Chapter 11: Jupiter

Giant of the Solar System

Outline

11.1 Orbital and Physical Properties
11.2 The Atmosphere of Jupiter
11.3 Internal Structure
11.4 Jupiter's Magnetosphere
11.5 The Moons of Jupiter
11.6 Jupiter's Ring

Summary

There are really only two dominant objects in the Solar System. The first is (obviously) the Sun and the second is Jupiter. Jupiter contains more than twice the combined mass of all other objects in the Solar System except the Sun. Due to its high mass and, therefore, far-reaching gravitational influence, Jupiter has played a major role in the formation and evolution of the Solar System. It moves comets into new orbits and to some degree keeps the asteroids in place. The Oort Cloud may owe its existence to Jupiter. Jupiter's system of moons, 61 and counting, is comparable to a solar system of its own. When first formed it must have been a major source of heat for those moons. Jupiter's tidal pull has kept one of its moons, Io, molten for billions of years and has likely provided Europa with a deep, liquid ocean of water. It has cloud swirls that are bigger than the entire Earth. There is little about Jupiter that can be understated.

When beginning this chapter, quickly review with students Tables 6.1 and 6.2 as well as Figure 6.7. These can be used as a springboard from the terrestrials to the jovians. Jupiter, as the jovian prototype, can be compared to the other giants as you progress through this and the next two chapters. When looking for drama in the solar system, look no further than Jupiter. It is large and exotic and nothing like the terrestrial planets. This sense of exaggeration in Jupiter is somehow appealing and it is this approach that makes Jupiter memorable to students.

Major Concepts

- Orbital and Physics Properties
  - Largest planet
  - Most massive planet
  - Fastest rotation rate
- Atmosphere and Interior
  - Temperature
  - Circulation
  - Great Red Spot
- Magnetosphere
- Moons
  - Individuality of the Galilean moons
- Ring System

Teaching Suggestions and Demonstrations

If Jupiter is visible during the night while you are teaching this course, try to arrange observing sessions for your students. Even with a small telescope, Jupiter's bands and the Great Red Spot are visible but perhaps the most exciting feature (or features) is the visible presence of the four Galilean satellites. The text shows many beautiful, high-resolution images of Jupiter, but, by observing through a small telescope, the students get a flavor for the earliest observations of Jupiter, which occurred when Galileo first aimed his telescope at the bright object hanging in the sky above Venice. If you do not have access to a telescope, you can show a transparency or slide of Jupiter as it would have looked through Galileo's telescope. The four **Galilean satellites** are clearly visible as a neatly arranged line of tiny points or "stars," as he referred to them. Additionally, you can point out the location of Jupiter in the sky and have students follow its motions through the background stars over the course of the semester. Encourage students to view Jupiter through binoculars as well. Although little or no detail will be visible, they will be able to see that Jupiter is a disk (unlike stars, which appear as points). The four Galilean moons are visible through most moderate binoculars.

Section 11.1

➲ **DEMO** Use the scale models from Chapter 6 for Jupiter, the four Galilean moons, and the Earth and Moon for comparison. Set up a scale model of the jovian system and compare it to the Earth-Moon system. If a scale of one Earth diameter = 5 cm has been used, place Io, Europa, Ganymede, and Callisto at 1.68 m, 2.69 m, 4.27 m, and 7.42 m from the center of Jupiter. Jupiter's ring is only 48 cm from the center and about 1.3 cm wide. A ring of paper can be cut out to represent the ring. Note that the thickness of the ring, on this scale, is 3 times thinner than the paper. The Moon, for comparison, is 1.5 m from Earth and only 1.3 cm in diameter.

One question that comes up every semester, certainly by this chapter if not before, is "How can we weigh a planet?" Obviously we cannot place planets on a balance or scale, but we can defer to Sir Newton. It is interesting to note, from the above model, that Io is just a little farther away from Jupiter than is the Moon from Earth. But the orbital period of Io is 1.769 days compared to 27.322 days for the Moon. Ask the students why a moon such as Io, which appears to be similar in size to the Moon and has a similar size orbit, should have a faster orbital period. The answer is that it is orbiting a much more massive planet. To calculate Jupiter's mass (in Earth masses), all that is needed is the orbital distance and period of one of its moons and Newton's form of Kepler's third law.

$$P^2 = \frac{a^3}{M}$$

Inserting appropriate values for the Moon's orbit and Io's orbit gives

$$\left(\frac{27.322}{1.769}\right)^2 = \left(\frac{384,000}{422,000}\right)^3 \times \frac{M}{1}$$

M = 317 Earth masses

The answer is very close to 318, the actual value. The mass, M, is actually the total mass of Jupiter and Io. If Io's mass is small relative to Jupiter, then M is the mass of Jupiter alone. How do we know that Io's mass is actually insignificant compared to Jupiter's mass? It is always good to check our assumptions! Notice from the next chapter that Io has a diameter about 3.5 times smaller than the Earth. This gives a volume about 40 times smaller (volume goes by the cube of the diameter or radius). So even if Io has the same density as the Earth, its mass would only be 0.02 Earth masses, i.e., quite insignificant compared to Jupiter's mass.

