Chapter 14: Solar System Debris
Keys to Our Origin

Outline

14.1 Asteroids
14.2 Comets
14.3 Meteoroids

Summary

Don't feel alone if you waited until discussing so called "debris" to talk about Pluto. Pluto is clearly an oddball when compared to the planets, but seems to fit right in when discussing solar system debris. If you waited until now to discuss Pluto, please refer to Chapter 13 for suggestions on introducing Pluto to your students.

Although debris carries negative connotations, the objects which fall under this heading are clearly important in their own right. In fact, as the subtitle to this chapter suggests, these objects may hold the key to the origins of life on Earth. Indeed the study of this debris, comets in particular, is at the cutting edge of astronomical research. Comets hold an abundance of water and possibly organic molecules that may have seeded our environment and helped spawn and nurture life. Asteroids, on the other hand, are the remnants of terrestrial planet formation and some are known to contain organic molecules that are found in certain meteorites.

Both types of objects have a darker side to them for they are also responsible for extinctions of life on Earth; the aftermath of fortunately infrequent collisions. With mass extinction events, such as the collision between Earth and an asteroid, the collisions that were so important in Earth's early history now bring wholesale death and destruction. But life always springs anew, so, using a broader perspective, these collisions may be still necessary for life by pruning it back occasionally. If we prevent future collisions, might we be preventing future generations of life forms from every evolving? Let your students decide.

Major Concepts

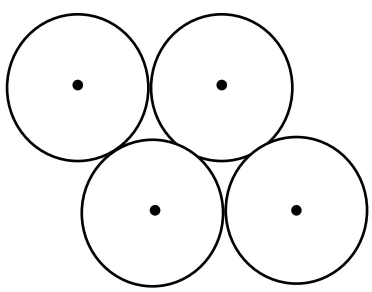
- Asteroid properties
  - Rocky
  - Most exist in the asteroid belt
  - Apollo asteroids
- Comets
  - "Dirty snowball"
  - Kuiper Belt
  - Oort Cloud
  - Elliptical orbits
  - Anatomy
    - Nucleus
    - Coma
    - Hydrogen envelope
    - Ion (or plasma) tail
    - Dust tail

- Meteoroids
  - Cometary fragments
  - Stray asteroids
  - Meteors (traveling in the Earth's atmosphere)
  - Meteor showers
  - Meteorites (reach Earth's surface)

Teaching Suggestions and Demonstrations

Section 14.1

➲ **DEMO** A very common description of **asteroids** is that they look like potatoes. Bring a couple of potatoes to class and set up a model of the belt environment. The question to be answered is "How far apart must the potatoes be placed to model the asteroid belt environment?" Assume the typical asteroid is 1 km in diameter, that there are 4,000 asteroids in the belt, and the belt extends from 2 A.U. out to 3 A.U. and is confined to a plane. Use two large potatoes (for visibility) about 15 cm long, and, assuming each represents a 1 km asteroid, the scale becomes 1 km = 15 cm. The area of the belt is given by $\pi(R^2 - r^2) = \pi(3^2 - 2^2) =$ 15.7 A.U.^{2}. Dividing this by 4,000 gives 0.00393 A.U.^{2} per asteroid. What is the radius of a circle with this area? $\pi r^2 = 0.00393$, so $r =$ 0.0354 A.U. or 5.3 million km. The distance between asteroids will actually be twice this distance, as illustrated.



If the dots represent asteroids and the circles are the areas just calculated, then each asteroid is about $2r$ from the nearest asteroid. The distances between these asteroids will be about 10.6 million km. On the scale of the classroom this will be almost 1,600 km or 1,000 miles.
Keep one potato at the front of the class and give the other to a student who offers to help with your demo. Do the above calculation with the expressed intention of telling the student how far away to stand to properly model the asteroid belt. The result comes as a bit of a surprise to most people when you tell the student to go stand one thousand miles away!

Because asteroids are relatively nearby objects it is often believed that they are easily observed. A more realistic view is understood when a typical asteroid's brightness and angular size are calculated. An easy brightness estimate may be made relative to Mars, which is a rocky planet nearest to the asteroid belt. Assume Mars and a typical asteroid have the same albedo and the asteroid is about twice as far away as Mars. If Mars and the asteroid were the same size this would make the asteroid 4 times fainter. But Mars is 6787 km in diameter and a typical asteroid is only 1 km. Since the brightness depends upon the apparent area of the disc, the asteroid will be fainter by $(1 / 6787)^2$ = 46 million times. This, combined with the other factor of 4, makes the asteroid a total of about 200 million times fainter than Mars. (Later, when the concept of magnitude is understood, this can be converted to about 21 magnitudes fainter than Mars. Mars is about 0.0 magnitude when at 1 A.U. from Earth, so a typical asteroid would be 21st magnitude when seen at 2 A.U., well within range of larger telescopes but still not easy.)

For the angular size it is helpful to remember that 1 arc second = 1/206265 in radian measure. Thus a 1 km object seen at about 200,000 km appears as 1 arc second. The asteroid 1991BA was slightly larger than 1 arcsec when it passed by the Earth. But this is certainly not typical of the belt asteroids viewed from 2-3 A.U. 200,000 km is 0.0013 A.U., so at 1 A.U. a 1 km asteroid would appear to be 0.0013 arcsec. At a more typical distance of 2.5 A.U. the angular size would be 0.0005 arcsec, which is about 100 times smaller than can be resolved by the Hubble Space Telescope!

When discussing asteroids, questions concerning Earth **collisions** invariably come up. This topic has developed increasing interest among the public and is certainly a subject that students find fascinating. Fortunately, the physics is very simple and informative. All that is needed is the concept of kinetic energy = $1/2mv^2$. At the time of the collision, all the energy is in this form. Only a few percent of its velocity is due to "falling" to Earth, i.e., the conversion of gravitational potential energy to kinetic energy, most of the velocity is due to the relative velocities of the Earth and the asteroid. Start with an estimated velocity of 50 km/s. (For an asteroid with an aphelion distance of 3 A.U. and a perihelion distance of 1 A.U., the velocity at perihelion, which is where the collision is likely to occur, is about 40 km/s. Since the Earth is moving at 30 km/s, the range in the relative velocities is 10 to 70 km/s.) Assume a 1 km diameter spherical asteroid of density 3 gm/cm^3 = 3000 kg/m^3. The volume will be $5.2\text{x}10^8$ m^3. The mass will be $1.6\text{x}10^{12}$ kg. The kinetic energy will equal $2\text{x}10^{21}$ Joules. One megaton equivalent of energy is equal to $4.20\text{x}10^{15}$ J. This gives 500,000 megatons of energy, close to the one million noted in the text. This is enough energy to boil (from 0° C water to 100° C steam) a cubic volume of ocean water 9 km on a side, just in case it falls into an ocean! Remember, the amount of energy goes by the square of the velocity and is proportional to the mass. However, the mass depends upon the cube of the radius of the asteroid. So, for a 10 km asteroid there is 1000 times more volume and mass and 1000 times more energy!

Section 14.2

Comets usually have very eccentric orbits, 0.99 or more. To easily demonstrate this, draw an orbit with a one-meter major axis and an eccentricity of 0.99. The minor axis will be 28 cm. ➲ **DEMO** Draw the major axis on the chalk board and from the center mark two points vertically 14 cm above and below the center. The ellipse can be easily sketched in. The Sun, at one focus, will be 1 cm from whichever end is chosen. If this were a scale model of a real comet, using a scale of 1 cm = 1 A.U., then perihelion occurs at the Earth's orbit and aphelion is over twice the distance to Pluto. Using Kepler's third law, the period would be about 350 years.

Long period comets may have orbits as large as 50,000 A.U. (aphelion distance). Since, in these cases, perihelion is much less than 1 A.U., the semi-major axis is about 25,000 A.U. The period would be about 4 million years. **Short period comets** have periods less than 200 years. Again, using Kepler's third law, the semi-major axis is calculated to be 34 A.U. Assuming a large eccentricity would mean their aphelion distance would take them to about 68 A.U. which is well beyond the orbit of Pluto but much closer than the long period comets.

Sun-grazing comets are interesting because they pass so close to the Sun at perihelion that they are destroyed. Such a comet is likely to be passing the Sun for the first time as any previous passage would, of course, have destroyed it. Sun-grazing comets can be destroyed if they come to within about one solar radius of the Sun's surface. They do not have to impact the Sun, but merely coming to within a solar radius or so may be sufficient to destroy them. Let's assume a comet has a perihelion distance of 2 solar radii = 0.01 A.U. If it has arrived from the distant Oort Cloud then a = 25,000 A.U. might be appropriate. The eccentricity is calculated to be 0.9999996!

A common analogy when discussing the composition of a typical comet is the "dirty snowball." ➲ **DEMO** A model of a comet can be easily, although messily, made. Take an empty half-gallon milk carton and fill it 80% full of water. Mix in very fine dirt and soot. Ashes from a fireplace are good to use, but make sure they are crushed. Put enough soot into the mixture to make it very dark. (You can always add some India ink to help the color.) Add sufficient dirt and soot to fill the carton and freeze overnight. While it is freezing you will need to mix it several times so that the dirt does not settle out. Before class, strip away the carton to reveal the frozen, dark mass. Chip off the edges if you want a more realistic appearance. It will be rather messy as it thaws. It's a dirty job, but someone has to do it!

Section 14.3

Meteorites are commonly available for sale (see the reference in the "materials" section of this chapter.) You will definitely want to have on hand at least one, preferably several, meteorite samples to pass around. This will most likely be the only opportunity in the lives of your students for them to touch something that did not originate somewhere on this planet.

Virtually all meteorites that are purchased are high density, highly differentiated examples. Do a demonstration to measure the density. Ask your students from what type of object must your meteorite have originated. If the meteorite has a high density, then it must have come from the core of a differentiated body. Ask the students "How did it get out of the core?" "How did it get to Earth?

Student Writing Questions

1. Asteroid belts have been shown in a variety of science fiction movies, such as *The Empire Strikes Back*. In what ways are these visualizations correct and incorrect? Is it possible to actually see a field of asteroids?

2. A comet is mostly water. Some day, space colonists may need to get their water by capturing comets. A one-kilometer comet is relatively small but would carry a substantial amount of water. Try to calculate how much water there is in such a comet. The density might be around 1,000 kg/m^3. (There are 2.2 pounds in a kilogram; a gallon of water weighs 8 pounds.) If a colony needs about 10,000 gallons of water per occupant (the water will be recycled), for how many people could this one comet provide water? In addition to water, comets carry other types of material. In relation to the previous question, to what use could a space colony put the other material in a comet, or would it be best to throw that material away?

3. Knowing that asteroid and comet impacts with Earth can cause extinctions on a global scale, some effort may soon be made to prevent them from happening. But the history of life on Earth shows that after each extinction, life arises anew and flourishes with large varieties of new life forms. Mammals came into dominance after the last impact. So if we prevent future impacts we are stopping the emergence of future life forms on Earth. For which do we have a higher moral obligation: to protect current life forms or to allow new forms to develop?

4. With our increasing dependence on a variety of Earth satellites we also realize an increased risk to these satellites from impacts by meteoroids. What do you propose could be done to protect these satellites from those impacts? Remember, most meteoroids are quite small. Think of them as being about the size of a grain of sand.

5. You are holding a meteorite in your hand. Trace back all the events that took place, over the past 4.6 billion years, that led to this meteorite being in your hand. Include the times when these events occurred. Be creative and use your imagination, but keep it founded in astronomy.

Answers to End of Chapter Exercises

Review and Discussion

1. The Trojan asteroids are found in the orbit of Jupiter, at either the L_4 or L_5 Lagrange points. Apollo asteroids have perihelion distances less than 1 A.U., or, more simply, they cross the orbit of the Earth. The Amor asteroids are similar to the Apollo asteroids, except they cross only the orbit of Mars, not Earth.

2. Asteroid masses can only be measured by studying the effects of gravity on another body. This second body may be a space probe or a moon of the asteroid.

3. The *Galileo* space probe photographed two asteroids on its way to Jupiter; Gaspra and Ida. These, to date, are the finest photographs ever taken of asteroids.

4. The Kirkwood gaps are orbits with semi-major axis that are not, or poorly, occupied by asteroids. They represent resonances with Jupiter's orbit. Jupiter essentially pulls asteroids out of these orbits.

5. The C-type asteroids are carbonaceous in composition. They have very low albedos, around 0.05. The S-type asteroids are more reflective, with albedos around 0.15 to 0.25. They have a composition of silicates. S-type asteroids are found in the inner portion of the asteroid belt; C-types are found farther out. 75 percent of asteroids are C-type and 15 percent are S-type.

6. Many asteroids are not found in the asteroid belt. See the answer to question 1.

7. Comets, when they are far from the Sun, are frozen chunks of ice, dust, and rocky particles. They are very cold and dark. When comets approach the Sun, the surface ices start to sublimate, releasing gases and particles of rock and dust. A large cloud of this material surrounds the comet and is called the coma. As the comet approaches the Sun one or more tails are formed, as discussed in the following question.

8. We must be careful answering the question "where are comets found?" because a comet can not be "found" until it becomes visible to telescopes on Earth. This means that only comets entering the inner solar system will be found. A broader view of the solar system tells us that we would find most comets in the Oort Cloud, thousands and tens of thousands of A.U. from the Sun. Some are also found in the Kuiper Belt, between 30 and 100 A.U.; observations seem to be confirming the Kuiper Belt comets, but the Oort Cloud comets will remain invisible for a long time.

9. The nucleus is the solid, rocky-icy body of the comet. Near the Sun, it develops a diffuse coma (halo) of dust and sublimated gases. A hydrogen envelope surrounds the coma and has a shape distorted by the solar wind. It can be millions of kilometers across. Finally, there are the two tails to the comet, stretching away from the nucleus; the ion tail and the dust tail.

10. The comet nucleus has a very dark surface with large quantities of dust and gas rising from its surface, as it is heated by the Sun. In some places, jets of matter are streaming from the surface. These jets can change the rotation rate of the comet and even make small changes to its orbit.

11. Although direct sampling of a comet's material is only a few years away, astronomers have a good idea of some of a comet's makeup. There are a lot of dust particles frozen in water ice. Gases such as carbon dioxide, ammonia, and methane are frozen and act like an ice. There are also organic compounds but the specifics still need to be determined.

12. All comets that we know of eventually die out. Some impact on planets or moons as they pass through the solar system. Others have a perihelion distance so close to the Sun that the comet either impacts with the Sun, completely disappears from heating, or breaks up into many fragments. Other, more "normal" comets continue to orbit the Sun until they have finally lost all their material.

13. A comet's orbit may be changed by a close encounter with a planet, most likely Jupiter. As ices are heated, jets of gas form and actually move the comet slightly to a new orbit.

14. The Kuiper Belt objects are icy leftovers from the formation of the outer planets and moons. The asteroids are leftovers from the formation of the inner planets. Gravity from the planets has moved all these objects into somewhat stable orbits. The asteroids are rocky and close to the terrestrial planets. Kuiper Belt objects are icy and orbit in the outer solar system.

15. A meteoroid is any particle of material orbiting the Sun which cannot be seen from Earth. (If it could be seen, it would be called an asteroid.) Sizes range from kilometers to microscopic dust particles. If a meteoroid passes through the atmosphere of the Earth (or any other atmosphere), it momentarily heats the gases, making them glow, as it passes through. This streak of light is known as a meteor. The meteoroid likely burns up when passing through the atmosphere. If it does not burn up, because of its size, composition, or low velocity, and lands on the surface of a planet or moon, it is known as a meteorite.

16. Meteor showers are caused by the Earth passing through the orbit of a comet. The orbit of a typical comet is filled with many particles of rock and dust left behind as its ices sublimated. When the Earth passes through this swarm of particles, a meteor shower is observed. Many meteors will be seen emanating from one location in the sky.

17. Meteorites are used to age-date the solar system. Examination of the rocky material tells us much about the body from which the meteorite originated. It can also tell us about the conditions in the early solar system when planets and moons were forming.

18. The Oort Cloud of comets, considered the source of most comets, is like a large, spherical halo around the solar system. Comets enter the inner solar system was a large range of orbital inclinations. Asteroids are mostly confined to the ecliptic. Their position indicates they are the product, maybe leftovers, of planet formation. The comets, from their distribution and composition, may date from an earlier period in the solar system's formation.

19. Earth's surface has been resurfaced many times since it was formed. Erosion and tectonic activity have erased virtually every bit of the original surface. Meteoroids remain in space fairly unaltered by time, except for occasional collisions. When found as meteorites they provide information dating back to when they formed.

20. The consequences of a 10–km meteorite striking the Earth today would be very unpleasant. There would be world-wide effects to the entire environment and likely extinctions of many of the highest-order animals. The Earth would likely be shrouded in clouds of dust, water, and even salt water for years. Huge tidal waves would result from a strike in one of the oceans. Large earthquakes could be triggered. Near the strike, the heat and blast wave would destroy everything for hundreds of kilometers. Debris falling back to Earth from the impact would devastate an even larger region. No part of the Earth would go unaffected. Keep in mind that the possibility of such an impact during your lifetime is very low; unfortunately, neither is it zero.

Conceptual Self-Test

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

Problems

1. (a) The gravitational acceleration is $a = GM/R^2 = 6.7\times10^{-11}\times3.2\times10^{20}/(2.6\times10^5)^2 = 0.32\ \text{m/s}^2$. Compared to Earth where a = 9.8 m/s^2, this is 30.6 times smaller. 100 / 30.6 = 3.3 kg equivalent.

   (b) The escape velocity will be $v_e = \sqrt{2(6.7\text{x}10^{-11}\ \text{x}3.2\text{x}10^{20} / (2.6\text{x}10^5))}$. v_e= 410 m/s or 0.41 km/s.

2. This is like (b) of the last question except the mass has to be calculated from the density. $\text{Mass} = \text{density}\times\text{volume} = 3000\times4/3\pi(5000)^3 = 1.6\times10^{15}\ \text{kg}$.
   $v_{escape} = \sqrt{2\times6.7\times10^{-11}\times1.6\times10^{15}/5000} = 6.5\ \text{m/s}$ or 15 mph. This would be child's play!

3. For your weight to be one percent would require a = 0.098 m/s^2. But the mass is unknown. So substitute the formula for the mass in Problem 2 into the equation for the acceleration in 1(a) to get $a = 4/3\pi G(\text{density})R$. Solving for R gives

$0.098 \; = \; 4/3\pi \times 6.7x10^{-11} \times 3000 \times R.$. R = 116,000 m or 116 km. This is a diameter of 230 km.

4. Jupiter's period is 11.86 yrs. From Kepler's third law, a semi-major axis of 2.7 A.U. gives a period of $P^2 = (2.7)^3$, P = 4.437 yrs. Dividing Jupiter's period by this gives 2.673, which is about 2 and two-thirds or 8/3. Try this: 8 × 4.437 = 35.50 and 3 × 11.86 = 35.58; these are fairly close.

   One problem in resolving this is that the semi-major axis is given to only two significant digits; certainly these period ratios agree within that accuracy. Let's work backward to the semi-major axis and see if there is reasonable agreement. 35.58 / 8 = 4.4475. Take this as the period of the gap. Using Kepler's third law gives a semi-major axis of $(4.4475)^2 = a^3$, a = 2.704 A.U. Yes, the agreement is very good. This gap is likely due to an 8:3 resonance.

5. Perihelion distance = $a(1 - e)$. Using the data given for Icarus gives 0.19 = a(1 - 0.83), a = 1.1 A.U. Aphelion distance = $a(1 + e)$, = 1.1(1 + 0.83) = 2.0 A.U.

   Although Icarus has an orbit that crosses the Earth's, a collision is only possible if it crosses the Earth's orbit at 1 A.U. when it is also in the plane of the ecliptic. This depends on the inclination of the orbit to the Earth's orbit.

6. The Sun appears to be 0.5° in diameter from Earth. The size will change in inverse proportion to the distance. At aphelion it will be 0.5 / 1.1 = 0.45° or 27'. At perihelion it will be 0.5 / 0.19 = 2.6°.

7. Use a mass of 7.5×10^{16} kg. Velocity is distance divided by time, so the orbital velocity uses the circumference divided by the orbital period P.

$$\frac{2\pi \times 90,000}{P} = \sqrt{\frac{6.67 \times 10^{-11} \times 7.5 \times 10^{16}}{90,000}}$$

P = 75,800 s or 21 hrs.

8. (a) First, calculate the semi-major axis of the orbit using periapsis = $a(1 - e)$. 100 km = a(1 - 0.3); a = 143 km or 143,000 m.

   Use Kepler's third law in the form given in *More Precisely 2.3*. The semi-major axis will be the same as the radius of the orbit.

$$P = 2\pi\sqrt{\frac{143{,}000^3}{6.7 \times 10^{-11} \; \times \; 6.7 \times 10^{15}}}$$

P = 507,000 s or 141 hrs. = 5.9 days

   (b) The semi-major axis now becomes a = (14 + 60) / 2 = 37 km = 37,000 m. Repeating (a) with this new distance gives P = 66,700 s = 18.5 hrs.

9. (a) The sum of the perihelion and aphelion distances give the major axis; half of this is the semi-major axis, which will be 25,000 A.U. in this case. Using Kepler's third law, $P^2 = (25{,}000)^3$. $P = 4 \times 10^6$ yrs, or 4 million years.

(b) Calculating the semi-major axis from its period gives $(125)^2 = a^3$. $a = 25$ A.U. Its major axis is 50 A.U., so aphelion distance is 50 - 1 = 49 A.U.

10. Using Kepler's Third Law gives: $(4200)^2 = a^3$, a = 260 A.U. $(2400)^2 = a^3$, a = 179 A.U. This is about 0.69 the previous size. With perihelion distance = 0.914, calculate the eccentricities using perihelion distance = a(1 - e). 0.914 = 260(1 - e), e = 0.996. 0.914 = 179(1 - e), e = 0.995.

11. In 100 days there are $100 \times 24 \times 3600 = 8{,}640{,}000$ s. The total mass lost = 8,640,000 s × 350,000 kg/s = 3×10^{12} kg. Dividing by the mass gives 0.0006 or about 0.06% of its mass was lost during this passage.

12. The mass of a comet will be its volume times its density. $m = 4/3\pi \times 5^3 \times 100$, m = 52,000 kg. The total number hitting the Earth per year will be 30,000 x 365 = 1.1×10^7. Multiplying this by the mass of each comet gives the total mass per year or 5.7×10^{11} kg. In one billion years this will amount to 5.7 x 10^{20} kg. This is about 0.0001 the Earth's mass.

    Chapter 7, Problem 5 gave the volume of the Earth's oceans to be about 1.3×10^{18} m^3. Water has a density of 1000 kg/m^3. This gives a total mass of the oceans to be 1.3×10^{21} kg. The comets, then, amount to about half the oceans' water, a rather interesting comparison.

13. First find the amount of rocky material in the comet. 0.05×10^{13} kg = 5×10^{11} kg. Since the average mass of a fragment is 0.1 kg, there must be 5×10^{12} fragments. Although this is a lot of fragments, in reality there would be many more; most fragments would be much less than 0.1 km in mass.

14. Number = $k \times$ Diam.^{2}, $k = 10^6$. For 1 km asteroids there will be 10^6. What is the mass of a 1-km diameter asteroid? Assume spherical shape and the density given of 3000 kg/m^3.

$$m = \frac{4}{3}\pi \times 500^3 \times 3000$$

$$m = 1.6 \times 10^{12} \text{ kg}$$

Notice that the mass depends on the cube of the radius and therefore also on the cube of the diameter. The following table gives the results for the masses.

Size	**Mass Each**	**Number**	**Total Mass**
1 km	1.6×10^{12} kg	10^6	1.6×10^{18} kg
10 km	1.6×10^{15} kg	10,000	1.6×10^{19} kg
100 km	1.6×10^{18} kg	100	1.6×10^{20} kg
1000 km	1.6×10^{21} kg	1	1.6×10^{21} kg

15. Aphelion is given by $a(1 + e)$, so calculating a from this gives $3 = a(1 + 0.8)$, $a = 1.7$ A.U. Calculating its period gives $P^2 = 1.7^3$, $P = 2.2$ yrs. In 2 billion years it has orbited the Sun 909 million times. But each time, it crosses the Earth's orbit twice, so 909 million × 2 = 1.8 billion times.

Resource Information

Student CD Media

Movies/Animations

Anatomy of a Comet - Part I
Anatomy of a Comet - Part II
Asteroid Comet Breakup
Comet Hale-Bopp

Interactive Student Tutorials

None

Physlet Illustrations

None

Transparencies

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Materials

Meteorite samples to pass around. These can be purchased from The Meteorite Exchange, Inc. Visit their website at www.meteorite.com

Suggested Readings

Basri, G. "What is a Planet?" *Mercury* (November/December 2003). p. 27. Overview of the debate concerning planetary status of several objects including Pluto. A good article for general comparative planetology.

Binzel, Richard P. "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.

Chapman, Clark R. "Worlds between worlds." *Astronomy* (June 1996). p. 46. Describes the results from the *Galileo* mission's observations of the asteroids Ida and Gaspra.

Cowen, Ron. "The day the dinosaurs died." *Astronomy* (Apr 1996). p. 34. Discusses evidence associating the crater Chixulub, the K-T boundary, and the extinction of the dinosaurs, and describes possible scenarios of how the impact actually resulted in the extinctions.

Graham, Rex. "Making an exceptional impact: Eugene Shoemaker." *Astronomy* (May 1998). p. 36. A biographical article about the life and work of planetary scientist Eugene Shoemaker.

Jenniskens, P. "Ready for the Storm." *Mercury* (November/December 2001). p. 14. Good article with informative discussion of how meteor showers are predicted.

Levy, David H.; Shoemaker, Eugene M.; Shoemaker, Carolyn S. "Comet Shoemaker-Levy 9 meets Jupiter." *Scientific American* (Aug 1995). p. 84. A summary of observations from the impact of comet Shoemaker-Levy 9 on Jupiter written by the discoverers of the comet.

Luu, Jane X.; Jewitt, David C. "The Kuiper Belt." *Scientific American* (May 1996). p. 46. Discusses our knowledge of the Kuiper Belt.

Morrison, D. "Target Earth." *Astronomy* (February 2002). p. 46. Discusses the possible scenarios concerning asteroid-Earth collisions. Also discusses common encounters with "large" meteors.

Phillips, J. "Meteorite Field Guide." *Mercury* (November/December 2001). p. 32. Recommendations for someone interested in starting their own meteorite collection. Includes list of reputable dealers.

Polakis, T. "Comet Seekers." *Astronomy* (January 2003). p. 74. Stories about amateur comet hunters and their tips on searching for comets.

Science (Sept 22, 2000). Issue featuring several articles on the science results from NEAR at Eros.

Semeniuk, I. "Asteroid Impact." *Mercury* (November/December 2002). p. 24. Excellent, detailed discussion of asteroid-sized impacts with the Earth. Also, discusses comet/debris impacts.

Shubinski, R. "The Lure of Meteorites." *Astronomy* (December 2003). p. 84. Everything you've ever wanted to know about the meteorite market.

Talcott, R. "Great Comets." *Astronomy* (May 2004). p. 36. Overview of some of the most spectacular comets of the 20th century. Many nice images.

Talcott, R. "Comet LINEAR breaks apart." *Astronomy* (Nov 2000). p. 28. A short news report about comet LINEAR and its break up as it passed close to the Sun.

Veverka, J.; Robinson, M.; Thomas, P. "NEAR at Eros: imaging and spectral results." *Science* (Sept 22 2000). p. 2088. Discusses the NEAR findings about the surface of Eros.

Weissman, Paul R. "The Oort cloud." *Scientific American* (Sept 1998). p. 84. Summarizes our current state of knowledge of the Oort Cloud.

Zimmerman, Robert. "When disaster strikes: extraterrestrial risks to earth." *Astronomy* (Nov 1999). p. 46. Discusses a wide range of possible risks to Earth from space.

Notes and Ideas

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

Demonstration and activity materials:

Notes for next time: