolution. Dividing 1000 years by 125 years per revolution gives 8 revolutions.

4. Determine the mass of the planetesimal first. $m = 4/3\pi \times 50{,}000^3 \times 3000$, m = 1.6×10^{18} kg. Divide this mass into the mass of the Earth to find the number of planetesimals it would take to form the Earth. 6×10^{24} kg / 1.6×10^{18} kg = 3.8×10^6 = 3.8 million

5. Their separation at closest approach is 0.01 A.U. = 1.5×10^6 km = 1.5×10^9 m. Applying Newton's law of gravity gives: $F = 6.7 \times 10^{-11} \times 10^{18} \times 10^{18} / (1.5 \times 10^9)^2$, $F = 3 \times 10^7$.

6. The temperature of the Earth will increase from 250 K (ignoring the greenhouse effect) to 1100 K, a factor of 4.4. Luminosity is proportional to the fourth power of the temperature. The energy radiated by Earth at this higher temperature will be 4.4^4 = 375 times more than it is now. If the energy it radiates is equal to the energy it received from the Sun, then the Sun must radiate 375 times as much as it does currently.

7. 2×10^{21} kg / 10^{13} kg water per comet = 2×10^8 comets (200 million comets). 200 million comets / 500 million years = 0.4 comets per year or 1 comet every 2.5 years.

8. If Neptune's orbit changed by about 10 A.U. then it was at about 20 A.U. Using Kepler's third law gives $P^2 = 20^3$, P = 89 years.

9. If a plutino is in a 3:2 orbital resonance with Neptune, then that plutino would orbit the Sun twice for every three Neptune orbital periods. When the orbital semi-major axis of Neptune was 25 AU, it had an orbital period of $P_{Neptune} = \sqrt{\left(a_{Neptune}\right)^3} = \sqrt{(25 \text{ A.U.})^3} = 125 \text{ years}$. The plutino's period would then be 3/2 of this, or 188 years.

10. Pluto's mass is 1.27×10^{22} kg. Dividing this by 5.2×10^{13} kg per comet gives 2.4×10^8 comets to form Pluto. That's 240 million comets.

11. Use Newton's form of Kepler's third law, all in solar units. $P^2 = 0.042^3 / 1.06$, P = 0.00836 yrs = 3.05 days. As of Jan. 1, 2002, there have been 1126 days. It has orbited 369 times.

12. A 2:1 resonance will give the outer planet a period of 60 days or 0.164 yr. Again using Kepler's third law, $0.164^2 = a^3 / 0.33$, a = 0.21 A.U.

13. First, determine the orbital radius of the hot-Jupiter using Kepler's 3rd law: $P^2=a^3$ using P=3/365=.008. This gives a=0.04 A.U. Now, the temperature at any distance from the Sun is a function of the solar energy flux there. Stefan's law gives

$$\frac{\text{total energy emitted by the Sun}}{\text{area}} = \sigma T^4$$

multiplying through by the area gives

$$\text{total energy emitted by the Sun} = \text{area} \times \sigma T^4$$

This relation can be used now to compare the temperatures at different orbital distances from the Sun since the total energy emitted by the Sun is a fixed quantity. Since Mercury has a temperature of 700 K and is located at a distance of 0.4 A.U., we can use the above relation to determine the temperature at a distance of 0.04 A.U. from the Sun:

$$4\pi\left(a_{Mercury}\right)^2 \times \sigma\left(T_{Mercury}\right)^4 = 4\pi\left(a_{hot-jupiter}\right)^2 \times \sigma\left(T_{hot-Jupiter}\right)^4$$

This simplifies to

$$\left(T_{hot-Jupiter}\right)^4 = \frac{\left(a_{Mercury}\right)^2}{\left(a_{hot-jupiter}\right)^2}\left(T_{Mercury}\right)^4$$

Solving for $T_{hot\text{-}Jupiter}$ we get $T_{hot\text{-}Jupiter}$=2,210 K.

14. The tidal pull is relative to a point half way between the Sun and Jupiter, a distance of R = 2.6 A.U. Let the star's distance from this point be D. The tidal force will be $2GMM_JR/D^3$. The gravitational force between Jupiter and the Sun is GMM_J/R^2. Take the ratio of these two expressions and set them equal to 0.001 (0.1 percent). $0.001 = 2(2.6 / D)^3$, D = 32.8 A.U. Add to this, 2.6 A.U. to get the total distance between the star and the Sun to get 35.4 A.U.

