Chapter 8: The Moon and Mercury

Scorched and Battered Worlds

Outline

Summary

Although Mercury is a planet and the Moon is, well, a moon, they share many features in common. In comparing Mercury to the Moon, there is the first hint that large moons may have more in common with terrestrial planets than terrestrial planets have with jovian planets. Comparative planetology works for both planets and moons.

The Moon is one of the most common objects in the sky and yet this chapter points out the many mysteries it holds. It is one of the largest moons in the solar system, yet it orbits a terrestrial planet, which as a class of planets, have no other naturally occurring moons. (Mars's moons were captured.) Theories for the formation of the moon are outlined and compared in this chapter.

Encourage students to observe the Moon regularly, especially during their study of this chapter. In addition to noticing phases and locations, as discussed in Chapter 1, they can pick out large-scale features such as maria and highlands. Try to include information and/or video segments of the Apollo program while covering this section of the text as well. Viewing astronauts bounding across the lunar surface is not only fun to watch, but also emphasizes the lower surface gravity of the Moon. The video of astronaut David Scott dropping a hammer and feather together point out that the Moon has no atmosphere and that Galileo really was right about acceleration due to gravity!

Major Concepts

- Properties of the Moon and Mercury
  - Mass
  - Density
  - Orbits
  - Interior structure
- Rotation rates
  - Synchronous rotation
- Surface features
  - Craters
  - Maria on the Moon
  - Caloris Basin on Mercury
  - Water ice

- Formation and evolution

Teaching Suggestions and Demonstrations

Section 8.1

The Moon is nearly 30% the size of Earth and orbits at a distance of approximately 30 Earth diameters. ➲ **DEMO** If you did not already demonstrate this in Chapter 1, it is a simple matter to set-up a scale model of the Earth-Moon system. Using a typical 12-inch diameter globe of the Earth, the Moon can be represented by a standard softball. Start with the softball held next to the globe and let the students see the size comparison directly. Then, begin to move the softball away from the globe and have the students tell you to stop moving away once you have reached the scale orbital distance. They usually start telling you to stop when you are about 6 or 7 feet away. They are generally surprised when you keep walking until you have reached a distance of 30 feet. Remind the students that the Moon orbits the Earth in a slightly elliptical orbit, making the annular eclipse possible. Mercury's orbit about the Sun, on the other hand, is the second most eccentric behind Pluto.

Since Mercury is so close to the Sun, it is only visible close to sunrise or sunset, depending on its position in its orbit. ➲ **DEMO** As you mention that fact in class and if you have an overhead projector handy, you can stress the difficulty in viewing Mercury by aiming the overhead projector directly at the class while holding a BB or marble near the bright light.

Section 8.2

Regarding the apparent brightness of the Moon and Mercury, discuss examples of objects with differing albedo. We often think an object is reflecting a lot of light when in fact it is not. Water ice, depending on the form it takes, has an albedo from 0.5 to about 0.9 (or 50% - 90%). An ice cube does not look as bright as fresh snow. Some objects reflect little light, although enough to be seen. Carbon black or graphite may reflect on about 1%. The Moon, with an albedo of only 0.07 may be thought of as being quite dark, in fact nearly black. Yet it appears bright in the sky. Why is that? It is seen in contrast with the sky, which is quite dark, and so the Moon appears relatively bright. Mercury, with an albedo of 0.106, is actually not as dark as the surface of the Moon.

A planet may be thought of as composed of X% high density material and Y% low density material. The Earth's interior is under enormous pressures, producing high densities. Mercury, being much less massive, has significantly lower pressures in its interior. But the X and Y percentages must be about the same for Earth and Mercury because the mean densities of both are very similar. Thus, the composition of the high density material in Mercury must be a substance that has a high density without necessarily being under high pressures. Iron and nickel are the most probable substances.

The surface temperature of the Moon alternates between about 400 K (130ºC) and 50º to 100 K - 200ºC). Although we think of the Moon as going through these extremes during its lengthy day, challenge your students to think of places where the temperature remains at one or both of these extremes. At the lunar poles it is possible for there to be little variation in temperature. Thus, it is not surprising that water ice has been discovered at the south lunar pole. There is no location that stays hot all the time. In comparison, Mercury's high and low are 675 K and 100 K respectively. Note that the low is about the same as for the Moon and the reasons for it are the same; long night, no atmosphere, rocky surface. Of course, the high temperature is much higher than that of the Moon due to Mercury's proximity to the Sun.

Stress that even though Mercury is the closest to the Sun, it does not hold distinction as having the hottest average surface temperature. Mercury gets much colder than expected, because its solar day is so long and it has no atmosphere to hold in the heat. In effect the atmosphere acts as a blanket. The thicker the blanket, the more efficiently it holds in the heat at night. For all practical purposes, Mercury has no atmosphere nor does the Moon. However, there are trace gases present primarily from outgassing, but in both cases, there is not enough gravity to "hold on" to any atmosphere. Mercury in particular has even less of a chance of maintaining an appreciable atmosphere due to its proximity to the Sun, where any candidate atmospheric elements are easily given ample kinetic energy to achieve escape speeds.

Section 8.3

With a resolution of 1 arc second, features as small as about 2 km can be seen on the Moon from Earth. Under the best of conditions, 1 km sized objects can be seen (about the size of the Barringer Meteorite Crater in northern Arizona).

Use a large projected picture of the Moon and a meter stick to measure the diameters of various maria and craters. Measure the diameter of the Moon and determine the sizes of the maria and craters by scaling their sizes to the diameter. Use 3500 km (or 3476 km) for the diameter of the Moon. Note the number of craters larger than 100 km and larger than 10 km. Show that there are significantly more smaller craters than larger craters.

Relate the sizes of the meteoroids to the sizes and depths of the craters. An impact velocity of 10 km/s, given in the example in that section, may actually be on the low side. (For comparison, note that a rifle bullet typically has a velocity of 1 km/s; 10 times slower than the meteoroid in this example. Cars travel no faster than 0.03 km/s on the freeway; 10 km/s is not so slow on the human scale!) Velocities of 50 or 60 km/s are quite possible in head-on collisions. The Earth (or Moon) moving in its orbit at 30 km/s around the Sun might be struck by an object head-on having a similar velocity. The energy released by any collisions depends on the square of the velocity; at 50 km/s, 25 times as much energy is released as in a 10 km/s collision. That is equivalent to 250 kg of TNT for a 1 kg meteoroid.

Alternate pictures from the far side and the near side of the Moon. Use these to contrast the differences, particularly in terms of the apparent lack of maria on the far side (due to the thicker crust). Relate this directly to the synchronous orbit and the way in which the Earth "protects" the near side of the Moon from meteorite impacts. Since we know the maria were formed when the Moon was relatively young, ask the students whether we can tell how long the Moon has been in synchronous orbit. The synchronous orbit must have been established when the Moon was young because otherwise the maria we see on the near side would have been exposed to more meteorite impacts.

Section 8.4

Students often do not know that the same side of the Moon faces the Earth. Show pictures of the Moon at various phases and indicate examples of features that are constantly in view. With this concept established, ask whether this means the Moon rotates, and if so, at what rate. A very common response is that the Moon does not rotate. ➲ **DEMO** Change the students' frame of reference to outside the Earth-Moon system. Place a globe on a table and play the part of the Moon by facing the Earth. Have the students agree ahead of time that in order for you *not* to rotate, you must face them at all times while orbiting around the Earth. Start moving around the Earth and at about half way, ask what the Earth is seeing of you. They will realize that the Earth's view of you (the Moon) has changed. Go back to your original starting point and try again, but this time make sure you face the Earth at all times. Have the students note how much you are turning your body while moving around the Earth. It becomes obvious that you must turn once for each orbit, i.e., the orbit must be synchronous.

By far one of the most unique features of Mercury, and one of the most difficult to explain, is the 3:2 spin-orbit resonance. There are three problems involved with explaining this concept. The first is the 3 rotations in 2 revolutions. Second is how this is related to the elliptical shape of the orbit. Third is how or why the 3:2 was "chosen" by Mercury. Showing Figure 8.13 is essential for better understanding.

➲ **DEMO** The demonstration is rather simple: all that is needed is the Sun (a bright yellow ball works well) and Mercury. For Mercury I prefer an oblong object that emphasizes the tidal distortion produced by the Sun. A balloon that is a bit elongated works well. A rugby ball, if available, is my personal favorite because of its size and ellipsoidal shape. Start the demo with one end of the balloon or ball pointing towards the Sun. Make the orbit vertical so that students can better view the changing orientation of Mercury. Suspend the Sun from the ceiling or place it on a ring stand. The 3:2 motion is not hard to produce if it is remembered that the ball must be turned 180° for each third of the orbit. At the completion of one orbit, the end of the ball that was initially pointing towards the Sun should be pointing away from the Sun (for one and a half rotations). Repeating the orbit again fully demonstrates the 3 rotations per 2 orbits. The length of the day can also be described during this demo.

Repeat the demo but now making the orbit in the shape of an exaggerated ellipse. The balloon must be tidally aligned at perihelion; high tide must point towards the Sun. Using a balloon is easier for this demo because as Mercury progresses through its orbit it can be pushed into a more spherical shape. Note that the greatest tidal effect occurs at perihelion. If you are very proficient with this demo, try varying the speed in the orbit, fastest at perihelion and slowest at aphelion. It is not easy to do, but the students will enjoy seeing you try! Now show how a 1:1 is not possible because the variation in the speed does not allow the tidal bulge to continue to point towards the Sun. (This requires turning the ball or balloon at a constant rate of one rotation per revolution while varying the orbital speed!) Remind the students that the rotational speed cannot vary like the orbital motion can. The planet cannot spin up or down but must maintain a constant rotation.

In the third part of the demonstration, show that during the brief time around perihelion, Mercury appears to mimic synchronous (1:1) rotation when it is in a 3:2 resonance. (The key phrases in the text are: "Tidal forces always act to try to synchronize the rotation rate with the *instantaneous orbital speed*" and "Mercury's orbital and rotational motion are almost exactly *synchronous at perihelion*.") This means that the tidal bulge tries to continue to point towards the Sun during its closest approach. You are now ready to prove mathematically that this will occur for only the 3:2 resonance.

For the orbital and rotational motion to be synchronous at perihelion means the orbital angular velocity must equal the rotational angular velocity at the time of perihelion. Orbital velocity is given by

$$v = \sqrt{G(m_1 + m_2)}\sqrt{\frac{2}{r} - \frac{1}{a}} \quad \text{m/s}$$

where a is the semi-major axis, m_1 is the mass of the Sun, m_2 is the mass of Mercury, and r will be, in this case, the perihelion distance

$$r = a(1-e)$$

For Mercury, $a = 5.7895 \times 10^{10}$ m, $e = 0.206$, and its rotational period is 58.646 days (remember to convert this into seconds). Mercury's mass, compared to the Sun's mass, is insignificant, so m_2 can be zero. Calculate the orbital velocity at perihelion

$$v = 5.90 \times 10^4 \text{ m/s.}$$

Angular velocity is given by

$$\Omega = \frac{v}{r} \text{ s}^{-1}$$

where Ω is the angular velocity. This gives

$$\Omega = 1.284 \times 10^{-6} \text{ s}^{-1} \qquad \text{(orbital)}$$

For the rotational angular velocity, Ω is more easily calculated by

$$\Omega = \frac{2\pi}{P}$$

where P is the rotational period. This gives

$$\Omega = 1.240 \times 10^{-6} \text{ s}^{-1} \qquad \text{(rotational)}$$

These two angular velocities are very close to being the same! Indeed, the planet Mercury does try to be in synchronous rotation during perihelion. Notice also, as stated in the text, the rotational angular velocity is a little slower than the orbital angular velocity at perihelion. Thus, the Sun exhibits retrograde motion around the time of perihelion.

These calculations may or may not be appropriate for the level of course being taught. What is significant is that by using some very simple physics and mathematics the 3:2 spin-orbit resonance can be completely understood!

Section 8.5

When comparing the Moon and Mercury, the surface features speak for themselves. It is instructive to show an image of Mercury next to an image of the Moon. Both are richly adorned with craters. Speaking of craters, this is a good opportunity to discuss impact cratering. Students often think that craters are formed by volcanic activity. Craters as seen on the Moon and Mercury are caused by impacts by objects from space. ➲ **DEMO** Impact craters can be easily demonstrated by using a bowl or anything capable of holding fine powder such as flour or baby powder. Drop small particles, such as BBs into the powder from a height of a few feet, craters will be easily observed. In lieu of this demonstration, or in addition to it, you can refer to figure 8.14 from the text. Cratering and other related topics will be revisited in some detail later on in Chapter 14.

The Moon differs from Mercury, with regard to surface features, in that the Moon has very large features, called maria, which are easily visible on Earth with the un-aided eye. Describe the maria as similar to a bowl, an impact crater, which has been partially filled with molten lava which later solidified.

Section 8.6

The large-scale features on Mercury differ somewhat from those on the Moon. The Caloris Basin, for example, which is one of the largest crater features in the solar system . Also, the scarps that appear on Mercury have no counterpart on the Moon. An example of how they formed can be illustrated by the analogy of the rotten orange. For whatever reason, most students seem to be familiar with the phenomenon displayed by an orange which has been left out on the kitchen counter too long. The interior of an orange shrinks as it ages, leaving the orange peel nowhere to go but toward the center of the orange, and wrinkles appear as the orange peel collapses into itself. This is similar to what happened to the crust of Mercury as it quickly cooled. Ask the students why Mercury would have cooled relatively quickly. Mercury cooled rapidly due to its small volume.

Section 8.7

Show the transparency of Figure 8.26, the cross-sectional view of the Moon and contrast it with Figure 7.1 (or use Figure 8.27). Use comparative planetology to point out the similarities and differences between the Earth and Moon. Of course the Moon has a smaller size, but it is structured in a similar way as the Earth. Again, this is due to density variations. The Moo's crust is much thicker than the Earth's and its mantle is relatively thicker (about 80% of the radius for the Moon compared to about 45% for the Earth).

Note especially the large core of Mercury. Ask students why Mercury doesn't therefore have a strong magnetic field. Both a conducting core and a high rate of rotation are needed for the creation of a magnetic field, and Mercury is missing the rotation part.

Section 8.8

Discuss the four major theories for the Moon's origin (co-formation, capture, fission, and collision or collision-ejection) and ask the students to critique each of them. See if the students can arrive at a consensus for a favored theory.

Show Figure 8.28. or visit one of several internet sites, which have animated video sequences of the collision between Earth and a Mars-sized object as well as the subsequent formation of the Moon from the elected fragments. These simulations, you might add, are generally computer computations based on applications of Newton's laws as previously discussed.

Section 8.9

Concerning the evolution of the Moon, start by revisiting the maria and their formation. Figure 8.29 should be displayed while discussing the formation of the maria and other major features of the surface as a function of age. ➲ **DEMO** The maria formation can be simulated quite easily by taking a bowl, representing a crater, which has had a small hole drilled into the bottom. Immerse the bowl into a pan of liquid representing the molten mantle, which existed briefly in the Moon's formation history. The bowl will fill with the liquid and a mare is formed. The fresh surface is pristine and awaiting only a small amount of bombardment in the coming ages.

Note that before the filling of the maria, the Moon's surface resembled Mercury's even more so than it does today. Review the fact that Mercury did not have an equivalent period of lava upwelling due to its relatively rapid cooling combined with the contracting crust constricting any flow from below.

Before leaving the subject of the Moon, you really should include some discussion of the *Apollo* space program. Most of what we know about the Moon came to us through the exploits of that program. The *Apollo* program ended nearly 30 years ago and will be viewed by most students as history. NASA produced films on each of the *Apollo* missions. Of these, *Apollo 11* and *Apollo 17* are particularly interesting. There is a tremendous difference between these two missions. In the first, everything is done with such caution and determination. It is a significant historical event. In *Apollo 17* the astronauts are very confident, making everything seem routine. Notice too the improvement in technology in terms of the quality of transmissions, now even the launch from the lunar surface can be viewed. These films are now available on video tape and laser disc.

Student Writing Questions

1. What are the English translations of the names given to the Moon's maria? What significance do you think these names have?

2. One entire side of Mercury has never been imaged; *Mariner 10* always viewed the same side. What do you think the other side might look like? Can an argument be made that it should look vastly different? Or will it be a repeat of the known side, except for details? Could you present a convincing argument for returning to Mercury to study its other side?

3. What arguments can be made in favor of returning to the Moon for more manned exploration? In a sense, what is the Moon "good for" in terms of human development?

4. Although most craters are formed by the impacts of meteorites, some are certainly formed by the impact of comets. Describe what the aftereffects of a comet impact might be on the surface of either the Moon or Mercury. What would happen to all the water ice, other ices, and organic compounds? What evidence might we look for today of such impacts having occurred in the past?

5. Mercury appears to contain the highest proportion of metals of any object in the solar system. If humans ever started building large spacecraft in space, Mercury may be able to supply the required metals. Is there anything wrong with using Mercury in this way? Would it be ok to completely use up Mercury?

Answers to End of Chapter Exercises

Review and Discussion

1. The distance to the Moon is most accurately measured by laser ranging. Reflectors were left on the surface of the Moon during the Apollo missions. Timing the laser beam's travel to the Moon and back will give an accurate measure of its distance.

2. Mercury is one of the brightest objects in the nighttime sky, but, as the closest planet to the Sun, it is never seen very far from the Sun. As a result, Mercury is always seen near the horizon just before sunrise or just after sunset. It is rarely high enough above the horizon to be easily seen.

3. It can be either a morning "star" or evening "star," depending on where it is in its orbit. Of course, it cannot be both at the same time, an issue apparently not recognized in ancient times.

4. Both the Moon and Mercury have low masses and low escape velocities. Yet both objects are in the inner solar system and experience high daytime temperatures. All gases, at these temperatures, will exceed the escape velocity. Neither object, then, has been able to hold an atmosphere.

5. The lunar maria were once "seas" of molten lava. Once solidified, the maria became large, flat regions that were remindful of seas of water.

6. Both Mercury and the Moon are heavily cratered. The crater walls on Mercury are generally not as high as on the Moon, however, and material ejected by striking meteorites landed closer to the impact site, just as you would expect on a world whose gravity is stronger than that of the Moon. Also, Mercury lacks extensive lava flow regions akin to the lunar maria.

7. The Moon's orbit is synchronized with its rotation in a 1:1 ratio. The Moon rotates every revolution. When the solar system was still young, the Moon was about two-thirds its current distance from Earth. The tidal effect of the Earth on the Moon distorted the shape of the Moon. Once it solidified, the shape was frozen in. Earth's gravity has aligned the Moon's high tide side to face the Earth.

8. Mercury's rotation is not synchronous in a 1 to 1 ratio but in a 3 to 2 ratio. It rotates 3 times for every two orbits. This was the result of Mercury's eccentric orbit and allows the same side of Mercury to face the Sun every other orbit at perihelion. It is at perihelion that the tidal forces are the strongest on Mercury and this locked it into the 3 to 2 ratio.

9. A scarp is a cliff formed when Mercury's surface wrinkled due to cooling. Scarps are found crossing craters, indicating they are younger than the craters.

10. The primary source of erosion on the Moon is cratering. There is no water or wind erosion and no erosion due to plate tectonics because none of these exist on the Moon. But they do exist on the Earth and therefore the rate of erosion on the Earth is much higher than on the Moon.

11. Both the *Clementine* and *Lunar Prospector* missions found evidence of water ice in a crater at the south pole of the Moon. In this location, sunlight never gets high enough to raise the temperature.

12. First, it is quite apparent that the lunar highlands are more heavily cratered. The maria were resurfaced by lava flows and all the old craters were covered over but the highlands remained untouched. Samples of highland and maria material were brought back by the Apollo program and age-dated. The highland material was shown to be much older than the maria material.

13. The extreme temperature variations of Mercury are due, in part, to its lack of an atmosphere. An atmosphere helps to insulate the surface of a planet from cooling at night. Mercury's very long day (slow rotational period) also plays a role. The Sun is up for a long period, allowing the rock to heat up. With an equally long night, there is ample time to cool down to a low temperature. Earth, in contrast to Mercury, rotates rapidly and has less time to heat up to high temperatures or cool down to low temperatures.

14. Mercury is composed of higher density material, on average, than is the Moon. Both differentiated when young; however, the Moon has at best a small core and Mercury has a large core. The Moon cooled faster than Mercury, which may account for the Moon having visible maria. These impacts had to have occurred when the Moon was rather young, with a thin crust. Both the Moon and Mercury, though, show similar histories of cratering, although Mercury does not appear as heavily cratered. Many of its oldest craters have been covered over by lava flows, more extensive than those that formed the maria on the Moon. It is unclear why this is the case.

15. The favored theory for the formation of the Moon is that a large body, maybe Mars-sized, struck the Earth a glancing blow. Material thrown off could have then coalesced into forming the Moon. This theory explains two major features of the Moon. If the Earth was young but already differentiated enough to have an iron core and rocky mantle, the Moon would have formed primarily out of mantle material. This is consistent with the Moon being composed of rock very similar to the Earth's mantle and explains why the Moon appears to have no iron core.

16. First, the Earth would change due to its own rotation. With an orbital inclination of just over five degrees to the ecliptic, the Earth would appear to move higher and lower in the sky, as seen from a location on the Moon. Finally, because the Moon's orbit is eccentric, the distance between the Earth and Moon changes. At times the Earth would appear larger than at other times.

17. The best place on the Moon to look with a telescope is along the terminator line, which separates day from night on the lunar surface. There the Sun is low in the sky, casting long shadows that let an observer distinguish small surface details. If you looked at the Moon through a telescope, you would see lunar mountains, low plains called maria, and numerous craters. If standing on the lunar terminator, the Sun would be on the horizon (or just slightly above it). The same is true for Earth's terminator; you would be viewing either sunrise or sunset.

18. The far side of the Moon would be best for astronomical observations. The bright Earth would never interfere with observations. The surface of the Moon has no atmosphere, so the resolution of telescopes would be at their maximum. With no atmosphere, the sky is always dark, even when the Sun is out. Radio astronomy would benefit from shielding by the Moon of man-made radio transmissions.

19. Mercury is the closest planet to the Sun and is always seen near the Sun. At midnight, the Sun is opposite of overhead and Mercury is not far away.

20. When the lunar material differentiated, Earth's gravity played an important role. Denser mantle material settled closer to the Earth; lighter crustal material settled farther away. The lunar crust on the near side of the Moon is consequently thinner; maria formed more easily. On the far side, the crust is thicker and maria were generally unable to form.

Conceptual Self-Test

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

Problems

1. Mercury has a semi-major axis of 0.39 A.U., so on average and at its closest, it would be 0.61 A.U. from Earth. This is equivalent to 91.5 million km. Dividing by the speed of light gives 305 s one way or 10 minutes and 10 seconds roundtrip. For Mercury at aphelion, its distance from Earth is reduced to 0.53 A.U. and the roundtrip time is 8.8 minutes.

2. Newton's law of gravity states that the gravitational force is proportional to the product of the masses and inversely proportional to the square of the distance to the center, in this case the radius of the Moon. With 1/4 Earth radius, the Moon's gravity will be $1/(1/4)^2$ times larger or 16 times. But the Moon's mass is 80 times less than the Earth's. The result is 16/80 = 0.2. The Moon's gravity is one-fifth the gravity of the Earth.

   A kilogram on Earth weighs about 2.2 pounds; 150 kg × 2.2 lbs/kg = 330 lbs. This is the weight on Earth of the astronaut plus backpack and spacesuit. On the Moon, the astronaut would weigh 1/5 of this, or 66 lbs.

3. Again, using a scaling approach, Mercury's mass and radius in Earth units are 0.055 and 0.38. The acceleration due to gravity will be $0.055 / (0.38)^2 = 0.38$ Earth. The astronaut will weigh an equivalent of 57 kg or 125 lbs.

4. Perigee and apogee distances for the Moon are 363,000 km and 405,000 km. Use the angular diameter formula from *More Precisely 1–4*. Maximum angular size = 57.3° (3476 / 363,000) = 0.549°. Likewise, the minimum size is 0.492°. The Sun's angular size is 0.533°

5. The Sun appears to be about half a degree from Earth or 0.53°. Mercury is at 0.31 A.U. and 0.47 A.U. from the Sun at perihelion and aphelion. The Sun will appear 1 / 0.31 and 1 / 0.47 times larger. This becomes 3.2 × 0.53 = 1.7° and 2.1 × 0.53 = 1.1°.

6. Use the angular diameter formula from *More Precisely 1–4*. Angular units will be in seconds of arc, not degrees. For the Moon, d = 380,000 (0.05 / 206,000) = 0.092 km or 92 m. Mercury, at a distance of 0.47 A.U. from the Sun, will be 0.53 A.U. from Earth, or 80 million km. This gives d = 80,000,000 (0.05 / 206,000) = 19 km.

7. Use the formula for speed from Chapter 2.

$$v = \sqrt{\frac{6.67\times10^{-11}\times7.4\times10^{22}}{(1738+10)\times1000}}$$

$$v = 1680 \text{ m/s or } 1.68 \text{ km/s}$$

The orbital period is calculated by determining how long the module takes to traverse a distance equal to the orbital circumference, *C*. This is $2\pi R$, where *R* is the radius of the Moon plus 10 km, or 1748 km. $C=1.1\times10^4$ km. At a speed of 1.68 km/s, this would take 6.5×10^3 seconds or 1.8 hours.

8. Use the form for the tidal force given in this manual for Chapter 7 and solve for ΔF. For the Earth's tidal effect on the Moon:

$$\Delta F = \frac{2\times1.7\times10^{6}\times6.7\times10^{-11}\times6\times10^{24}\times7.4\times10^{22}}{\left(3.8\times10^{8}\right)^{3}}$$

$$\Delta F = 1.8\times10^{18}$$

Similarly, for the Sun's tidal effect on Mercury:

$$\Delta F = \frac{2\times2.4\times10^{6}\times6.7\times10^{-11}\times2\times10^{30}\times3.3\times10^{23}}{\left(5.8\times10^{10}\right)^{3}}$$

$$\Delta F = 1.1\times10^{18}$$

This is about 60% the Earth-on-Moon tidal force.

9. To obtain the orbital distance at perihelion and aphelion, refer to *More Precisely 2-*. For Mercury we have

$$\mathrm{R_p} = a(1-e) = .39(1-.206) = .31 \text{ AU} = 4.64\times10^{10} \text{ m}$$

and

$$\mathrm{R_a} = a(1+e) = .39(1+.206) = .47 \text{ AU} = 7.1\times10^{10} \text{ m}$$

Now, the area, A, of a sector of a circle is given by $A = \dfrac{\theta\pi R^2}{360^\circ}$, where R is the radius of the circle, orbital distance, and θ is the angle swept out by the orbiting object. First, find the value for this area based on the mean orbital speed and mean orbital radius. Mercury completes one full orbit in 88 days and has a mean orbital radius of $5.79\text{x}10^7$ km. In one day, then, the area swept out by mercury will be $\dfrac{1}{88}\times\pi\left(R_{mean}\right)^2 = \dfrac{1}{88}\times\pi\left(5.79\times10^7\text{ km}\right)^2 = 1.2\times10^{14}\text{ km}^2$. Kepler's 2nd law states that this area will constant over any two equal time periods as a planet orbits the Sun. So, over a one day time period when Mercury is at perihelion, we have $1.2\times10^{14}\text{ km}^2 = \dfrac{\theta\pi {R_p}^2}{360^\circ}$, the angle swept out in one day will then be $\theta_p = \dfrac{360^\circ\times\left(1.2\times10^{14}\text{ km}^2\right)}{\pi\times\left(4.64\times10^7\text{ km}\right)^2} = 6.4^\circ/\text{day}$.

Similarly, for one day at aphelion we have $\theta_a = \dfrac{360^\circ\times\left(1.2\times10^{14}\text{ km}^2\right)}{\pi\times\left(7.1\times10^7\text{ km}\right)^2} = 2.7^\circ/\text{day}$.

10. Mercury's orbital period is 88.0 days. At a 4:3 resonance, one full rotation takes 66 days. A sidereal day = 3 × 88 / 4 = 66 days. A solar day would take 3 orbits or 264 days.

11. Towards the end of *More Precisely 8–1*, the situation for Mercury is given. Its average molecular speed of 0.8 km/s must be multiplied by 6, = 4.8 km/s, to get the escape speed needed to keep a nitrogen atmosphere. The current speed is 4.2 km/s. The speed is proportional to the square root of the planet's mass. Square both sides of this equation and form a proportion of new / old. $(4.8 / 4.2)^2$ = New mass / Original mass = 1.31. The new mass is 31% larger than the current mass or 4.3×10^{23} kg.

12. The average molecular speed is one-sixth the escape speed = 4.2 km/s / 6 = 0.7 km/s. Molecular speed depends inversely on the square root of the molecular mass. $(0.8 / 0.7)^2$ = 28 / New mass = 1.31. New mass = 1 / 1.31 × 28 = 21 molecular weight.

13. From the text, a 10 km crater is formed every 10 million years. Such a crater has an area of 78.5 km^2. The surface area of the Moon, assuming a spherical shape, is $4\pi(1738\text{ km})^2$ = 3.8×10^7 km^2. Dividing this area by the area of a 10 km crater gives the number of such craters needed to cover the entire surface; 3.0×10^7 km^2 / 78.5 km^2 = 4.8×10^5. Multiplying this result by 10 million years gives 4.8 trillion years; about 1,000 times longer than the age of the solar system.

    The cratering rate for 10 km craters would have to be approximately 1,000 times what it is today in order to have cratered the Moon in the 4.6 billion years since its formation. This would be one 10 km crater every 10,000 years. That's rather often!

14. From Problem 13, the surface area is 3.8×10^{13} m^2. A one-meter crater has an area of 0.78 m^2. Dividing the crater area into the surface area gives the total number of craters needed = 4.8×10^{13} craters. Over the age of the solar system this would be about 10,000 craters per year.

15. The erosion rate is given as 5 m per billion years.

(a) 2 cm erodes in 2 cm / (500 cm / 10^9 yr) = 4 million yrs.
(b) The crater is 0.2 km = 20,000 cm deep but the rate is 10,000 times faster. 20,000 cm / (500 cm / 10^5 yr) = 4 million yrs.
(c) The text suggests a crater depth of one-fifth the diameter. Reinhold is 40 km in diameter and therefore 8 km = 800,000 cm deep. Using the method in (a) 800,000 cm / (500 cm / 10^9 yr) = 1.6 trillion yrs.

Resource Information

Student CD Media

Movies/Animations
Terrestrial Planets

Interactive Student Tutorials
None

Physlet Illustrations
Rotation of Mercury
Meteor Energy

Transparencies

T-69	Figure 8.4	Full Moon, Near Side	p. 203
T-70	Figure 8.13	Mercury's Rotation	p. 209
T-71	Figure 8.14	Meteoroid Impact	p. 212
T-72	Figures 8.21/22	Crater Chain and Lunar Volcanism	p. 217
T-73	Figure 8.24/25	Caloris Basin and the "Weird" Terrain	pp. 219/220
T-74	Figure 8.26	Lunar Interior	p. 221
T-75	Figure 8.27	Terrestrial Interior	p. 222
T-76	Figure 8.29	Lunar Evolution	p. 224

Materials
Moon Globe
Meteorite examples to pass around
Models or images of Apollo spacecraft including the Saturn V rocket and the lunar module

Suggested Readings

Armstrong, J. "Heading Back to the Forgotten Planet." *Astronomy* (October 2002). p. 40. Discusses the Messenger Mission, a probe to Mercury scheduled for launch in the Summer of 2004. Lots of nice Mercury images as well as a description of the probe, Messenger, and its mission.

Binder, Alan B. "Lunar Prospector: overview." *Science* (Sept 4, 1998). p. 1475. A summary and overview of the Lunar Prospector mission.

Culler, Timothy S.; Becker, Timothy A.; Muller, Richard A. "Lunar impact history from $^{40}Ar/^{39}Ar$ dating of glass spherules." *Science* (Mar 10, 2000). p. 1785. Discusses a recent analysis of the ages of glass spherules found in lunar soil, and relates this to the rate of cratering on the lunar surface.

Davis, Bill. "The mountains of the moon." *Sky & Telescope* (Nov 1998). p. 114. Describes an observing project to determine the elevation of lunar features by observing the length of their shadows.

Foust, Jeffrey A. "NASA's new moon." *Sky & Telescope* (Sept 1998). p. 48. Describes the results from the Lunar Prospector mission, with particular emphasis on the evidence for water ice on the lunar surface.

Hodge, Paul. "Naming the man in the moon." *Astronomy* (Feb 1999). p. 82. An interesting discussion on the origin of names for lunar features.

Krupp, E. C. "Beyond the pale: the planet Mercury is the go-between from day to night, just as its namesake was the courier for the spirit world." *Sky & Telescope* (Mar 1998). p. 88. An interesting discussion of the mythology associated with Mercury.

Nelson, Robert M. "Mercury: the forgotten planet: profile of one of Earth's nearest neighbors." *Scientific American* (Nov 1997). p. 56. A summary of what we know about Mercury, and the possibilities and difficulties in its exploration.

Ryder, Graham. "Glass beads tell a tale of lunar bombardment." *Science* (Mar 10, 2000). p. 1768. Discusses a recent analysis of the ages of glass spherules found in lunar soil, and relates this to the rate of cratering on the lunar surface.

Sheehan, William; Dobbins, Thomas. "Mesmerized by Mercury." *Sky & Telescope* (June 2000). p. 109. Describes the history of observations of Mercury.

Spudis, P. "Harvest the Moon." *Astronomy* (October 2002). p. 42. Detail-oriented article advocating the return to the Moon. Benefits of Lunar prospecting are discussed along with a very nice overview of a potential transportation/cargo ferrying system architecture.

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: