Chapter 6: The Solar System
Comparative Planetology and Formation Models

Outline

6.1 An Inventory of the Solar System
6.2 Measuring the Planets
6.3 The Overall Layout of the Solar System
6.4 Terrestrial and Jovian Planets
6.5 Interplanetary Matter
6.6 How Did the Solar System Form?
6.7 Jovian Planets and Planetary Debris

Summary

Chapter 6 provides an introduction to our solar system as a whole. This chapter lays the foundation for the next several chapters, which look in depth at our Earth, the Moon, the planets, and the Sun. Section 6.4 highlights the significant differences between the two types of major planets, terrestrial and jovian. The chapter finishes with a description of how the solar system formed. The properties of the solar system overall do not happen by chance. This chapter describes the "Condensation Theory" for the formation of the solar system, which tries to explain why the solar system looks the way it does. Section 6.6 discusses the overall requirements of a theory for solar system formation, as well as an overview of how the inner planets formed. Section 6.7 carries this through for the gas giant planets, and it describes how lesser objects such as asteroids and comets fit into the picture.

Major Concepts

- Solar System Inhabitants
  - Planets
    - Sizes
    - Distances
    - Properties: Comparative Planetology
    - Terrestrial vs. Jovian
  - Asteroids, Comets, and Meteoroids
- Formation of the Solar System
  - Model Requirements
  - The Condensation Theory
  - Angular Momentum
  - Planet Formation
    - Differentiation of the Solar Nebula
    - Accretion of Terrestrial Planets
    - Controversy over Formation of Jovian Planets
  - Fate of Leftover Planetesimals

Teaching Suggestions and Demonstrations

Of all the chapters in the book, this one and Chapter 15 have undergone the most revision. You will want to read over both carefully. A great deal of the material on the formation of the solar system has been moved here from Chapter 15. I still save this origins material for the end of the semester, after I have surveyed the solar system as a whole. My rationale is as follows: Trying to discuss the origin of the solar system breaks away from what some would consider "science," since we cannot actually observe the formation of the solar system directly. This does *not* mean that we can't take a scientific approach to it, however. I ask the students to think about the discipline of forensic science, popularized in the various *CSI* television shows. If forensic scientists could witness the actual crime firsthand, their jobs would be laughably easy. However, they must put together clues found at the scene and try to create a picture of what actually happened. In the same manner, astronomers look at the way the solar system is today, and try to put those pieces together in an explanation for how it all came to be. Therefore, I don't feel I can really talk about the origin of the solar system until the end, after I have spent a semester dropping clues! There is a good rationale for talking about it early, however; some instructors are of the opinion that talking about the formation of the solar system early "sets the stage" for talking about the objects of the solar system. This is especially true if you are doing a one-semester "survey" course.

Teaching the material in this chapter (and the material in the last few chapters of the text as well) can be very challenging, since some students may have strong religions convictions that they see as conflicting with scientific explanations. Such conflicts must be dealt with delicately, lest things degenerate into a science vs. religion debate. Insulting religion and people of faith is a certain way to "turn people off" to science and undo all your hard work thus far in helping students appreciate astronomy, so be careful! Science and religion are two very different ways of looking at the universe, and each person must make his or her own decisions about the legitimacy of each. Remind students that no scientific theory is perfect, and that all scientific theories are subject to challenge and change. However, nothing is *ever* "just" a theory, because all theories are based on solid observations and rational thought. We should never treat theories like facts, but neither should we sell any theory short. Being honest about the weaknesses as well as the strengths of the scientific process is the surest way I've found to win students' trust when talking about matters such as the origin of the solar system.

Section 6.1

If you are teaching a one-semester "survey" course on astronomy, and have very little time to devote to the Solar System, this chapter probably has everything you will need. On the other hand, if you are teaching a two-semester sequence, and have a whole semester to devote to the Solar System, you may wish to only spend a brief time in the first few sections of this chapter, and refer to the material here many times during the semester.