15. Determine the semi-major axis from the given period of 5 years. $5^2 = a^3$, a = 2.924 A.U. The maximum velocity in an orbit occurs at perihelion, at a distance $r = a(1 - e)$. Use the equation given in Chapter 8 of this manual for the orbital velocity at any distance r from the Sun. This can be simplified to be $v = 30\sqrt{(2/r - 1/a)}$ where the velocity, v, is in km/s, the 30 is the Earth's velocity and r and a are given in A.U. Substituting for r using the perihelion distance and putting 40 in for v gives e = 0.68.

Resource Information

Student CD Media

Movies/Animations
Solar System Formation

Interactive Student Tutorials
None

Physlet Illustrations
Conservation of Angular Momentum

Transparencies

T-131	Figure 15.1	Solar System Formation - Condensation Theory	p. 386
T-132	Figure 15.3	Making the Inner Planets	p. 388
T-133	Figure 15.4	T-Tauri Star	p. 389
T-134	Figure 15.5	Jovian Condensation	p. 389
T-135	Figure 15.6	Solar System Formation - Timeline	p. 391
T-136	Figure 15.7	Planetesimal Ejection	p. 392
T-137	Figure 15.9	Planets Revealed	p. 395
T-138	Figure 15.10	An Extrasolar Transit	p. 396
T-139	Figure 15.12	Extrasolar Orbits	p. 397

Materials

Two wood dowels, two Styrofoam balls and black paint to create demo discussed in "Teaching Suggestions" section 15.5 above.

Suggested Readings

Doyle, Laurance R.; Deeg, Hans Jorg; Brown, Timothy M. "Searching for shadows of other earths." *Scientific American* (Sept 2000). p. 58. Details the search for extrasolar planets.

Frank, Adam. "Crack in the clockwork: the solar system may have lost several planets, and Mercury or Mars might be the next to go." *Astronomy* (May 1998). p. 54. Discusses studies of chaos theory applied to the orbits of the planets.

Gluck, P. "MBL Experiment in Angular Momentum." *The Physics Teacher* (April 2002). p. 230. Studies the loss and conservation of angular momentum using a small direct current motor as generator.

Jayawardhana, Ray. "Spying on planetary nurseries." *Astronomy* (Nov 1998). p. 62. Discusses observations of circumstellar disks and how these are related to planet formation.

Konacki, M. et al. "An extrasolar planet that transits the disk of its parent star." *Nature* (30 January 2003). p. 507. Interesting article discussing a research project where an extrasoler planet's size was determined by combining the Doppler shift technique with the technique that measures a star's varying apparent magnitude when a planet transits it.

Lissauer, J. "Extrasolar Planets" *Nature* (26 September 2002) p. 355. Good overview of modern techniques for searching out extrasoler planets.

Lubick, N. "Goldilocks and the Three Planets." *Astronomy* (July 2003). p. 36. Outstanding and very useful (in the classroom) article comparing Venus, Earth and Mars. Excellent comparative planetology. Relevant to this chapter concerning discussions of planetary evolution.

Malhotra, Renu. "Migrating planets." *Scientific American* (Sept 1999). p. 56. Discusses recent advances of our understanding of the dynamics of planet orbits.

Marcy, Geoff; Butler, Paul. "Hunting planets beyond." *Astronomy* (Mar 2000). p. 42. Discusses the characteristics of the known extrasolar planets.

Marcy, Geoffrey; Butler, R. Paul. "The diversity of planetary systems." *Sky & Telescope* (Mar 1998). p. 30. Describes the techniques used to find extrasolar planets, and discusses the characteristics of the known extrasolar planets.

Naeye, R. "Unlocking New Worlds." *Astronomy* (November 2002). p. 48. Probably the only reference you will need to read to prepare for class discussions about the techniques used in the hunt for extrasolar planets. Includes images and diagrams.

Pechan, M.; O'Brien, A.; and Burgei, W. "Conservation of Angular Momentum Apparatus Using Magnetic Bearings." *The Physics Teacher* (January 2001). p. 26. A simple laboratory exercise on angular momentum.

Sincell, Mark. "Switched at birth." *Astronomy* (Mar 2000). p. 48. Discusses new models for the formation of gas giant planets.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: