XI. Astronomy: Solar-System Debris and Comets

A. Pluto **was** generally the ninth planet from the Sun.
   1. Clyde Tombaugh discovered Pluto in 1930, after calculations suggested that the observed and predicted orbits of Uranus did not agree.
      a. However, it is now known that Pluto is too small to have produced the perceived discrepancy.
      b. The discrepancy probably wasn't real: the wrong mass had been assumed for Neptune when predicting the orbit of Uranus.
      c. Thus, Pluto just happened to be in the predicted part of the sky! However, the discovery of Pluto remains a testament to Tombaugh's skill and thoroughness: it was a very dot among tens of thousands of stars in the photographs that he examined.
   2. Pluto's 249-year orbit is very peculiar.
      a. It is highly eccentric (e = 0.25).
      b. For 20 years each orbit, Pluto is actually closer to the Sun than Neptune is. (The most recent such interval was 1979-1999).
      c. The orbit is highly inclined to Earth's orbital plane (I = 17^0).
   3. The physical properties of Pluto are also unusual.
      a. It is small, with a radius of only 0.2 earth radii and a mass of 0.0025 earth masses, quite unlike the neighboring giant planets.
      b. It's density is about 2 g/cm^3, between those of the giant and terrestrial planets, and similar to that of Neptune's moon Triton. Pluto probably consists of icy rocks.
      c. Pluto's rotation axis is nearly in the Earth's orbital plane, like that of Uranus.
      d. It has a thin methane atmosphere (thickest when Pluto is closest to the Sun).
   4. In 1978, J. Christy discovered Pluto's moon, Charon.
      a. It has a radius half that of Pluto.
      b. This ratio of radii makes the system look like a "double planet".
      c. Charon completes one orbit in 6.4 days. Both Charon and Pluto are in synchronous rotation, so the same hemispheres always face each other.

d. Because of the extreme tilt of Pluto's axis of rotation (and the axis about which Charon orbits), there are two 5-year intervals during Pluto's 249-year period when the two objects eclipse each other.
e. Measurement of these eclipses yields the radii of the bodies, etc.

5. Pluto is the only planet in the Solar System that has not been visited by spacecraft. It was roughly opposite the direction in which the Voyagers were traveling.
6. Pluto is definitely a strange planet.
   a. Astronomers have speculated that it is a former moon of Neptune, torn away by a gravitational encounter or a collision, but this now seems unlikely.
   b. Pluto may be simply the largest and one of the nearest objects in the "Kuiper belt", a reservoir of comets in the outer parts of the Solar System. Triton may have initially been a similar object, subsequently captured by Neptune.
   c. On July 14, 2015 our New Horison spacecraft successfully flew by Pluto. During this encounter, it collected more than 1,200 images of the dwarf planet and tens of gigabits of intensive downloading of this information began on Sept. 5, and will continue for around a year. With the information being returned for the duration of a year, we still have a lot more to learn about Pluto. Here are a few things we've discovered so far:

i) Pluto's vast icy plain, informally called sputnik planum, resembles frozen mud cracks on Earth. It has a broken surface of irregularly-shaped segments, bordered by what appear to be shallow troughs. In other areas, the surface appears to be etched by fields of small pits that may have formed by a process called sublimation, which is when ice turns directly from solid to gas, just as dry ice does on Earth.

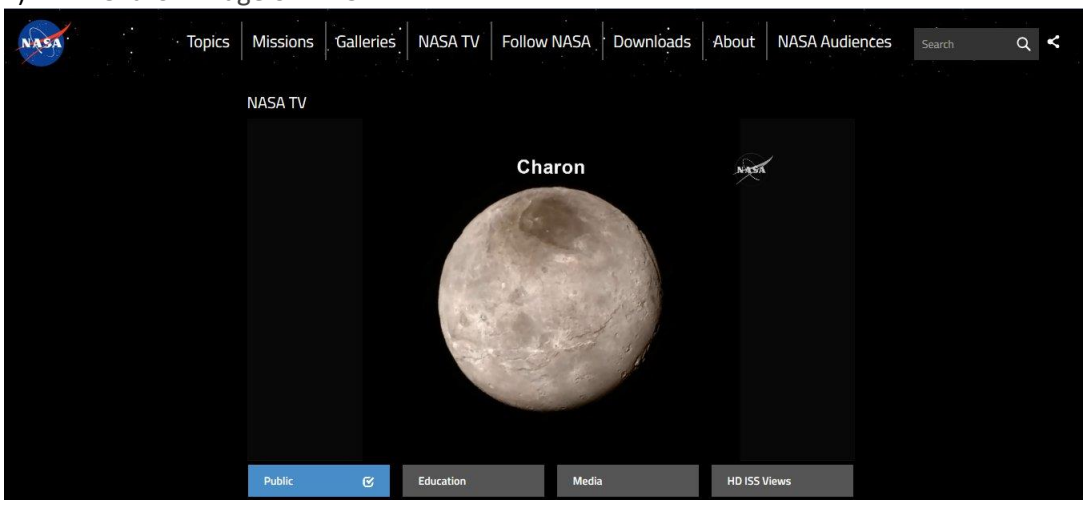
ii) Images from the spacecraft display chaotically jumbled mountains that only add to the complexity of Pluto's geography. The rugged, icy mountains are as tall as 11,000 feet high.

iii) This high-resolution enhanced color view of Pluto combines, blue red and infrared images taken by the New Horizons spacecraft. The surface of the dwarf planet has a remarkable range of subtle color variations. Many landforms have their own distinct colors, telling a complex geological and climatological story of the planet.

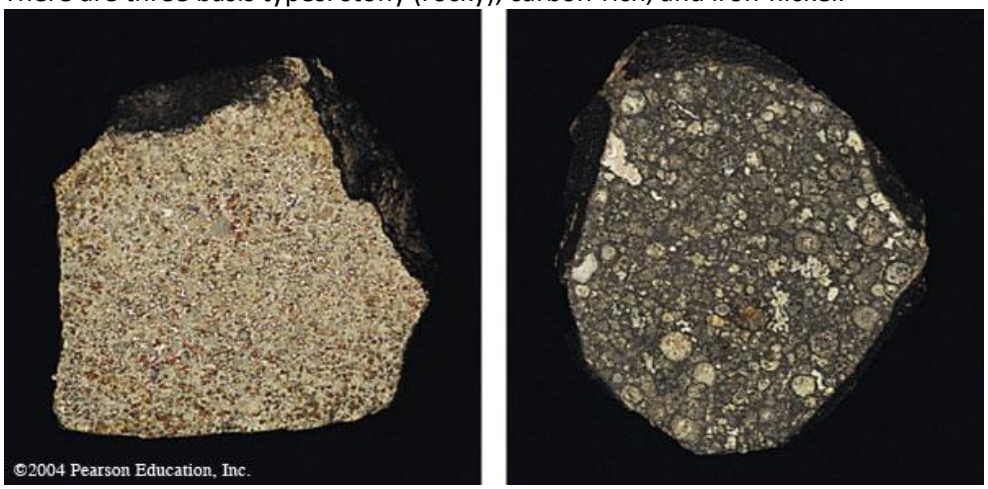
iv) Images returned from the New Horizons spacecraft have also revealed that Pluto's global atmospheric haze has many more layers than scientists realized. The haze even creates a twilight effect that softly illuminates nightside terrain near sunset, which makes them visible to the cameras aboard the spacecraft. Today, a new

announcement was made about Pluto's atmosphere after the most recent image returned from New Horizons showed that Pluto's hazes are blue. The haze particles themselves are likely gray or red, but they way they scatter blue light has created this tint.\

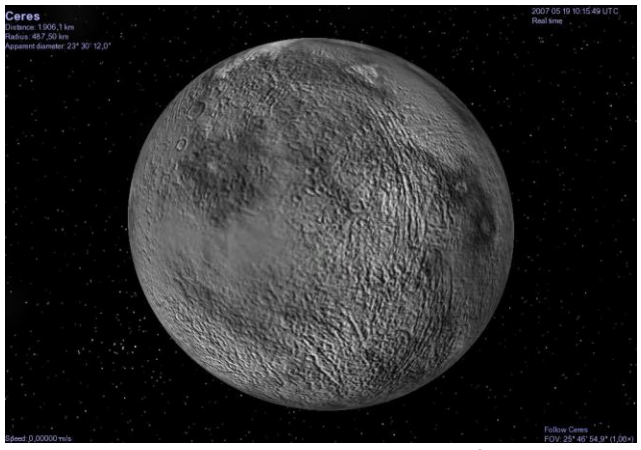
v) Charon image on NASA TV



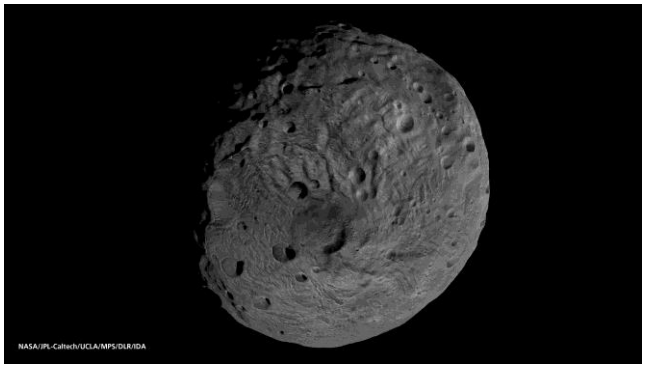
B. Asteroids and meteoroids (Drawf Planets) constitute important "debris" in the Solar System.
   1. Most asteroids ("minor planets") occupy a belt about 2.8 A.U. from the Sun, where astronomers expected to find a planet.
      a. The first one (Ceres) was discovered in 1801.
      b. Several others were found in subsequent years.
      c. Thousands are now known; there may be 10^5 total.
      d. About 6 are larger than 300 km in diameter; most are small (<10 km).
      e. There are three basis types: stony (rocky), carbon-rich, and iron-nickel.



f. Probably Jupiter's tidal forces prevented the planet from forming.
g. Being primitive objects, asteroids provide clues to the Solar System's origin.
h. Asteroids in the inner half of the asteroid belt are light-colored, like terrestrial rocks, composed of different kinds of silicate minerals and metals. (Stony = upper left figure above). Some melted and resolidified long ago, due possibly to primordial, short-lived radioactive isotopes, or even to electrical currents induced by the strong electromagnetic fields of the primeval sun. Once they melted, iron drained to the center, forming melted cores. Fragments of these asteroids can thus be lava like rock or pure metal chunks. (Iron-Nickel = lower center figure above).
i. From the zone of Ceres outward, away from the sun, asteroids are of a different type, black in color. These are called carbonaceous asteroids, colored by soot like carbon compounds that condensed in the cold temperatures of those regions. (Carbonaceous = upper right figure above).
j. 1 Ceres is of carbonaceous material at about 914 km across. It is almost twice as big as the next largest asteroid.
    i) Ceres is located in the middle of the asteroid belt, among the thousands of asteroids between Mars and Jupiter.
    ii) Ceres was formed by the aggregation of dust in the same way as planets aggregated, and at the same time.
    iii) Although the asteroid belt contains thousands of asteroids, they are small enough and far enough apart so that an observer on Ceres sees a sky similar to our own.



k. The most peculiar large asteroid is 4 Vesta, the fourth asteroid to be discovered, and first seen in 1807. Telescope observations of it's spectrum indicate that among 100 or more largest asteroids, Vesta is the lny one with a surface of lava-like rock.



i) Watching Vesta as it rotates reveals a patchiness in the basalt----more on one side than the other.

ii) The fuzzy images above reveal an oblate object, 458-578 km, with some irregularities and brighter patches. According to astronomers, there is a crater 460 km across and 13 km deep near the south pole.

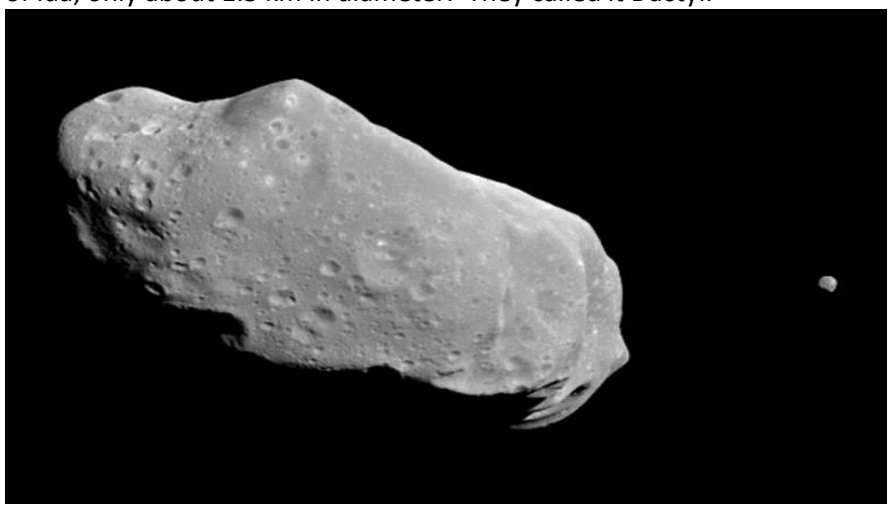
l. When the 1990s Galileo probe was being launched on it's multiyear voyage to Jupiter, mission controllers recognized that it would have the first opportunity in history to fly past one or more asteroids, while it was on the way to the giant planet.

i) Galileo's first encounter with an asteroid—the first in history---came in 1991 when it zipped past the stony (S-type) world-let, 951 Gaspra, and confirmed that it was a city-sized pebble (about 20 by 11 km). Spectra and colors confirmed the rocky composition pocked with impact pits.

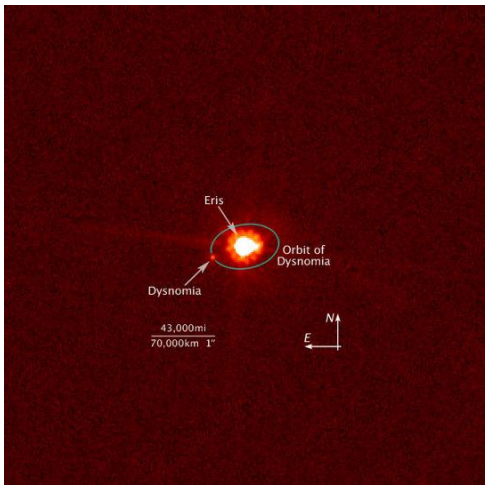
m. Galileo's second asteroid encounter, in 1993, took it past another seemingly typical asteroid, a stony example named 243 Ida-----but this time, nature provided an expected bonus.

i) Ida turned out to be a potato-shaped rocky world with a dimension of 30 x 13 x 9 km.

ii) In the black sky surrounding the asteroid was another object----a small satellite of Ida, only about 1.5 km in diameter. They called it Dactyl.



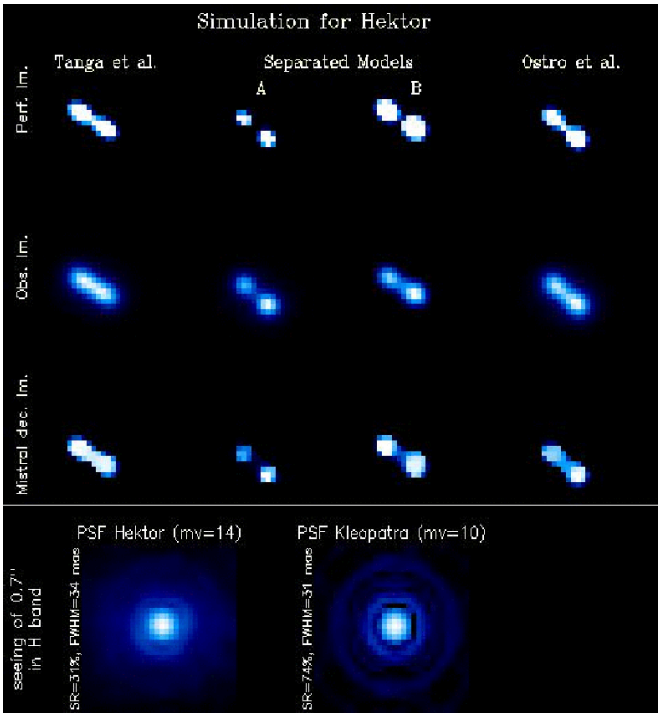
n. Eris is the largest dwarf planet in the Solar System, and the ninth largest body orbiting our Sun. Sometimes referred to as the "tenth planet," its discovery is responsible for upsetting the traditional count of nine planets in our Solar System, as well as leading the way to the creation of a new astronomical category.



i) Located beyond the orbit of Pluto, this "dwarf planet" is both a trans-Neptunian object (TNO), which refers to any planetary object that orbits the Sun at a greater distance than Neptune – or 30 astronomical units (AU). Because of this distance, and the eccentricity of its orbit, it is also a member of a population of objects (mostly comets) known as the "scattered disk."

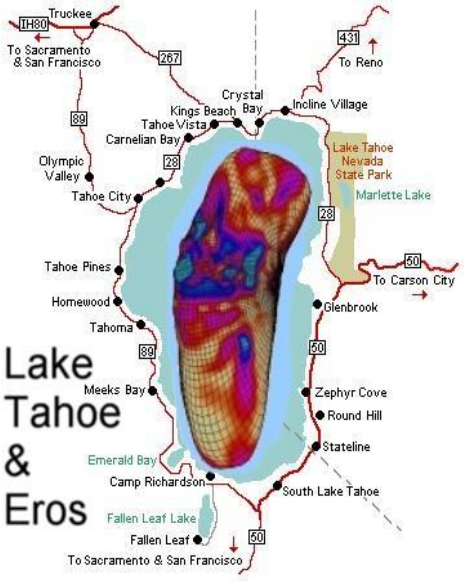
ii) The discovery of Eris was so important because it was a celestial body larger than Pluto, which forced astronomers to consider, for the first time in history, what the definition of a planet truly is.

2. Meteoroids are chunks floating through the Solar System, not in the asteroid belt.
   a. The majority are small (<10m).
   b. Among the most interesting of these mavericks are 2 groups that follow the same orbit as Jupiter ---one 60^0 ahead of Jupiter and the other 60^0 behind. The gravitational forces of both the sun and Jupiter conspire to hold them in place.
      i) Since astronomers named these asteroids after heroes in the Trojan Wars, they have become known as the Trojan asteroids.
      ii) There are as many asteroids among the Trojans as in the main belt. One survey published n 2000 estimated more than 160,000 larger than 1 km---and that was in only one of the 2 swarms.
      iii) The largest and brightest Trojan is 624 Hektor. It has a very dark, brownish-black color, which has long suggested that it is dominated by sooty-black carbon-rich material, like that found on Ceres and among most asteroids in the outer asteroid belt.
      iv) Hektor varies in brightness by a factor of three. Such variations are not unprecedented, but in this case some conclusions resulted.
      v) Studies suggest that, allowing for gravity, tidal stretching, rotation, and weak, fractured material, Hektor would have distorted into a shape like two eggs stuck end to end. We called this a "compound asteroid". Perhaps an initial collision produced a loosely consolidated, fragmented mass, which then deformed into the weird compound configuration.



c. Most meteoroids are probably affected from the asteroid belt by collisions.
d. When they enter the Earth's atmosphere, they burn due to friction; this is the phenomenon known as a meteor ("shooting star").
e. Most meteors are just small pebbles or grains of sand.
f. Meteors are best seen after midnight, when you are on the side of the Earth that is heading through the oncoming debris.
g. To answer near Meteoroid and Asteroid weathering, a "near Earth Asteroid Rendezvous" spacecraft was launched in 1996 and rendezvoused with 433 Eros in 1999.
    i) NEAR spacecraft, as it come to be known, was designed to approach Eros, fire it's engines, and go into a lazy, looping orbit around the floating rock, and study it with many instruments for about a year. (Completed in 2000).

    ii) Renamed NEAR-Shoemaker made many discoveries. Eros was found to be almost wiener-shaped, 34 x 13 x 13 km.



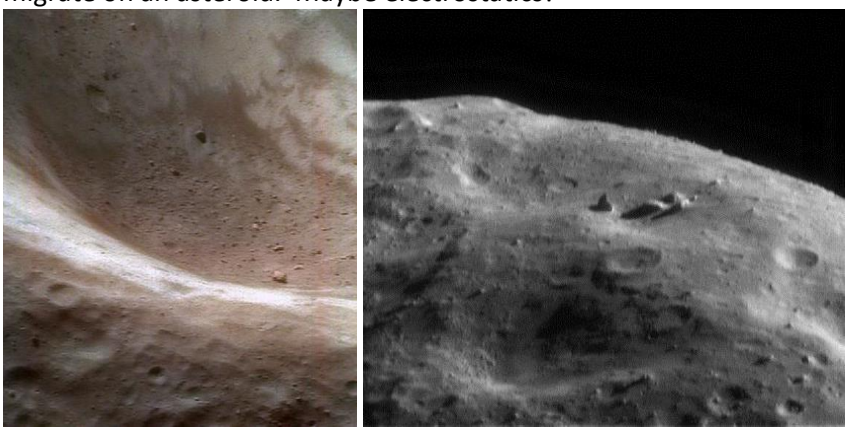
iii) The surface was not rough, but sandblasted by countless micrometeorites, like a smooth, rounded pebble.

iv) The gravity was so low that a good pitcher could throw a rock clear off Eros into interplanetary space. The gravitational effect on the orbit showed that the interior structure of Eros was relatively uniform, with a mean density of 2.67 g/cm^3, which would be consistent with impact-fractured chondritic meteorite rock, where the fractures created cracks and pore spaces in 10-30% of the volume.

v) One prominent round crater, 7.6 km across, was also name after Dr. Shoemaker.

vi) After a year of observing Eros from orbit, the spacecraft was beginning to age, and a bold plan was conceived to climax the mission. By firing the engines carefully with the remaining fuel, it would be possible to bring the spaceship down onto the surface of Eros!

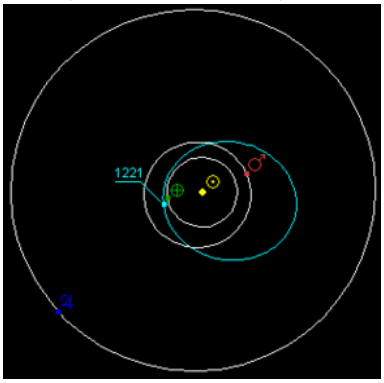
vii) In February 2001, the descent was made. Something surprising emerged from the final pictures. Crater floors were often smooth, flat deposit of dust, as if dust had migrated and filled depressions. But what could cause dust to migrate on an asteroid. Maybe electrostatics!



h. Meteoroids that cross over the orbits of planets in the inner solar system planets are grouped according to different names.

i. Meteoroids crossing inside Mars's orbit are called Amor Meteoroids, named after a prominent example that was one of the first of the group to be recognized.

j. Amor, discovered 1932, is a tumbling, rocky worldlet about 33 km in diameter.



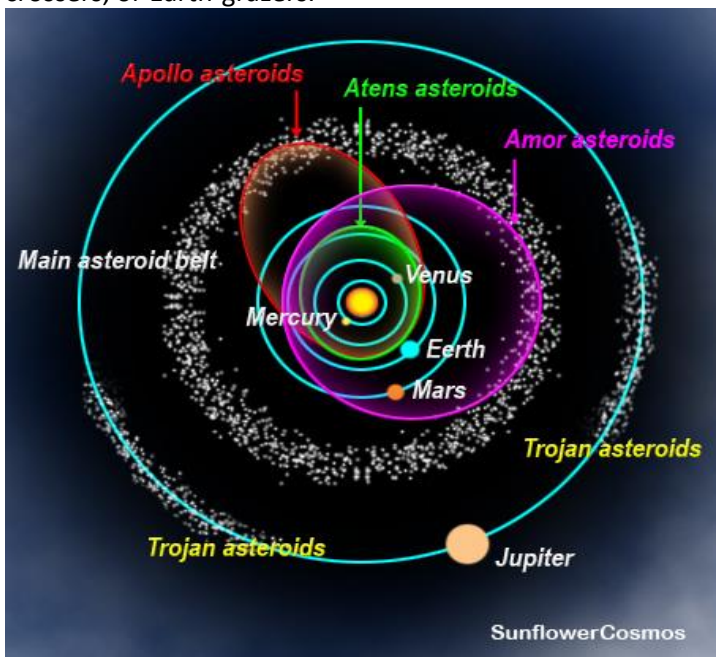
i) Many dozens of Amors are now known. Among other large ones are 422 Eros (34.13 km) and 1036 Ganymed (30 km).

ii) Gravitational disturbances by the planets are likely to change Amor orbits slowly over millions of years, so that eventually they will move into configurations in which close approaches and impacts are possible.

iii) Those that don't directly hit Mars may be thrown into new courses by close encounters with Mars; these new courses may take them on Earth-crossing orbits, or orbits that allow close approaches to some other planet.

k. Apollo Meteoroids are related to Amor Meteoroids, differing in that they drop far enough into the inner solar system to cross over the orbit of Earth. Their closest approach to the sun (0.5-0.9 A.U) is usually in the asteroid belt.

i) Apollo asteroids, like Amors, are named aft the classic example of their group, 1862 Apollo, a tiny, 1.5 km meteoroid. They are sometimes called Earth-crossers, or Earth-grazers.



ii) Of the many dozen Apollo meteoroids now known, the biggest are about 8-10 km across, and nearly all are bigger than 1 km. Many smaller ones also exist,

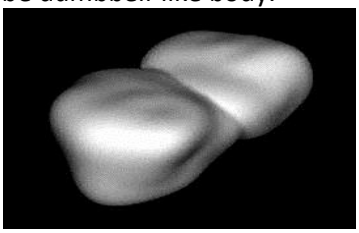
all too tiny to detect with telescopes, but the tiny ones are so numerous that many hit Earth each year, breaking into pieces in the atmosphere and hitting the ground as ***meteorites.***

l. As astronomers discover more Apollo meteoroids, they add to the list of bizarre objects in the solar system. An interesting new radar technique allows amazing images of the ones that pass closest to Earth. This technique involves bouncing radar waves off the interlopers.

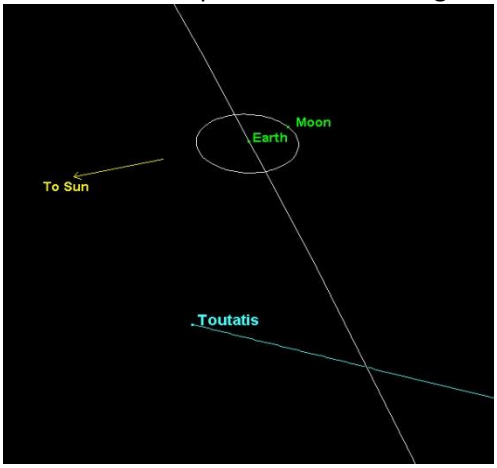
m. The first striking radar result come from an Earth-passing meteoroid name 4769 Castalia.

i) It is about 1.7 X 1.0 km in size and rotates in about 5 hrs.

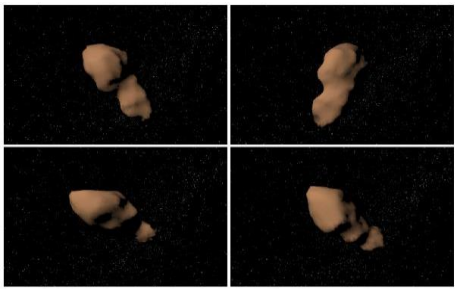
ii) They found it to be dumbbell-like body.



n. By 1992, the radar technique had improved and the close pass of Apollo Meteoroid 4179 Toutatis enabled them to make a photolike radar image of the object.



i) The astonishing image, released in January 1993, show that Toutatis resembles two lumpy, cratered rocks stuck together. Roughly 4 X 7 km in size, it is the slowest-rotating meteoroid known, taking about 10-11 days to make one turn.



ii) It is theorized that during chaotic fragmentation of a larger parent, two neighboring kilometer-scale fragments flying out of the explosion might find themselves on parallel courses and could fall together by their own gravity. This would produce a compound double body like Castalia and Toutatis.

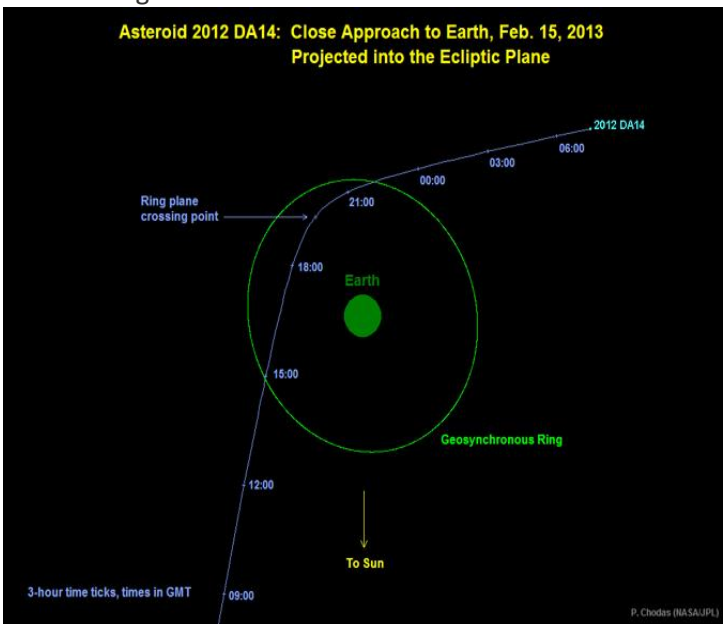
o. Earth-passing asteroids are visible for only a few weeks or months until they sail away into-distant space. In order to observe such an object, astronomers have to hustle to get the coordinates and prepare their equipment.

i) Meteoroid 6178 was an example of this in 1986. However, this meteoroid was found to have unusual properties. The nature of the radar signal indicated that the surface bounced back an unusually strong radar signal, and that it is unusually rough.

ii) The only interpretation that made sense was that 6178 is bare metal, possibly twisted into grotesque fine-scale shapes due to impacts. (Potential to mine).

iii) This 2 km chunk of iron and nickel would contain over 10 trillion tons of metal. This could represent an economic value of a trillion dollars or more.

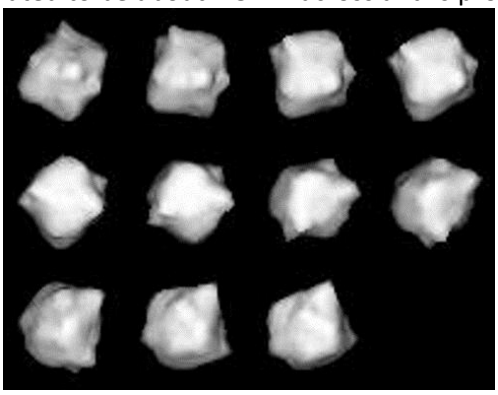
p. On February 15, 2013, the 150-foot wide Asteroid 2012 DA14 flew past earth, closer than any other object its size. Though earth was in no danger what-so-ever, the frightening close flyby (only 17,200 miles) has many wondering if this near-miss is a hint of things to come.



3. Some meteoroids reach Earth's surface and are then called meteorites.

a. The chance of hitting a human is low, but it has happened (or nearly so).

b. Meteorites are readily found in the Antarctic; there are few indigenous rocks and little erosion on the ice fields.
c. Radioactive-dating shows that meteorites are about 4.6 billion years old. They are the oldest known objects, and effectively define the age of the Solar System.
d. Chemical analysis shows that a few known meteorites came from the Moon or Mars. They provide a cheap way of getting samples from these bodies.
e. Recall that possible signs of microbial life were found in the Martian meteorite ALLH84001. Analysis of impact craters on Mars reveals two good candidates from which this rock may have been ejected.
f. Some carbon-rich meteorites have complex molecules like amino acids, the precursors of life as we know it.
g. About 7% of meteorites that fall on Earth are pieces of ancient basalt lava, formed about 4,400 MY ago. Since Vesta is the only large basaltic source in the asteroid belt, it is probable that the basalt meteorites come from it.
    i) Fragments of Vesta, after an asteroid collision, orbiting close to resonance positions in the belt, could have been defected onto Erth-crossing orbits.
    ii) Apollo meteoroids have been identified to have come from Vesta. The largest is 3908 Nyx.
    iii) Nyx is estimated to be about 1.5 km across and is probably irregular in shape.



C. Comets ("hairy stars") are diffuse, luminous patches that move across the sky form night to night and sometimes have long tails.
1. They are basically "dirty snowballs" that evaporate as they approach the Sun.
    a. The head of the comet consists of various ices (water, carbon dioxide, methane). A typical mass is 10^{-11}Earth masses.
    b. The tail of a comet is very dilute, nearly a vacuum. There is no danger when Earth passes through it, as was the case in 1910 with Halley's Comet, in which cyanide was present.
    c. Although comets have a long history of being bad omens, they are generally harmless (but not always, as we will see).
    d. The tail of a comet consists of dust and gases evaporated from the head and pushed away by the Sun's radiation pressure and solar wind. It therefore points away from the Sun.
    e. Actually, there are two tails: (1) a straight, bluish "ion tail" composed of charged particles rapidly swept back by the solar wind, and (2) a curved, yellowish "dust tail" composed of particulate matter pushed gently by the Sun's radiation pressure.
2. *Periodic* Comets visit the solar vicinity many times: their orbits are high eccentric ellipses.

a. According to Kepler's second law, a periodic comet spends most of it's time far from the Sun, and swings past the Sun very quickly.
b. A famous example is Halley's Comet, whose orbital period is about 76 years. It's last visit to the Sun was in 1985/86, and It's orbit goes out past Neptune.

c. Comet Hale-Bopp, which flew past the Sun in April 1997, was the brightest comet in about 20 year. I's orbital period is a few thousand years.

i) Comet Hale-Bopp made its closest approach to Earth on March 22, 1997 at a distance of 1.315 AU (1 AU = 93 million miles or 150 million km). It reached perihelion (closest distance to the Sun) on April 1, 1997 at 0.914 AU.
ii) The comet did not pass particularly close to either the Sun or the Earth, but because of its rather large size, the comet was very bright and reached a peak magnitude of about -1. In fact, Comet Hale-Bopp was at magnitude 0 or brighter for an astounding 8 weeks, the longest ever recorded for a comet.
iii) Also, Comet Hale-Bopp holds the record for the longest period of naked eye visibility, an astonishing 19 months, easily breaking the the previous record of 9 months held by the Great Comet of 1811.

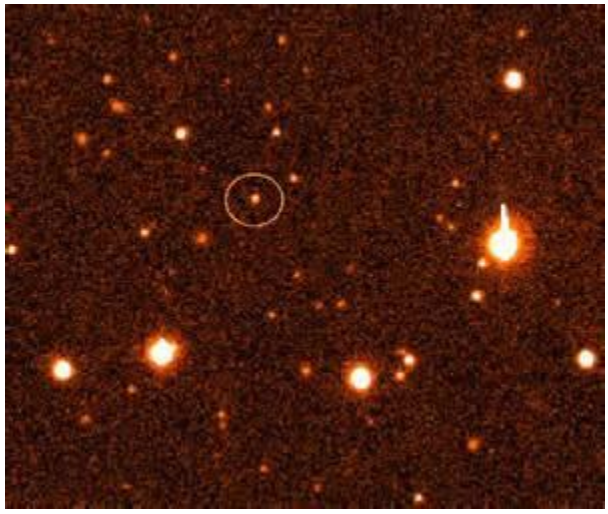
d. A periodic comet loses mass whenever it's near the Sun, and gradually disappears.

e. Meteor showers occur when Earth passes through the orbit of an old or disintegrating comet. This happens at the same time each year for a given shower. Meteor showers are generally best viewed after midnight because more debris is intercepted.
f. If the debris form an old periodic comet is not spread uniformly throughout the orbit, but instead is clumped, a "meteor storm" may occur if Earth passes through the main clump.
g. A good example of this is the Leonid meteor shower; every 33 years it has the potential of being very active, as it was for a brief interval in 1966.

3. Most comets are not periodic; they are on hyperbolic orbits and visit the Sun only once.
   a. They originate in comet reservoirs known as the "Kuiper belt" (in the plane of the Solar System, beyond the orbit of Pluto) and the "Oort cloud" (a sphere of about 10^{12} comets, roughly 50,000 A.U form the Sun).
   b. Objects have been seen in the Kuiper belt (KBO), but the Oort cloud comets are too faint.
   c. Sometimes a passing star or other perturbation directs comets toward the Sun.
   d. If Jupiter or another giant planet gravitationally perturbs an incoming comet in the right manner, the comet can become periodic.
4. Pluto is close to where we expected to find at least the inner members of the long-hypothesized *Kuiper Belt (KBO)*.
   a. Some of the KBO are quite large. Quaoar, the largest known, is over half the diameter of Pluto itself and was found only recently.
   b. All this evidence makes it almost certain that Pluto is fundamentally a KBO, though the largest one known at this time. But there are others of comparable size.
      i) Thus, either Pluto is not a planet or there are many additional planets similar to Pluto.
      ii) If other large KBOs had been discovered shortly after Pluto was found, Pluto probably would not have been called a planet---at least not for long.
   c. 2004 DW is a classic KBO, meaning that it's orbit lies close to Pluto's realm.
      i) 2004 DW's closest approach to the sun is 31 AU and it's farthest distance is 48 AU. Compare these figures to the very similar figures for Pluto: 30 AU and 49 AU.
      ii) The inclination of the orbit of 2004 DW to the plane of the Solar system is 21^0, compared to a similar 17^0 for Pluto. This compare to a well-behaved 1.7^0 for a

nearby Neptune; no other planet strays more than 7^0 out of the solar system's plane.

iii) The diameter of 2004 DW is between 1000-1500 km, roughly 43-65% of the diameter of Pluto itself.



iv) These figures further emphasize the Pluto is more accurately called "King of the Kuiper Belt" than the "ninth planet".

. d. One could perhaps use sphericity as part of the definition of a planet or , at least, a …… minor planet.

i) Most asteroids have an odd shape; they aren't large enough for their own self-gravity to have made them spherical.

ii) Those with a diameter larger than about 400 km (about 6 asteroids) became spherical; we might consider these to be true minor planets (and the rest to be simply asteroids).

iii) In that case, however, Pluto and at least three other known KBOs should be called minor planets as well, giving a total of at least 10 minor planets (and probably quite a few more that are still undiscovered).

e. An additional potentially relevant point is that Pluto has a large moon, Charon. At first glance, one might think that this qualifies Pluto to be a true planet.

i) However, such moons are common: About 5% of the know KBOs have a moon, and the moon's mass is often nearly the same as that of the KBO to which it is bound.

ii) These pairs probably formed early in the history of the Solar System, as a result of gravitational encounters between several bodies.

iii) About 5% of the asteroids have moons, too, but generally the moon is much smaller than the asteroid itself.

iv) The moons of asteroids are probably the debris produced by the asteroid collisions, in many cases, quite recently.

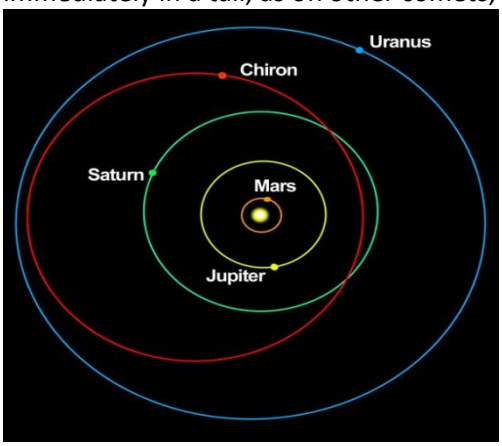
5. Chiron was discovered in 1979 by astronomer Charles Kowal. Appearing only as a starlike point on the original photographs, it was cataloged as an asteroid, #2060. However, 2060 Chiron was immediately recognized as unusual because it's orbit, lying between Saturn and Uranus, is much farther from the sun than any other known asteroid.

a. In 1988, Chiron was discovered to be twice as bright as it was supposed to be.

b. The brightening continued for months, reaching nearly 3X the "normal" brightness.

c. Chiron had turned into a comet.

d. Then, over many months, it's brightness faded, as if the cometary eruptions had declined.
e. The observations place the diameter at about 180-300 km. This turns out to be by far the largest comet known.
f. Because Chiron is larger than other comets, the dust and gas is not blown away immediately in a tail, as on other comets, but is held somewhat by Chiron's gravity.

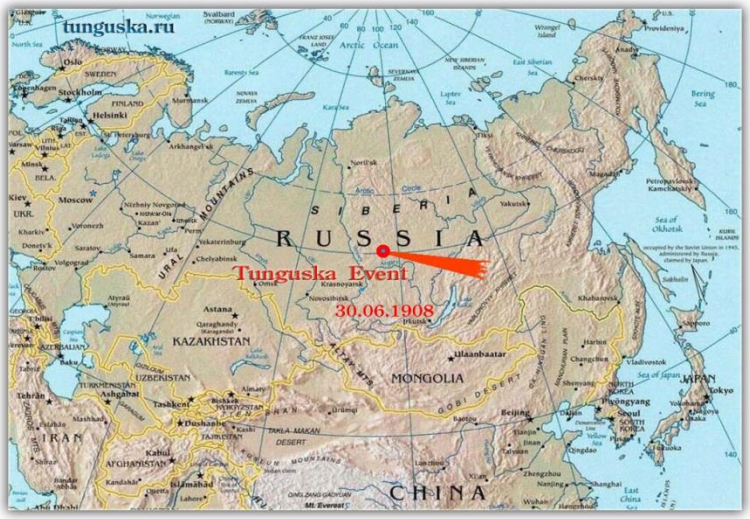


g. Chiron orbit is unstable. Every few thousand years it comes close to Saturn, and within a million years of so it may pass so close that Saturn's gravity will radically change Chiron's orbit. Chiron will eventually be thrown into the inner solar system, to pass by Earth as one of the brightest comets of all time.

6. Comets are made of primitive, cold material whose properties were not affected by planet formation. They therefore offer clues to physical conditions in the early Solar System. It is also possible that much of the water on Earth, and perhaps even some of the organic compounds, came from comets.

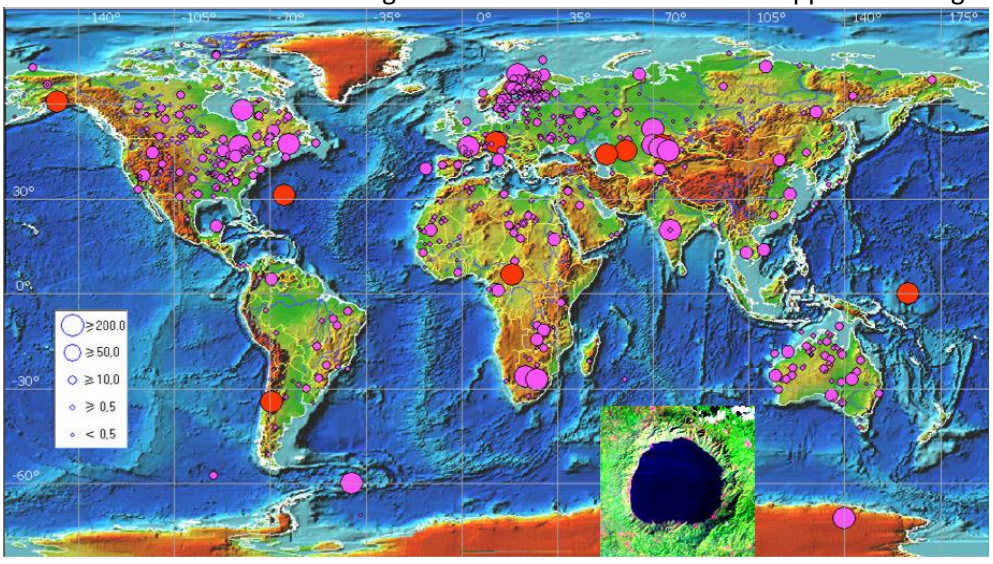
D. Life on Earth is threatened by cosmic collisions.
1. Some group of asteroids (mainly "Apollo") have orbits that cross Earth's orbit. Usually Earth is not at the location of the asteroid at the time it crosses Earth's orbit, but sometimes it is.
2. Random meteoroids and comets can also cross Earth's orbit.
3. Recent collisions have clearly occurred.
   a. The Barringer meteor crater in Arizona, for example, has a diameter of 1.2 km and an age of about 50000 years.
      i) It was probably produced by a meteorite with a diameter of about 60 m.

b. The famous “Tunguska event” in 1908 leveled 2000 square km of forest in Siberia.



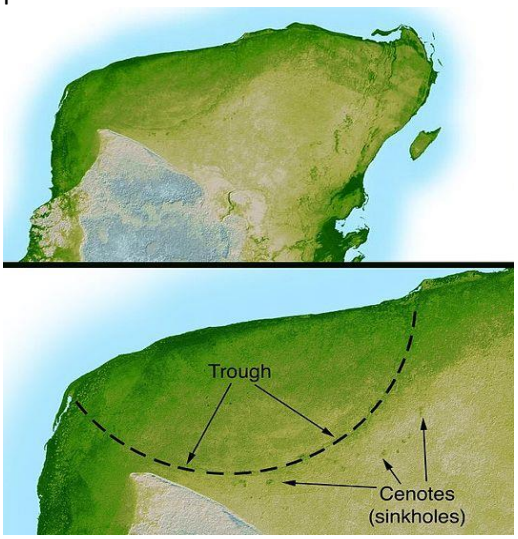
i) It had an energy of about 15 megatons of TNT. For comparison, the largest hydrogen bomb ever exploded had an energy of 60 megatons.

c. Despite erosion on Earth, over 140 terrestrial craters have been identified. The amount of erosion and radioactive dating can be used to determine their approximate ages.



4. There is some evidence that the crater ages cluster around intervals of roughly 30 million years.
    a. A hypothetical distant companion star to the Sun might cause periodic disturbances of the Oort cloud, sending comets toward Earth, but such a star has not been found, and there are also theoretical difficulties with it's existence.
    b. Nearly periodic disturbances might instead be produced by Earth's passage though spiral arms of the Milky Way Galaxy, or by some other mechanism.
5. There are roughly 300 Earth-crossing asteroids known with diameters of 1 km.
    a. It is estimated that there are 2000-4000 such Meteoroids.
    b. Statistically, we expect 1 collision per 300,000 years, releasing 10^5-10^6 megatons.
    c. "Small" blasts like Tunguska might occur every 300 years, on average.
6. Statistically, averaged over tens of millions of year, a person is as likely to die form a cosmic collision as from an airplane crash, flood, or tornado.
7. The largest threat is from asteroids or comets with a diameter of about 10 km. These hit Earth roughly every 30 million years, and would probably spell the end of human civilization.
    a. The 10^8-10^9megaton explosion devastates the surroundings to a radius of about 1000 km.
    b. The rest of the Earth is like an oven set to "broil" as debris form the impact crashes down. Widespread fires erupt.
    c. A collision in the ocean would also produce enormous tidal waves.
    d. All this is followed by an "impact winter" produced by dust in the atmosphere; sunlight is blocked for several months, destroying the food chain. Acid rain is produced.
    e. Subsequently, there could be thousands of years of global warming due to the large amounts of greenhouse gases (water, carbon dioxide) dumped into the atmosphere.
    f. It is not clear that the human race could survive such a destructive event. Perhaps a few people would continue living in specially designed underground caverns, but they would need a large storehouse of supplies.
8. An intriguing and well-supported hypothesis is that an event of this type caused the "Cretaceous/Tertiary (K/T) extinction" 65 million years ago.
    a. Although dinosaurs may have already been dying out due to climatic changes (this is controversial), the remaining dinosaurs perished quite suddenly.
    b. About 2/3 of all living species were wiped out at that time. Curiously, some species survived, while other related ones were fully extinguished.
    c. The short duration of the extinction event is vividly demonstrated by small marine creature ("forams"): below the K/T boundary certain species are highly abundant, and above it they are completely absent. The boundary itself is very narrow and hence short-lived.
    d. In 1979, Luis Alverez and his team at UC Berkeley (including his son Walter) found a thin layer rich in the element iridium in the K/T boundary.

e. Iridium is normally very rare on earth's crust because it tends to stick to iron, and most of the iron sank to the core early in Earth's history when it was molten.
f. It's abundance in the K/T boundary is consistent with the collision of an asteroid or comet, whose iridium would have dispersed throughout the Earth's surface.
g. In 1991, the probable impact site was identified just offshore from the Yucatan peninsula of Central America.



9. Regardless of how the dinosaurs died, such an event is a real threat, as shown by the collision of Comet Shoemaker-Levy 9 with Jupiter.
   a. This comet, having a diameter of about 10 km, was captured into a highly eccentric orbit around Jupiter several decades ago.
   b. In 1992, during it's penultimate close approach, it was torn apart into more than 20 pieces by Jupiter's tidal forces.
   c. The pieces crashed into Jupiter the next time around, on 16-22 July 1994.
   d. The energy released by the largest chunk was about 6 million megatons---100,000 X larger than the biggest hydrogen bomb. (40 million megatons).
   e. Telescopes all over the world were used to observe this, mostly at infrared wavelengths because so much heat was generated.
   f. Several new spots formed on Jupiter, in some cases larger than Earth.

   g. Such collisions occur on Jupiter roughly every 2-3 thousand years, much more frequently than on Earth, since Jupiter has a large cross-sectional area and it's gravity tends to pull comets in.

h. It would be wise to devote more resources to systematic searches for searches for Earth-crossing asteroids and comets.

E. Questions:

1. List the basic physical and orbital properties of comets.

2. Discuss the origin and importance of comets.

3. Explain the process by which a meteor shower occurs.

4. Identify the evidence for relatively recent cosmic collisions with Earth.

5. Describe what is thought to happen when a large (diameter about 10 km) asteroid or comet hits Earth.

6. Summarize the evidence that the Cretaceous/Tertiary extinction was triggered by a catastrophic collision.

7. Discuss the significance of the collision of Comet Shoemaker-Levy 9 with Jupiter.

8. Do you worry about asteroid or comet collisions? What could be done to save the Earth if an asteroid were discovered sufficiently far in advance of the collision?
9. Discuss the peculiarities of Pluto and their implications.

10. Distinguish between asteroids, meteoroids, meteors, and meteorites.

11. Explain what a “shooting star” is.

12. Discuss the importance of meteorites in studies of the Solar System.

13. Now that many objects have been discovered in the Kuiper Belt, do you think Pluto should still be called a planet? Why?

14. Asteroids are among the oldest, most primitive objects known in the Solar System. However, since there are three different types (stoney, iron-nickel, and carbon-rich), is it fair to say that all asteroids consist of original, completely unprocessed (raw) material?

15. Describe the main characteristics of 1 Ceres:

16. What are the differences between the Apollo, Trojans and Amor Asteroids?

17. Describe the main characteristics of Chiron:

18. Describe the main characteristics of 4 Vesta:

19. When is and what causes the Leonid Meteor Shower?

20. What is the main characteristic of 243 Ida?