Review the scientific method here, especially the idea that theories are modified when new information becomes available. Prior to the invention of the telescope, mankind had documented the existence of only five planets other than Earth itself. Not surprisingly, these are the planets visible with the unaided human eye. In fact, in ancient times, seven "wanderers" were recognized. These ancient planets gave us the days of the week, although this may not be obvious:

Day of the Week	Spanish name	"Planet"	Deity
Sunday		Sun	
Monday	Lunes	Moon	

Tuesday	Martes	Mars	Tyr (Norse)
Wednesday	Miercoles	Mercury	Woden (Norse)
Thursday	Jueves	Jupiter	Thor (Norse)
Friday	Viernes	Venus	Frey/Freya (Norse)
Saturday		Saturn	

The Earth was not considered a "planet" because it didn't seem to "wander." With the invention of the telescope and the development of sophisticated ideas such as the theory of gravity, the planets Uranus and Neptune as well as asteroids, comets and other objects could be discovered. Most of what we know now of the structure and evolution of the solar system has come about only within the last 150 years. Discuss this fact with the students and elicit their ideas on what new discoveries might be possible in their lifetime. This can result in lively discussions, particularly in the area of the search for extra-solar planets and extraterrestrial intelligence.

The idea of comparative planetology can be a powerful teaching tool, and a good way to provide structure to your course. For example, I try to follow a particular structure as I talk about each of the inner planets in turn. First, I discuss what information we can gather simply by looking at the planet from a distance – albedo, oblateness, average density, etc. Then, I talk about the planet's atmosphere, or lack of same. Next, I present what evidence we can gather about a planet's interior. Finally, I discuss the major features of the planet's surface. Although it may necessitate diverging from the order of topics in the text, I find that this parallel structure helps students organize their notes, and helps them in making comparisons between the planets. I also think it is very important to talk about each planet in turn, rather than simply having a lecture on "planetary atmospheres." These combined lectures run the risk of running all the planets together in the students' minds.

An interesting comparative planetology activity by LoPresto and Murrell can be found in the May 2010 issue of *The Physics Teacher* (see reference below). Students are given a table of various planetary properties (distance, mass, density, number of moons, etc.) and asked to work in groups to spot patterns and groupings in the data. The class should eventually arrive at the conclusion that planets can be arranged into groups, and that planets within a group can have very similar characteristics. This can be a nice "icebreaker" activity for a solar system oriented course, or a good way to begin the solar system section of a survey course. It may take up a little more class time to let students uncover these patterns themselves, but it may help them retain the knowledge longer and more accurately.

Section 6.2

This is a good time to discuss (or review) the human mind's propensity to categorize objects in nature. This represents one of the thrusts of scientific investigation and has a history dating back to Aristotle himself. Categorization is one way for us to break-down the complexities in nature into more manageable portions for analysis.

As you review Table 6.1, make sure to go over the units in the table with students. Many of the quantities are given relative to Earth. This can confuse students: when they have to get data from this table for calculations, students may think that Mars has a mass of 0.11 kg, or a radius of 0.53 km! Be sure to emphasize these relative units; for example, Mars has 11% of the mass of the Earth.

Density is a concept that pervades the chapters on the solar system, but it is common for students to confuse density with weight. You can make the analogy of how crowded an elevator is to clarify the idea of density. First, make the simplifying assumption that all people are roughly the same size. Then ask the students what determines how crowded an elevator is. Hopefully, students will answer than the number of people in the elevator and the volume of the elevator are important. Lead students to the conclusion that increasing the number of people makes the elevator more crowded, while increasing the volume makes it less crowded. Now relate this to an object filled with atoms. The simplifying assumption is a good one, as atoms are similar in size.

DEMO – Bring in a variety of objects, such as a wooden block, a marble, a rock, and a Styrofoam cube and demonstrate finding their densities. The volumes of objects with irregular shapes can be determined by immersing them in water. This demonstration is most effective if at least one high-density object has a lower mass than a low-density object. Try using a small marble and a large wooden block.

DEMO – Another approach to density is to bring in objects of the same size, but different compositions, and let the students hold them. This drives home in a visceral way the idea that density is a measure of how tightly atoms are packed in an object.

Section 6.3

Most likely your students will have never seen a scale model of the solar system that has the same scale for both sizes and distances, because such a model would be very hard to make. If you choose a scale so that the model can be laid out in a room or even a long hallway, the inner planets would all be indistinguishably small dots. If you choose a scale that clearly shows sizes, the planets must be so spread out that it is impossible to see them all at once.

It is a very useful and enjoyable exercise to have students construct scale models. Try dividing the students into groups and give them different challenges. For instance, give one group a large collection of spherical objects of different sizes. You could include various balls used in sports (basketball, volleyball, soccer ball, baseball, golf ball, hackysack, Ping-Pong ball) as well as other larger (beachball) and smaller (bead, chickpea, pinhead) objects. The challenge for the group is to use any of the objects they wish (as well as others they can find in the classroom) to create a model showing the sizes of the planets to scale. When they are done, ask students to also calculate where a couple of the balls would be placed if the model were to show distances to the same scale. Have the students refer to Table 6.1 for the above exercises.

Meanwhile, give another group a roll of cash register tape (or masking tape or the long, thin rolls of paper used in kinematics experiments in physics) and send them out to a hallway to construct a model showing the distances of the planets to scale. When they are finished, ask them to calculate the sizes of a few planets to the same scale. A third option is to give a group a road map of your state and ask them to place the Sun at one edge and Pluto as far away as possible. They should then calculate where the other planets would lie and how big they would be. If you live in a state capitol or have a similar domed building, you might want to have that dome represent the Sun. Finally, if you can get access to a hallway in your school, you could have students construct a semi-permanent scale model of the solar system, making the planet models themselves. Students will have to pick what kind of scale the model will have; it is probably best to scale the distances instead of the sizes. You may also want to have students submit brief informational sheets to hang with the models, so passers-by can learn from the model. If your class structure does not allow for group work of this type, you can modify the activities into demonstrations.

DEMO – Bring in the collection of balls, hold up the one you have designated to be Earth, and ask students to guess which objects could be used to represent the other planets and the Sun. Or, assign planet roles to various students and ask them to place themselves across the classroom such that their distances are to scale. For purposes of scale, use the following rules of thumb: The diameter of Earth is about 1% the diameter of the Sun and is situated about 100 Sun diameters distant. Jupiter is about 10% of the Sun’s diameter and is about 560 Sun diameters distant. Neptune is less than 3% the Sun’s diameter and is about 3000 Sun diameters distant. Plan accordingly when performing scale model demonstrations or activities.

Weather permitting, a very enjoyable and engaging modification to the above-described activities can be performed outdoors. A place like a football field that is already marked off is ideal, but you may also want to use a long rope with ribbons tied at distance intervals. First, consider a scale model where the Sun is represented by a basketball. It is fun and surprising to start with this scale, which places a BB representing Earth about 30 meters away from the basketball. Place each of the four terrestrials accordingly then ask for volunteers willing to carry the outer planets to their appointed distances. Tell them to start walking and you will yell for them to stop when they are at the appropriate distances (it is even more entertaining to let them know that this would be the only need they would have all semester for the use of their cell phone in class). Knowing yourself that Neptune would be almost 1 km away, let them get some distance away (use your own discretion) before calling them back to explain how far they would have had to have walked to achieve the proper scale. At this point select a more appropriate size ball, such as a softball, to represent the Sun. In this case, Mercury would be smaller than the head of a pin and located at a distance of about 41 Sun diameters away, or about 41 cm away. The Earth would be smaller than the head of a pin and situated about 11 meters away. Jupiter, represented by a small marble 1 cm in diameter would be located about 56 meters away. Even at this scale, Neptune would be the size of a small pea and located over 300 meters away so you may want to end the exercise with Saturn.

These models will help to dispel typical student misconceptions. For instance, many students believe Jupiter is about halfway out to Neptune, when in fact it is closer to halfway to Saturn and only about a sixth of the way to Neptune. Students also often enter introductory astronomy classes thinking that Uranus and Neptune are about the same size as Jupiter and Saturn, when in fact they are less than half the size. Emphasize the difficulty encountered in attempting to show sizes and distances of the planets to the same scale.

Section 6.4

The classification of the planets into terrestrial and jovian should be fairly easy for students to understand. Re-introduce Table 6.1 and ask them for suggestions of characteristics used to compare and contrast the two types of planets. Try splitting the class into groups according to selected planetary properties. Have each group categorize the planets according to their assigned property and report their results to the class, preferably in a table that they can display on the blackboard or overhead projector. For a majority of the properties, each group will have similarly divided the planets into two clear categories.

Be sure to mention how the terrestrial and jovian planets illustrate how “orderly” the solar system is. Instead of rocky and gaseous planets being mixed together, they are divided neatly into two distinctive groups of four. Get the students to start thinking about how this can be so, to prepare for a more detailed discussion of the structure and origin of the solar system.

Much of the information that we have about the planets has come to us from robot space probes. Use the information in Discovery 6-2 as a framework to discuss the various missions. Try to give students a feel for the complexity of the missions. One obvious point is that the spacecrafts are aiming for moving targets! The Discovery 6-1 box on gravitational slingshots is very interesting. Students may be surprised to hear that most spacecraft use gravity to accelerate them to high speeds, and that they generally use rockets only for maneuvering.

Also have students consider what happens to the spacecraft after their missions are complete. The *Galileo* probe was directed into the planet Jupiter at the end of its lifetime. However, both *Voyager* spacecraft wandered out of our solar system. The book *Murmurs of Earth: The Voyager Interstellar Record*, by Carl Sagan, details the record of pictures and sounds constructed to send along with the craft should it ever be found by extraterrestrials. The idea of other intelligent beings possibly finding a spacecraft from Earth is rife with possibilities. Impress upon your students that the process of deciding what to include in the record is fascinating by itself. If you have time, divide students into small groups and charge each team with deciding on a list of pictures and sounds they would choose to represent Earth. You could also assign this as a group project to be completed outside of class.

Section 6.5

The main categories of "loose material" in the solar system include asteroids, meteoroids, comets, and the newest category, Trans-Neptunian objects. Spend some time comparing and contrasting these different types of objects. Calculate the size of a typical asteroid to the same scale as you used in a previous scale model.

DEMO – A very common description of asteroids is that they look like potatoes. Bring in a couple of potatoes to use as models. Using a typical asteroid size, calculate the scale of the model. Students often believe that the asteroid belt is very crowded with little room between neighboring asteroids. This is largely due to science fiction movies that try to have exciting chases through crowded asteroid fields. Hand one of the potatoes to a student and calculate how far away she needs to stand from you, using the same scale you used for the size of the asteroid, to represent a typical distance between asteroids. Students will probably guess that both potatoes should be in the classroom, when in fact they should be perhaps 1000 km apart! (For calculations, see Chapter 14 of this manual.) Reassure students that we have sent many space probes through the asteroid belt, with no mishaps yet!

Be sure to distinguish among the terms meteor, meteorite, and meteoroid. Ask your students if any have ever watched a meteor shower, and encourage them to try to view one—given the right conditions, they can be spectacular! (See Table 14.1 for a list of major meteor showers.) You can make a model of a comet by freezing a mixture of water, fine dirt, and soot (details in Chapter 14 of this manual).

Sections 6.6 and 6.7

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. The text presents one way to present these characteristics. I give my students the following list:

1. The orbits of the planets and most of the planetary satellites all lie in roughly the same plane -- the plane of the ecliptic.

2. Nearly all the planets and satellites orbit and rotate in the prograde direction -- counterclockwise as viewed from the north.
3. Most planets and satellites have axis tilts less than 30 degrees.
4. Most planets and satellites have nearly circular orbits.
5. The terrestrial planets are made of high-density rock; the outer planets are made primarily of low-density gas, and their satellites get icier and icier the further out you go.
6. The outer planets are large in both mass and radius; the inner planets are much smaller.
7. The Jovian planets have large ring systems and many satellites, while the terrestrial planets have no rings and very few satellites.
8. The Jovian planets rotate more rapidly than the terrestrial planets.
9. The Sun has a slow rotation period -- 25 days. This means that although the Sun has most of the mass in the solar system, the planets have most of the angular momentum.

Whatever list of characteristics you present to the students, you should constantly reference it as you explain the formation of the solar system. Use it as a framework to build your narrative around, and for the students to guide their studying.

Students are often confused by the actual sequence of steps in the formation of the solar system, as well as some of the new terminology. You may find it 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. An interstellar gas and dust cloud, about 1 light-year in diameter, starts to gravitationally collapse.

2. The solar nebula, now about 100 A.U. in diameter, develops the shape of a rotating disk.

3. Dust particles form condensation nuclei through collisions. Particles grow rapidly in size.

4. Planetesimals acquire sufficient mass to attract other objects gravitationally; the largest bodies start to dominate and grow rapidly.

5. 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. Over about one billion years the material left over from the solar system formation is cleared. This is the period of major bombardments for the inner planets, and for the moons of the outer planets. Also, icy planetesimals are cleared out of the outer solar system to form the Oort cloud and the Kuiper belt.

Students may have difficulty understanding why dust is so important to the process of condensation and accretion. To help them out, ask them why their cars actually get *dirty* when it rains. Dust is every bit as important to the formation of raindrops in the upper atmosphere as it is to the formation of "lumps" in the solar nebula.

DEMO – A classic demonstration of the principle of conservation of angular momentum can be done with any spinning chair. Most office chairs have a small enough amount of friction to suffice, so no special stool is required. Get two weights of at least 1 kg – the heavier the better. Start spinning with the weights held out at arms length. After a short spin, draw your arms in. You can solicit a student volunteer or two as well. If any of your students are dancers, ask them to demonstrate a spin in which the arms start far from the body and end up close. Students can try to think of other examples of the conservation of angular momentum as well.

The slow rotation of the Sun is a real challenge in trying to explain the origin of the solar system. Some simple computations can illustrate the problem. Angular momentum, L, can be calculated for a point mass, m (such as a planet), moving in a circle of radius r and velocity v with the formula $L = mvr$. For a spinning solid body with a 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, and m is its mass. Assuming the Sun rotates as a solid body (it doesn't, but the problem requires complicated mathematics 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 the Sun's spin angular momentum is $L = 1.1\times10^{42}\ \text{kg m}^2/\text{sec}$. For comparison, we can calculate the orbital angular momentum for Jupiter using $L = mvr$. 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 times 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. The Sun transferred a great deal of its angular momentum to the planets in its early days.

Throughout the semester, I emphasize to students that when a small celestial object is “grabbed” by the gravitational force of a larger object, one of three things can happen:

- The smaller object strikes the larger, and merges with it
- The smaller object goes into orbit
- The smaller object misses, and flies off into space, typically at a greater speed.

In each of these three instances, there is the potential to change the larger body dramatically. An impact can change an object’s spin, or even its axis tilt. Capture can give the larger object a satellite. Even a near miss from a small object can steal some orbital momentum from a large planet, and change its orbit, as you see in Figure 6.19. Ask the students to recall some unusual aspects of our solar system, and see if they can be explained by catastrophes. In Chapter 8, they will see that the result of one such catastrophe is very close – our Moon!

The end of section 6.7 presents the idea that water and other light materials returned to the inner solar system via comet impacts. I ask my students to calculate how many comets it would take to “fill up” the Earth’s oceans. If you assume a mass of the oceans of 10^{24} grams, and the water mass of a typical comet as 10^{14} grams, you get 10 billion comets!

Suggested Readings

Websites

There is probably more information that anyone would need about the major bodies of the Solar System at the Nice Planets website: http://nineplanets.org/

The Exploratorium website (http://www.exploratorium.edu/ronh/solar_system/) has a handy calculator for setting up a solar system model. You'll want the students to do the work for themselves, but it's handy to see just how much space you'll need!

A list of the current space missions in which NASA is participating can be found at the NASA website: http://www.nasa.gov/missions/current/

The Voyage site (http://voyagesolarsystem.org/) describes a scale model of the solar system in Washington DC, and gives advice for constructing one in your town.

Magazine Articles

(Note: For articles about a specific planet, see the chapter about that planet.)

Aguirre, E. and Lyster, T. "Walking tours of the solar system: three scale models of the Solar System." *Sky & Telescope* (Mar 1998). p. 80. Describes three exhibits which demonstrate the solar system to scale.

Basri, G. "What is a Planet?" *Mercury* (November/December 2003). p. 27. Article explores the definition of "Planet." Many nice diagrams, charts and images comparing various planet-like objects.

Binzel, R. "A New Century for Asteroids." *Sky & Telescope* (July 2001). p. 44. A review of what we now know about asteroids since Ceres was discovered 200 years ago.

Canup, R. "Origin of Terrestrial Planets and the Earth-Moon System." *Physics Today* (April 2004). p. 56. Technical description of the process of planetesimal acceretion.

Frank, A. "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 the idea that the solar system may be a chaotic system.

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.

Hartmann, W. "The great solar system revision." *Astronomy* (Aug 1998). p. 40. Summarizes the highlights of 25 years of planetary exploration.

Johnson, T. "The Galileo mission to Jupiter and its moons." *Scientific American* (Feb 2000). p. 40. Summarizes the highlights of the first five years of the Galileo Mission.

Laughlin, G.. "Hanging in the balance." *Sky and Telescope* (April 2010). p. 26. Describes efforts to determine how stable the orbits of the planets will be in millennia to come.

LoPresto, M. and Murrell, S. “A comparative planetology activity.” *The Physics Teacher.* (May 2010). p. 296. Details the use of a student discussion activity involving the properties of the planets and how they can be grouped according to those properties.

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

Malhotra, R. “Migrating Planets: Did the solar system always look the way it does now?” *Scientific American* (September 1999).

McIntosh, G. “Wind in the Solar System” *Physics Teacher* 48:2 (2010) p. 94. Comparative planetology with atmospheric dynamics.

Newbury, P. “Exploring the Solar System with a Human Orrery” *Physics Teacher* 48:9 (2010) p. 573. Description of an activity to get students moving to demonstrate the motions of the planets.

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

Reddy, F. “Calling all space probes.” *Astronomy* (October 2009). A summary of recent spacecraft explorations of the solar system

Ryan, J. “SkyWise: distances.” *Sky & Telescope* (Dec 2000). p. 116. A cartoon strip which illustrates relative distances in the solar system.

Slater, T. “Inner Solar System Concepts.” *The Physics Teacher* (May 2000). p. 264. Discusses teaching comparative planetology on a conceptual level.

Stern, S. “Journey to the Farthest Planet.” *Scientific American* (Fall 2003). Special Issue.

Stevenson, D. “Planetary Diversity.” *Physics Today* (April 2004). P. 43. Review of the major questions and issues in solar system astronomy.

Thommes, E.; Duncan, M.; Levison, H. “The formation of Uranus and Neptune in the Jupiter-Saturn region of the Solar System.” *Nature* 402, 635 - 638 (09 Dec 1999).

Yeomans, D. “Small bodies of the Solar System.” *Nature* 404, 829 - 832 (20 Apr 2000). News and Views Feature.