Note that numerical examples are often avoided in mostly descriptive science courses, but the previous example can show students the power of mathematics combined with observation and the physical principles discussed in Chapter 2. Kepler's third law is the physical principle, the period and size of Io's orbit are the needed observations (along with the same for the Moon's orbit). With very little effort we can determine Jupiter's mass. This method can also be applied to any planet with at least one small moon. It is much more important for students to understand how the mass of a distant planet can be determined than to memorize all their masses. It is all part of the *process* of science and scientific investigation. When we discuss in later chapters the masses of stars and entire galaxies, this same method will be available as an easily-applied tool.

Keeping in mind the concept of comparative planetology, a discussion of **differential rotation** is encouraged. The rotational characteristics of Jupiter are interesting and different from that of the terrestrials. Jupiter undergoes differential rotation, meaning the equatorial regions appear to rotate faster than the upper northern and lower southern latitudes. How can the equatorial regions of Jupiter rotate faster than the entire planet? If winds are blowing clouds in the same direction as the rotation, then the rotation will appear faster than it actually is. ➲ **DEMO** This may be easily demonstrated using any large globe or ball. Mark a point on the equator and another point to which it will move due to wind during one rotation. Rotate the globe once and show that the second mark shows up "early" and gives the mistaken impression of a faster rotation rate. Since the equatorial radius is 71,400 km and the circumference is 2π times the radius, in 9^h50^m the speed is 45,600 km/hr. For 9^h56^m, which is the true rotational period, the speed is 45,200 km/hr. The difference in these two speeds, about 400 km/hr is about the speed of the winds, blowing to the east, given later in the chapter.

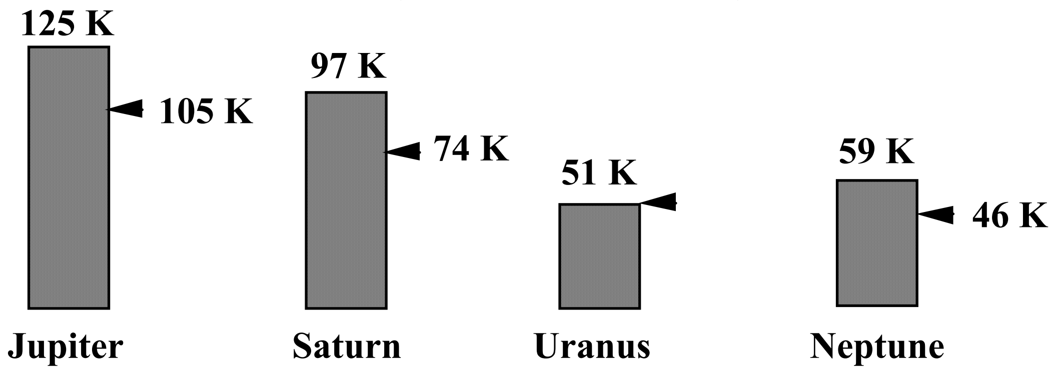
Section 11.2

Sections 11.2 and 11.3 are often difficult to distinguish. 11.2 discusses **Jupiter's atmosphere** while section 11.3 discusses the **interior** of the gas giant. They are difficult to separate because there is no physical interface marking the boundary. Discussions of the atmosphere tend to focus on the upper layers of Jupiter, those visible from space. These features include the motion of the zones and belts, the zonal flow and the Great Red Spot. Spend some time looking in detail at Jupiter's beautifully colored belts, zones, and spots. The Great Red Spot is about two Earth diameters in length. Cut out an oval to scale and paste it on the sphere representing Jupiter; this can be compared to the Earth model to convince students of the relative sizes. The longevity of the Great Red Spot on Jupiter also surprises students.

Concerning the motion of the upper atmosphere, it is not uncommon to use terms ranging from "turbulent" to "Chaos." The motion of each feature affects the motions of its neighbors. This seems to be true everywhere around Jupiter, but is best exemplified by the zonal flows above and below the **Great Red Spot**, which are in opposite directions. Demonstrate how this can produce the whirlpool motion seen in the spot. ➲ **DEMO** Take a round balloon or ball between your two hands, held horizontally. (Choose a red balloon for emphasis.) Move one hand to the left, the other to the right. The balloon will turn in place, moving neither left nor right. This helps explain the fact that the Great Red Spot rotates around Jupiter at the same rate as its interior; its true rotation rate. The action of the winds to its north and south offset each other, producing only the whirlpool of the spot. It would be nearly impossible to hold this discussion without showing a video clip of the circulation associated with the region around the Red Spot. This video clip is contained in the "Voyager Odyssey" video listed in the materials section below.

Concerning the **temperature** profile for Jupiter, refer to Figure 11.6. Also, set the now-familiar thermometer at 125 K for a low and roughly 300 K for a high. Since the high depends strictly on the depth, this is given approximately for the lowest cloud layer, about 80-100 km in depth. 300 K is the temperature of a warm day on Earth. For the most part, Jupiter is a very warm (hot!) planet. This is not due to warming from solar radiation but due to internal sources of heat.

For the outer planets, solar heating is often less important in determining the planet's temperature than other sources of heating. By examining the temperature of their cloud tops, we realize that 3 out of 4 of them emit more energy than they receive from the Sun. The following figure demonstrates this by showing their measured temperatures as a bar graph and an arrow pointing to the temperature they would have if it were due only to the Sun's energy they receive. For convenience and comparison, the graph is shown here for all 4 jovian planets.



Section 11.3

For the terrestrial planets, a meter stick model of the atmosphere has been used. Here, a meter stick model of the entire planet is helpful. Jupiter will scale at about 714 km/cm. In the following example, zero centimeters marks the center of Jupiter.

99.9 - 100 cm	Cloud layers in the upper atmosphere
93 - 100 cm	Gaseous atmosphere
71 - 93 cm	Hydrogen is liquid
14 - 71 cm	Hydrogen is liquid metal
0 - 14 cm	Rocky, high density planetary core

What we see of Jupiter is really the very thin outer layer of its atmosphere and not representative of most of the planet. This layer makes up the outer 1/1000 of the planet. However, the atmosphere of the Earth and the region within which life exists on Earth also makes up about the same fraction. We are often the most interested in the smallest parts of a planet!

Students often find it difficult to understand the fact that Jupiter consists mostly of hydrogen in its liquid metallic form. A **liquid metal** is, in itself, an unfamiliar concept. Bring some mercury to class to show students. Remember that mercury is a hazardous material, so handle it appropriately. Discuss the differences between the gaseous, liquid and solid phases of matter. Most students think of these different phases as a function of temperature only. Stress to them that it is rather a function of the "mobility" of the individual molecules. Temperature can affect the mobility of a group of molecules, but so can pressure. Recall to them the core of Earth. It is the enormous pressure at the center of the Earth that restricts the mobility of the iron to such a degree that it is effectively bound in a solid state. Jupiter is no different in this respect. As the depth of the atmosphere increases, so does the pressure and as the pressure increases the mobility of the molecules decreases. As the mobility decreases the phases move from gas to liquid and finally to solid at the center of the planet.

Students are often intrigued by the notion that there is no "surface" on which to stand. An astronaut, if he or she could survive the plummet, would not perceive any interfaces, only a continual increase in the density and a continual change from gas through liquid to solid.

Section 11.4

Jupiter's magnetic field is strikingly large compared to all other planets in the solar system. As discussed previously, a rapid rotation and metallic interior are necessary for a strong magnetic field. Review, again, Table 6.1 showing the rotational period of each planet. Jupiter has the highest rotation rate of any planet and it also has the largest quantity of liquid metal. It is no surprise, then, that Jupiter has the strongest magnetic field as well. Show Figure 11.13 and mention that the magnetosphere extends well beyond the right side of the figure to beyond the orbit of Saturn more than 4 astronomical units away!

Section 11.5

Often, students believe that there is not much to the solar system beyond the nine planets, the Sun, and perhaps asteroids. In fact, there are over 100 moons in the solar system and guess which planet takes the lion's share. Students are more likely to remember the moons as individual bodies if they can relate special characteristics to them. Each of the four large moons of Jupiter has at least one unique property that makes it particularly interesting or memorable. **Io** has active volcanoes, **Europa** has an ocean of liquid water, and **Ganymede** is the largest moon in the solar system. **Callisto**, the fourth Galilean moon, has a large pattern of concentric cracks on its surface.

These four moons are relatively close to Jupiter and so Jupiter, seen from the surfaces of these moons, would appear large. The following are the angular sizes of Jupiter from the distance of each moon.

Io	20°
Europa	12°
Ganymede	8°
Callisto	4°

Jupiter, from Io, would appear about as large as your fist when your arm is fully extended. Even from Callisto, Jupiter would be 8 times larger than the full moon. (From Metis, the closest of the Jovian moons, Jupiter would be 68° across, reaching across over one third of the sky. Quite a view!)

Io's volcanoes are spewing material at velocities of 1-2 km/s. The altitude to which the material should rise can easily be calculated. From simple motion laws in physics and Newton's law of gravity we know

$$v^2 = v_0^{\,2} + 2gs$$

where g is the acceleration due to gravity on Io and is calculated from its mass and size

$$g = \frac{GM}{r^2}$$

and *s* is the distance to which material with an initial velocity of v_0 will rise. The final velocity, *v*, is zero. For an initial velocity of 1 km/s, s = 280 km and for an initial velocity of 2 km/s, s = 1100 km. Note that the escape velocity from Io can also be easily calculated and is about 2.5 km/s. If some of the material ejected from a volcano is very hot, and much of it is, when raised to a high elevation, some of it can escape. Due to temperature, some of the molecular velocities may exceed escape velocity.

Io's orange color makes it a rather unique object in the solar system. The color is attributed to sulfur and sulfur compounds. Sulfur usually appears yellow or pale yellow. ➲ **DEMO** A very impressive demonstration can be easily done to show how sulfur can appear orange. In a test tube or beaker place some powered sulfur. You will definitely want to perform this demonstration under a hood unless you want visitors from all neighboring classes popping their heads into you class wondering where the horrible odor is coming from. Heat the sulfur slowly over a Bunsen burner or on a hot plate. Be careful not to ignite it! Since its melting point is about 113°C it can safely be heated in boiling water and then "finished" over the flame. When melted, the sulfur will turn an orange or orange/brown color. The color compares nicely to the usual pictures of Io.

When discussing the moons of Jupiter, you may get several questions as to the origin of the names. The names of most of the moons in the solar system refer to mythological characters. Often, a connection exists between the names of the moon and its parent planet. For instance, Jupiter is the ruler of the gods, and Ganymede is a cupbearer to the gods. Although it might be easy to get lost exploring the tangent of moon names, the students often appreciate it and it can serve as a break from the technical details of the discussion at hand. (See Resource Information for a good Web site, or do your own Web search.)

Section 11.6

Which of the planets has rings? "Saturn" will most likely be the response. Be sure to mention that the presence of **rings** is an attribute shared by all four of the jovian planets. As is appropriate for each of the planets discussed, which have been visited by manmade probes, provide a brief overview of the ***Voyager*** program. *Voyager* was a probe that visited Jupiter in 1979 and provided an abundance of information concerning the planet and its system. Many discoveries were made by the Voyager team including the presence of a ring as shown in Figure 11.26. Point out that this ring would not have been detected except for the ability to go beyond the planet and look toward the inner solar system. The ring is so faint that it required backlighting by the Sun in order to be seen.

Student Writing Questions

1. You are in a spacecraft descending through the planet Jupiter. First you move slowly through the atmosphere and then more quickly through the interior. The spacecraft, being indestructible, protects you completely but allows you to observe the environment. Describe what you see and feel.

2. Imagine you have discovered life in the atmosphere of Jupiter. Describe what it is like and how it has adapted to its environment. Please use your imagination but remember, the environment must be consistent with what we know about Jupiter.

3. Imagine that life does exist below the ice crust of Europa, in its warm, deep ocean. What might this environment be like? How might life differ from what we know of it here on Earth? If intelligent life evolved in this environment, would they know of the "outside," the universe that surrounds them?

4. What would it be like to live in a research station on the surface of Io, on the side facing Jupiter? What would make this exciting, fun, dangerous, interesting? What would you want to study scientifically while there?

5. Look far into the future when humans might be doing interplanetary travel more routinely. Rocket engines use hydrogen fusion and what better source, almost unlimited in quantity, than Jupiter. But Jupiter is a massive planet with very strong gravity. Describe how a refueling mission might arrive at Jupiter to "fill 'er up."

Answers to End of Chapter Exercises

Review and Discussion

1. The two most massive bodies in the solar system are the Sun and Jupiter. Although Jupiter is 1000 times less massive than the Sun, it contains more mass than the rest of the solar system objects combined. In terms of the gravitational force on other bodies, these two objects dominate.

2. The equatorial regions of Jupiter appear to rotate faster than the polar regions. This is known as differential rotation. It is the first indication that Jupiter is not solid. The faster motion of the atmosphere at the equator gives rise to a wind moving at about 300 km/h relative to the overall rotation of Jupiter's interior.

3. Because Jupiter is observed to be flattened, i.e., smaller through the poles than through the equator, the interior of the planet can be modeled. From the observed rotation and total mass, models show that Jupiter must have a high density core.

4. Most of the data presented in these chapters on the outer planets came from the *Voyagers*. They made it possible to obtain accurate measurements of the amount of helium in Jupiter's atmosphere. They showed the Great Red Spot to be characterized by swirling circulation much like a whirlpool or a terrestrial hurricane. The *Voyagers* made it possible for us to recognize the full extent of Jupiter's magnetosphere. They showed that the plasma torus surrounding Jupiter is created as the planet's magnetic field sweeps past the Galilean moon Io. They discovered small moons orbiting closer to Jupiter than Io. They sent back some remarkably detailed photographs, allowing us to see fine detail on the surface of the Galilean moons and revealing that these moons are very different not only from Earth's moon but also from each other. They made possible the discovery of active volcanoes on Io. They found that Jupiter is surrounded by a ring.

5. The probe sent into Jupiter by *Galileo* found the atmosphere to be much windier to a greater depth, due to the interior heat of the planet. It was also hotter and drier than expected but this was, in part, due to the clear area in the clouds where it entered the atmosphere. No complex organic molecules were discovered except ethane, which is simple, and phosphine, which is not organic but may give rise to the colors in the clouds.

6. The Great Red Spot is a reddish colored spot in Jupiter's atmosphere that has been seen for over 300 years. It is a region of swirling, circulating winds like a whirlpool or a terrestrial

hurricane. It is about twice the Earth's diameter in length. The source of its energy appears to come from the zonal atmospheric flows to its north and south. However, there are still some uncertainties as to how it continues to be maintained.

7. The colors indicate clouds with various compositions. The highest clouds are white and composed of ammonia ice. The yellows, reds, and browns are found in lower clouds that contain ammonium hydrosulfide ice. It is possible that sulfur, phosphorus, or their compounds contribute to these clouds. Even organic compounds are a possibility. Below these clouds are bluish clouds of water ice.

8. Jupiter has retained most or all of its original atmosphere for two reasons. It is a massive planet, and, as such, has sufficiently strong gravity to hold an atmosphere of hydrogen and helium. Second, it is located in the outer part of the solar system where temperatures are low. The atoms and molecules of gas cannot attain a high enough velocity to escape the planet's gravity.

9. When Jupiter formed, gravity compressed its gases, causing the temperature to rise. The atmosphere has allowed this energy to slowly leak out of Jupiter, causing it to continue to emit more energy than it receives from the Sun.

10. The cloud layers of Jupiter are relatively thin, a few hundred kilometers thick at most. Below this layer, the atmosphere of hydrogen and helium becomes denser and denser with depth. At a few thousand kilometers hydrogen is compressed into a liquid. At about 20,000 kilometers the hydrogen changes to a liquid metallic hydrogen. Finally, there is a small, dense core made of rocky material similar to Earth. Although a little larger than Earth, it has a mass of about 15 Earth masses.

    Our understanding of the interior of Jupiter, and the other jovian planets, comes from a combination of theoretical modeling and observation of the bulk properties. The model must be consistent with the mass, radius, composition, rotation, temperature, flattening, and so on, observed for Jupiter.

11. Magnetic fields, in general, are produced by rapid rotation and some sort of conducting material in the interior of the object. In the case of Jupiter, it has a rotation rate of just under 10 hours and a larger amount of liquid metallic hydrogen in its interior that apparently produce its magnetic field.

12. The Galilean moons appear like a small solar system around Jupiter. They have relatively circular orbits in the equatorial plane, they all orbit in the same direction, their densities decrease with increasing distance from Jupiter, and they are all significantly smaller than Jupiter. These moons also have well-defined surfaces and are at least composed of some rocky material. Jupiter and its Galilean moons can therefore be likened to the Sun and the terrestrial planets.

13. The densities vary from high to low, corresponding to the position of the moons. Io is high with a density of 3.6 g/cm^3. The other densities are 3.0, 1.9, and 1.9. The decline in the densities appears to be related to an increase in the amount of water that makes up each moon.

14. Io's interior must be very hot in order to support the volcanic activity observed. The source of the energy needed to keep it hot is the gravitational pull and tug from Jupiter and Europa. It is not allowed to have a simple synchronous rotation, and with a tidal bulge always

pointing towards Jupiter, Europa keeps Io in a slightly noncircular orbit. The twisting of Io inside of its tidal bulge keeps it heated.

15. The evidence comes from many separate observations: fractured ice crust suggesting iceberg-like motions, cracks filled in (apparently) from below with water, soft appearance of impact craters, regions where water appears to have erupted and flowed before freezing, and a magnetic field suggestive of a liquid, saline ocean of water below the icy crust.

16. Ganymede has evidence of tectonic activity. In addition, it has a magnetic field and a possible layer of water under its crust. This is only possible if it was recently heated and still retaining some of that heat. But models suggest that at the rate Ganymede cools off, the heating event had to have been recent.

17. Io has no impact craters because its volcanism continually resurfaces it. Europa has very few impact craters; its icy surface is also subject to resurfacing. Ganymede and Callisto both show significant cratering, with Callisto showing the most. Again, this appears to be related to how frequently the surfaces are resurfaced.

18. Europa appears to be covered by an ocean of water that is frozen on top. If this is true, its ocean might be suitable for supporting life.

19. The consequences of discovering life on (in!) Europa are enormous. It would be the first evidence that life could arise independently of Earth. Its environment would suggest a greater diversity of environments for life to arise. Life there would mostly be independent of sunlight, proving life does not have to have sunlight to survive. Most of all, it would give us a chance to study the fundamental structure of life different from our own and to discover what factors we have in common; what factors can vary. It would be the greatest scientific discovery in all of history.

20. There is a lot of water among the moons of Jupiter and measurable amounts in Jupiter itself. The cooler temperatures of this part of the solar system inevitably made it possible for water to remain in solid form and participate in the formation of these many objects.

Conceptual Self-Test

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

19. A
20. C

Problems

1. The force of gravity is proportional to the mass and inversely proportional to the square of the radius. The force of gravity for Jupiter can easily be compared to the Earth's by noting how much larger and more massive it is than the Earth. Jupiter is 318 times more massive and 11.2 times larger than Earth.

$$317.9 / (11.21)^2 = 2.5$$

   Jupiter's gravity is 2.5 times that of the Earth's gravity, exactly what is given in the Jupiter Data box.

2. The distance to Jupiter will be 3.95 A.U. or 5.92×10^8 km. For Io, with an orbit of 422,000 km, the angular size of the orbital diameter will be 844,000 km = 5.92×10^8 km (θ / 3438'). θ = 4.9'. The other solutions are the same, using orbital diameters of 1,342,000, 2,140,000, and 3,760,000 km for Europa, Ganymede, and Callisto. The answers are 7.8', 12.4', and 21.8'.

3. The equatorial radius is 71,400 km and the circumference is 2π times the radius, which equals 449,000 km. The zonal flow has a speed of about 300 km/hr. Dividing this into the circumference gives 1500 h or 62 days. This is in contrast to the almost 10 h rotation period of the planet.

4. With a radius of 71,492 km, the circumference is $2\pi71{,}492$ = 449,200 km. The rotational period is 0.41 solar days = 35,424 s. Dividing this into the circumference gives 12.7 km/s.

   From *More Precisely 2–3,* orbital velocity is $V = \sqrt{GM/R}$. Putting in the numbers = $\sqrt{(6.7\times10^{-11} \times 1.9\times10^{27} / 7.15\times10^7)}$ = 4220 m/s = 4.2 km/s = 33% of rotational speed.

5. In *More Precisely 8–1*, the average molecular speed for hydrogen at Earth's surface is 2 km/s. Since speed is proportional to the square root of the temperature,

$$\frac{2}{\sqrt{300}} = \frac{\text{speed}}{\sqrt{124}}$$

$$\text{speed} = 1.29 \text{ km/s}$$

   Multiply the above speed by 6, which equals 7.71 km/s. This will be the escape velocity from Jupiter at some lower mass. Escape speed is proportional to the square root of the mass, if the radius does not change. Then:

$$\frac{60}{\sqrt{318}} = \frac{7.7}{\sqrt{\text{mass}}}$$

   mass = 5.2 Earth masses or 1.6% of it's actual mass.

6. The gravitational pull is proportional to the mass of the attracting body divided by the square of its distance. Set up the ratio of the Sun's pull to the enlarged Jupiter's pull. For Jupiter's mass, it is now 1/1000 solar mass but would be 80 times bigger if a star. That would make

its new mass 0.08 solar masses. It will be at a distance of closest approach or 5.2 - 1 = 4.2 A.U., compared to the Sun's 1 A.U.

$$F_{Sun} / F_{Jupiter} = (1/0.08) \times (4.2/1)^2$$

$$F_{Sun} / F_{Jupiter} = 220$$

Although the Sun would seem to still dominate us gravitationally, this number should be compared to the current value, using Jupiter's actual mass, of almost 18,000.

The tidal effect is similarly computed except that it changes with the cube of the distance. Therefore:

$$F_{Sun} / F_{Jupiter} = (1/0.08) \times (4.2/1)^3$$

$$F_{Sun} / F_{Jupiter} = 926$$

Again, the Sun seems to dominate but this is a big increase over the current ratio of over 74,000.

7. Using the information in Table 11-1, the Galilean moons have a total mass of 5.36 Moon masses or 4.0×10^{23} kg. Jupiter has a mass of 1.9×10^{27} kg, so the ratio is 4750; Jupiter is this many times more massive than the combined mass of its four major moons. For the Earth-Moon system, this ratio is 80. For a planet of its mass, the Earth has a rather large moon.

8. Use Kepler's third law in ratio form, comparing the unknown orbit to that of Io's orbit.

$$(10 / 42)^2 = (R / 6)^3$$

$$R = 2.3 \text{ radii} = 164{,}000 \text{ km}$$

9. Use the orbital radii from Table 11.1 to draw the scale model of the system. Using 1 cm = 1 Jupiter radius is a useful scale to try.

10. The general formula for comparing the tidal force on a moon to the moon's surface gravity is derived from the tidal force given in *More Precisely 7–3* and Newton's Law of Gravity. With R the radius of the moon and D, its distance from Jupiter, the result is:

$$2\frac{M_{Jup.}}{M_{Moon}}\left(\frac{R}{D}\right)^3$$

For Europa, this will be 0.001. For the Earth-Moon system it is 1.5×10^{-5}.

11. Use the same formula as in Problem 10. For Ganymede the result is 3.8×10^{-4}.

12. Use the same formula as in Problem 10. For Callisto the result is 7.4×10^{-5}.

13. $$1 / S = 1 /3.55 - 1 / 1.77$$

$$S = -3.53 \text{ days}$$

Jupiter's mass, in lunar masses, is 318 × 80 = 24,640. Io's and Europa's orbits around Jupiter are 5.91 and 9.40 planet radii. The closest they get is 3.49. Comparing Europa's gravitational pull to that of Jupiter on Io gives:

$$\frac{F_{Europa}}{F_{Jupiter}} = \frac{0.65}{24,640} \times \frac{5.91^2}{3.49^2}$$

$$\frac{F_{Europa}}{F_{Jupiter}} = 0.000076$$

Jupiter's pull is about 13,000 times stronger.

14. Using the formula for escape speed from Chapter 2 gives:

$$v_{escape} = \sqrt{\frac{2 \times 6.7 \times 10^{-11} \times 4.8 \times 10^{22}}{1.565 \times 10^6}}$$

$$v_{escape} = 2023 \text{ m/s or } 2.02 \text{ km/s}$$

The acceleration due to gravity on the surface will be $v_{escape} / 2R$ (can you see why) = 1.3 m/s^2.

15. The angular size of the Sun is the easiest to calculate. Since Jupiter is 5.2 A.U. from the Sun, the Sun will appear 5.2 times smaller than it does from Earth. The Sun is about one half degree in diameter from Earth or 30 arc minutes, so from Jupiter it will be 30 / 5.2 = 5.8 arc minutes.

To calculate the angular diameter of each of the Galilean moons as seen from the top of Jupiter's clouds, it is necessary to subtract one Jupiter radius, 71,400 km, from the distances to each moon, as given in Table 11-1. Thus, from cloud top to Io is 422,000 - 71,400 = 350,600 km.

For Io, angular diameter = 57.3° (3630 / 350600) = 0.59° = 35.6'.
For Europa, angular diameter = 0.30° = 18 arc minutes
For Ganymede, angular diameter = 0.30° = 18 arc minutes
For Callisto, angular diameter = 0.152° = 9.1 arc minutes

Since all four moons have angular sizes larger than the Sun's angular size, all of them can produce solar eclipses.

Resource Information

Student CD Media

Movies/Animations

Galileo Mission to Jupiter
The Gas Giants Part 2
Galileo Flyby of Io
Io Cutaway
Jupiter's Moon Europa

Jupiter's Moon Ganymede

Interactive Student Tutorials
None

Physlet Illustrations
None

Transparencies

T-95	Figure 11.3	Jupiter's Red Spot	p. 279
T-96	Figure 11.4	Jupiter's Convection	p. 280
T-97	Figure 11.6	Jupiter's Atmosphere	p. 282
T-98	Figure 11.10	Jupiter's Interior	p. 285
T-99	Figure 11.13	Jupiter's Magnetosphere	p. 287
T-100	Figure 11.16	Galilean Moons	p. 289
T-101	Figure 11.17	Galilean Moon Interiors	p. 289
T-102	Figure 11.18/19	Io	p. 292/293
T-103	Figure 11.26	Jupiter's Ring	p. 298

Materials

The Web site http://www.r-clarke.org.uk/planets/ contains a page for each planet that includes the mythology surrounding the names of the planet and of its moons.

The movie *Voyager Odysses*, released by Image Entertainment shows very nice animated images of the circulation of the upper atmosphere of Jupiter including the Great Red Spot.

Suggested Readings

Beatty, J. Kelly. "Galileo: an image gallery III." *Sky & Telescope* (July 1999). p. 40. Showcases images from the Galileo mission.

Burnham, Robert. "Into the maelstrom." *Astronomy* (Apr 1996). p. 42. Describes the results from Galileo's atmospheric probe.

Dobbins, Thomas; Sheehan, William. "Jupiter's deep mystery: South Equatorial Belt." *Sky & Telescope* (Dec 1999). p. 118. Describes observations of Jupiter's South Equatorial Belt.

"Galileo probes Jupiter's atmosphere." *Science* (May 10, 1996). p. 837. This issue contains a special section devoted to the Galileo mission results.

Hamilton, D. "Planetary Science: Jupiter's Moonopoly." *Nature* (15 May 2003). p. 235. Discusses recently discovered, small satellites of Jupiter.

Johnson, Torrence V. "The Galileo mission to Jupiter and its moons." *Scientific American* (Feb 2000). p. 40. Summarizes Galileo mission results about each of the Galilean moons and the Jupiter atmospheric probe.

Levy, D. "A Farewell to Galileo." *Mercury* (November/December 2003). p. 16. A short tribute to the Galileo Probe. Includes a direct image frame sequence of Comet Shoemaker-Levy 9 impacting Jupiter.

McAnally, John W. "A Jupiter observing guide." *Sky & Telescope* (Oct 2000). p. 124. Offers advice on observing the features on Jupiter.

McEwen, A. S.; Belton, M. J. S.; Breneman, H. H. "Galileo at Io: results from high-resolution imaging." *Science*, **288**, 1193-1198.

Pappalardo, Robert T.; Head, James W.; Greeley, Ronald. "The hidden ocean of Europa." *Scientific American* (Oct 1999). p. 54. A nice summary of the Galileo results on Europa.

Peach, D. "Jupiter at its Best." *Astronomy* (April 2004). p. 70. Good observers guide with some timeless tips on observing the giant.

Sanches-Lavega, A.; Perez-Hoyos, S.; Rojas, J., Hueso, R.; French, R. "A strong decrease in Saturn's equatorial jet at cloud level." *Nature* (05 June 2003). p. 623. A good demonstration of the state of research into weather patterns on Jupiter and Saturn.

Science (May 19 2000). p. 1193. Presents high resolution images of Io taken by the *Galileo* spacecraft in late 1999 and early 2000.

Seydel, C. "Into Thick Air." *Mercury* (January/February 2002.) p. 25. Excellent, detailed discussion of Jupiter through the eyes of the *Galileo* Probe. Many nice images.

Sheppard, S., Jewitt, D. "An abundant population of small irregular satellites around Jupiter." *Nature* (15 May 2003). p. 261. Discusses the capture theory of irregular satellites around Jupiter. Good information for comparison to moons around other planets such as Earth (Collision-Ejection) and Mars (capture).

Showman, Adam P.; Malhotra, Renu. "The Galilean satellites." *Science* (Oct 1, 1999). p. 77. Provides a detailed summary of our understanding of each of the Galilean moons.

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: