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Asteroids, Comets, and Meterorites: Their Intimate Relation with Life on Earth

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I. INTRODUCTION (WHAT IS BIOGEOPLANETOLOGY?)

This curriculum unit presents an interdisciplinary approach to the study of science, bringing together information from astronomy, earth science and ecology. The unit, written as part of the seminar "Outstanding Problems in Contemporary Astronomy and Cosmology," addresses the question, "how is and how has life on Earth been influenced by events occurring in our Solar System?" More specifically, I present information on the relation between asteroids, comets and meteorites and life on Earth. I review current scientific thinking about how our Solar System's asteroids and comets interacted with a young Earth to create the necessary conditions for the origin of life, and how meteoritic impacts have altered the evolution of life through Earth history. Sample teaching strategies are presented to suggest ways of presenting the subject matter to students.

In developing this topic, I have drawn on my deep interest in ecology and an interest in earth science, including the fields of paleontology and mass extinction theory. The Teachers Institute seminar has been an excellent vehicle for learning more about astronomy and cosmology, especially solar system astronomy and planetary science. It has given me an opportunity to read and talk about issues in astronomy and to combine pertinent information from the fields of astronomy, earth science, and ecology.

The underlying theme of the unit is that we now known enough about the origin, evolution, and dynamics of our Solar System to establish a new branch of ecology called astroecology, or perhaps more aptly called biogeoplanetology by ecologist Stephen Collins. Biogeoplanetology is a logical extension of the hierarchy of study used in ecology, which pursues an understanding of life at organismal and population, community, ecosystem, and landscape and global levels. Each of these branches of ecology asks its own set of questions about the nature of life, based on the selected scale of study and appropriate temporal and spatial considerations. Populations are groups of organisms of the same species. Communities are collections of different species living in the same area. Ecosystems are made up of communities of organisms and their non-living environments. Landscapes typically are broad regions (e.g., Yellowstone National Park) which serve as management units but cross recognized ecosystem boundaries. The Earth's biosphere in its entirety is the largest landscape considered by ecologists.

Recent developments in science beg for a broadening of our study of the world of life. One can point to at least four key advances in our understanding of life made in the last two decades: (1) microbial life, which has had four billion years to evolve on Earth, is vastly more diverse and more widely distributed than previously comprehended; (2) the Earth's biosphere is far more expansive than we have recognized; only recently have we discovered communities of organisms in moist subterranean rocks deep in the Earth's crust and in the darkest depths of the sea at hydrothermal vents; (3) the space program has revealed secrets of our Solar System through space probe exploration of the planets and their satellites; technological advances in how we handle scientific data obtained from these missions have given us a new picture of our Solar System as a complex system characterized by the regular exchange of material among major and minor planets; (4) persuasive evidence for life on Mars has just been found, and we're on the verge of exploring other candidate Solar System bodies for life.

As a consequence of the scientific developments listed above, we need a more coherent blending of astronomy, earth science, and ecology in order to obtain a more complete picture of life. We have known for a long time that life on Earth is influenced profoundly both by the Sun and our Moon. Climate and weather, (precipitation, temperature, wind, storms), amount of solar radiation reaching Earth and length of the growing season, the tides, seasonal change, and long-term variation in solar luminosity are some of the ways that life on Earth is affected by the Sun and the Moon. Animal behavior, life history strategies, adaptation, and evolution all are influenced by factors of extraterrestrial origin. For example, the Milankovitch theory of climate change holds that the shape of Earth's orbit around the Sun (its eccentricity), the wobble of Earth on its axis of rotation (precession), the changing tilt of Earth's axis (obliquity) combine to cause periodic global alterations of climate. As another example, current research is aimed at tracing and understanding a recently recognized long-term phenomenon linked with varying solar radiation, the periodic flow of ice sheets and surges of icebergs which transport debris from continents to ocean basins.

UNIT SCOPE AND OBJECTIVES: A thorough consideration of the relation between Solar System events and life on Earth would include those topics listed above. For the purposes of this unit, however, I concentrate on questions of the origin of life and the disruption of life caused by the regular collisions over geological time between Earth and asteroids and comets. I first present information on the early Solar System and the Solar System of today, then look at what we know about asteroids, comets, and meteorites. I then consider impact theory and extinction and the fossil record. I complete the unit by discussing the latest information on possible life on Mars and the theory of panspermia (the natural insemination of life through the Solar System).
The unit is intended for use in high school 9-12 chemistry, biology, and environmental science classes at general, college, and honors levels. Much of the subject matter and lesson plans are adaptable to middle school and elementary school instruction. The questions asked by high school science students often are the same questions as those asked by younger students: what is life? where is life found? where does life come from? why is life so diverse? how does life change? why do some living things become extinct?

The objectives of this unit are to:

> (1) identify some of the common subject matter of the three scientific disciplines of astronomy, earth science, and ecology, and look for new ways to integrate these topics;
> (2) describe the dynamic nature of our Solar System, particularly its minor planets (asteroids and comets) and the likelihood of their colliding with Earth over long periods of time;
> (3) distinguish among the different types of meteorites found on Earth by their physical appearance and chemical makeup;

(4) invoke asteroid extinction theory as a way of further extending the interdisciplinary nature of ecological study;
(5) develop strategies for using the resources of a university natural history museum in precollege science instruction;
(6) introduce use of computer technology in science instruction, particularly the many World Wide Web addresses available on the Internet which relate to space science and solar system astronomy.
(7) promote use of current events in science instruction.
(8) give students and teachers direction in using the popular and professional scientific literature in astronomy and ecology.

II. THE EARLY SOLAR SYSTEM (WHY DID THE SOLAR NEBULA NOT REMAIN NEBULOUS?)

Current theory holds that our Solar System formed 4.56 billion years ago from a rotating cloud of gas and dust, the solar nebula. Gravitational attraction of solar nebula material led to the formation of the Sun, center of the Solar System and location of the greatest percentage of its mass. Material not incorporated into the Sun aggregated into far smaller bodies, planetesimals, each a few kilometers in diameter. The Sun is a G spectral type star of average size. The age of the Solar System is determined not by the study of Earth rocks but by radioisotopic dating of meteorites, the most primordial materials to which we have access.

As the early Solar System evolved, planetesimals accreted with other planetesimals to form the planets. Nine planets formed (8 with a parsimonious view) at varying distances from the Sun, each planet orbiting the Sun at its own pace, each consisting of a spherical mass of gas and melted rock. As they cooled during the first tens of millions of years of the Solar System, the smaller or terrestrial planets (Mercury, Venus, Earth and Mars) lost their volatile gases (carbon dioxide, water, methane, and ammonia) to surrounding Solar System space. They formed solid, crusty surfaces over molten cores. The larger planets, called giant, jovian, or gaseous (Jupiter, Saturn, Uranus, and Neptune), consisted mostly of hydrogen, helium and other light gases and retained their gaseous condition. The ninth planet, Pluto, is farthest from the Sun and is unlike any of its neighboring jovian planets. Its status as planet is discussed below. These major planets have 60 satellite bodies (moons) in orbit which are themselves structurally diverse.

A vast number of original planetesimals did not aggregate to form the Sun or the planets. They remained as smaller bodies, called planetoids. Mankind has been aware of one category of planetoid, the comets, for more than 2000 years. Comets are grouped into two broad types, the long-period comets and the short-period comets, and they reside in different regions of the Solar System. Taken together, they comprise the most distant objects from the Sun in the Solar System. Another category of planetoid, the asteroids, was discovered only 200 years ago. Most of these reside in a belt between the orbits of Mars and Jupiter. We know very little about the asteroids and comets during the earliest period of formation of the Solar System. However, they may have played a critical role in the formation of an Earth hospitable to life. It is believed that a period of heavy cometary bombardment of Earth during its first half billion or so years delivered the vast quantities of water to the planet which now comprise its oceans and atmospheric water.

Earth's Moon underwent a 200 million year period of massive bombardment by asteroids and comets beginning approximately 4 billion years ago. Known as the Late Heavy Bombardment (LHB) or the Lunar Cataclysm, these colossal collisions with the Moon led to the formation of its great craters. We have every reason to believe that the inner planets were subjected to the same bombardment through their own gravitational attraction of planetoids. One theory, however, holds that only the Earth-Moon system experienced the LHB during this period. Discovery in Antarctica of a meteorite (described below) dated at 4.0 billion years provides some evidence that Mars experienced the LHB, so it is likely that all the terrestrial planets did. This early period involved the largest and most abundant collisions to occur in the history of the Solar System. Life originated on Earth shortly after the end of the LHB, at least 3.8 billion years ago.

III. THE SOLAR SYSTEM TODAY (WHAT'S THE NEXT SURPRISE GOING TO BE?)

The last three decades have seen a tremendous growth in our understanding of Solar System structure and dynamics. The space program has sent manned missions to the Moon and unmanned missions to the terrestrial and the gaseous planets. We have learned that the Solar System is incredibly diverse, with no two bodies (major planets or their satellites) very similar to each other.

Distance from the Sun to each of its planets is measured in astronomical units (AU), one AU being defined as the average distance from the Sun to Earth, or 149,597,870 kilometers (about 93 million miles). The innermost planet, Mercury, is 0.3871 AU from the Sun, Earth is by definition 1.00 AU away, and the most distant planet, Pluto, with a highly elliptical orbit of the Sun, averages 39.44 AU. There are periods in its annual orbit when Pluto moves within the orbit of Neptune, as is the case from 1979 to 1999. Neptune thus is the planet farthest from the Sun today. Check the National Audubon Society field guide for details on the planets.

I include here brief information on Mars and on the four Galilean satellites (Io, Europa, Ganymede, and Callisto) which applies to this unit. Mars (D = 6786 km; 1.5237 AU; escape velocity 5.0 km/sec) has a widely varied topography colored a distinctive red, huge volcanic mountains including Olympus Mons, the largest known volcano in the Solar System, deep valleys, a very thin atmosphere of carbon dioxide with some nitrogen and argon, huge dust storms, polar ice caps of carbon dioxide and water, evidence of liquid surface water early in its history, meteorite impacts, and two small satellites (Phobos and Deimos) which are believed to be captured asteroids. Mars has been explored by Mariner 4 (1965) and by Viking 1 and 2 landers in 1975.

The Galilean moons of Jupiter are extraordinarily diverse in their composition and dynamics: Io is the most volcanically active object in the Solar System; Europa is covered by an ocean of deep ice and may be geologically active and harbor life forms; Ganymede is the largest satellite of the Solar System; Callisto is completely cratered. Four smaller outer satellites of Jupiter probably are captured asteroids. Uranus (D = 51,118; 19.1914 AU; escape velocity 21.3 km/sec), discovered by Herschel in 1781, rotates in reverse direction from the other planets and has a severely tilted axis suggesting it was knocked into its present orientation by a Solar System body. Pluto (D—2300 km; 39.5294 AU; escape velocity 1.1 km/sec), discovered by Tombaugh in 1930, is an anomaly of the outer Solar System—smallest of the planets, farthest from the Sun, least dense, not gaseous like its outer neighbors but rocky, with a strongly elliptical orbit, a thin atmosphere, extreme cold, and one known satellite, Charon (discovered in 1978). Pluto may be an exhausted comet captured from the trans-Neptunian belt of comets called the Kuiper Belt (see below), and Charon may be a comet captured by Pluto. Careful examination of meteorites originating from the asteroid belt, the Moon, and Mars has provided further information on the diversity of the Solar System.

IV. THE ASTEROIDS (WHY IS THERE NO PLANET BETWEEN MARS AND JUPITER?)

Asteroids are leftover planetesimals that date from the early period of formation of the Solar System. They formed in and reside in the inner Solar System, between the orbits of Mars and Jupiter, 2 to 4 AU from the Sun. Planetary physics suggests that conditions might have been right for a planet to form between Mars and Jupiter, but that the intense gravitational pull of the giant jovian planet prevented sufficient aggegation of planetesimals to constitute a planetary body there. Instead, we have a Main Belt of asteroids ranging in size from small to large. At least 6000 asteroids have been discovered to date, with several hundred being discovered each year. There may be hundreds of thousands of asteroids in the Main Belt, too small to be seen from Earth. Kirkwood gaps exist in the Main Belt as a result of disturbance to these regions by gravitational forces of Jupiter.

The combined mass of the asteroids is less than that of Earth’s Moon. The largest of the asteroids is Ceres, with a diameter of 914 kilometers. Ceres accounts for approximately 25% of the mass of all the asteroids. The next largest asteroids are Pallas (588 km), Vesta (576 km and possibly possessing an internal heat source), and Hygiea (430 km). Some 26 asteroids are known with diameters greater than 200 kilometers. It is estimated that we have identified 99% of the asteroids of this size. In comparison, we know of just 50% of those asteroids in the range of 10-100 kilometers diameter, and we have located only a small percentage of perhaps a million smaller asteroids with 1 kilometer diameters.

The only asteroids which have been studied at close range are Ida and Gaspara. Their surface appearances have been recorded by photographs taken by the Galileo probe. As mentioned above, the two moons of Mars, Deimos and Phobos, have chemical composition suggesting that they are captured asteroids originally from the Main Belt. Saturn’s moon Phoebe and some newly discovered moons of Uranus and Neptune also may be captured asteroids.

Asteroids are classified on the basis of their brightness or albedo, and by spectral evidence of their composition. They contain silicaceous minerals, carbon compounds, and iron and nickel metals. Some asteroids also contain small quantities of trapped crystalline water. There are C-type, S-type, and M-type asteroids identified in these classification schemes. Asteroids also are classified according to location, and not all have orbits within the Main Belt. The five basic groupings of asteroids are: (1) Main Belt asteroids, those found between Mars and Jupiter at 2-4 AU; (2) Atens asteroids, with semimajor axes greater than 1.0 AU and aphelion distances (the point of farthest orbit from the Sun) of more than 0.983 AU; (3) Apollo asteroids, which cross the radius of Earth's orbit, and semimajor axes greater than 1.0 AU and perihelion (closest approach to the Sun) distances less than 1.017 AU; (4) Amor asteroids, lying just outside Earth's orbit, with perihelion distances between 1.017 and 1.3 AU; (5) Trojan asteroids having resonant motion, as they are locked in orbit with Jupiter and located approximately 60 degrees in front of and 60 degrees behind the planet, at its "Lagrange" or "trojan" points. Jupiter has at least several hundred trojan satellites, and there may be a thousand or more. Earth and Venus also may have small Trojan asteroids orbiting in synchrony with them; evidence of the existence of Earth's "other moons" dates to the mid-1840s and has been the subject of popular science fiction stories.

Those asteroids which are in near-Earth orbits are on highly chaotic, unstable orbits about the Sun. One of these near-Earth asteroids, 1995CR, traveled within 4.5 million miles of Earth in February 1995. It was detected by the 0.9 meter telescope at Kitt Peak National Observatory as it made this close passage by Earth. An upcoming space mission will fly by the near-Earth asteroid Eros (discovered in 1898) in the months ahead.

V. THE COMETS (WHY IS HALLEY'S COMET RUNNING OUT OF GAS?)

The structure of a comet is far different from that of an asteroid, although the distinction between asteroids and comets is almost one of convention. Low activity comets look much like asteroids. In fact, the term "near-Earth object" applies both to some comets and some asteroids. The three regions of a comet are its nucleus, coma, and tail. The nucleus consists primarily of water ice and solid carbon monoxide, with additional small quantities of carbon dioxide, methane, ammonia, nitrogen, formaldehyde, and hydrogen cyanide. The coma is a spherical cloud of gas and dust; it is the main portion of the comet that can be seen by Earth observers. The tail of the comet extends out from the nucleus, always pointing away from the Sun. Thus, as a comet approaches the Sun, the tail extends behind. As a comet completes its closest approach to the Sun and begins its sweep back toward the outer Solar System, the tail leads the way. A comet's tail may be millions of kilometers long, and it is thinner than the best vacuum produced on Earth.

The best known short-period comet is Halley's Comet (76 year orbital cycle), named for the English astronomer who studied it in the 1690s. Observations have been made of Halley's Comet over a 2000 year period by many different human civilizations. The comet orbits the Sun clockwise, in the opposite direction from that of Earth. It is tilted 162 degrees from the Earth's ecliptic. During Halley Comet's March 1986 closest flyby of the Earth, five spacecraft (2 Soviet, 2 Japanese, and one from the European Space Agency) were sent to examine the comet. The ESA satellite, Giotto, flew to within 360 miles of the nucleus of the comet.

From space probes we have learned that the nucleus of Halley's Comet is about 6 kilometers long and 3 kilometers in width and depth, making it equivalent in size to a gouged out, flying Manhattan Island. The nuclear surface is a dark, sooty black with extremely low light reflectance (albedo), making this and other comet nuclei among the darkest objects in the Solar System. Surface temperature is about 675 degrees Celsius. The surface is very irregular (suggesting that the comet was formed from smaller bodies), with mountains and valleys rivaling the highest and deepest in Connecticut. The nucleus is highly porous and has a density significantly less than that of ice. Jets of expanding gas shoot out from about 10% of the nuclear surface at a rate of 25 tons per second when the comet is close to the Sun. These jets of gas cause a comet's flight path to alter course unpredictably, with quick starts and stops as it approaches and leaves the Sun.

The coma, surrounding the comet nucleus, interacts with the solar wind and interplanetary magnetic field as it flies past the Sun and planets. It is 80% water ice, and carbon monoxide and dust are additional components. The dust consists of silicates, light elements (sodium, magnesium, sulfur), and a mix of carbon, hydrogen, oxygen and nitrogen in which the proportion of carbon matches that of carbon in the Sun and other stars. For this reason, comets are viewed as remnants of the early Solar System.

Other features of Halley's Comet are: a bow shock region nearly a million miles in front of the nucleus, the site of first interaction with the solar wind; a magnetosheath behind the bow shock which builds up magnetic field lines in front of the nucleus; and solar wind and ions draping behind the comet head to form a very long tail. Halley's and other comets have much greater orbital speeds (60 km/sec) than do asteroids. The shortest of short-period comets orbit the Sun in 10 years. In addition to Halley's Comet, the comets Encke (closest to the Sun of all comets catalogued), Swift-Tuttle (130 yr orbit), Tempel-Tuttle (33 yr orbital), and Shoemaker-Levy 9 have received considerable study. Shoemaker-Levy 9 crashed into Jupiter's atmosphere during the week of July 16-22, 1994. The comet's trajectory toward Jupiter had been discovered by Eugene and Carolyn Shoemaker and David Levy. High-resolution infrared images of the impact of Comet Shoemaker-Levy-9 with Jupiter were made from the University of Hawaii's 2.2 meter telescope, during the period July 20 and July 21. Images were also made by the Hubble Space Telescope. This was the first and only impact of a comet and a planet ever observed, and it has produced a tremendous surge in interest in collisions of Solar System bodies. A special issue of *Science* (3 March 1995) is devoted to Shoemaker-Levy 9 and the impacts with Jupiter.

Comets reside at the greatest distances from the Sun of any Solar System bodies. More than 850 had been identified by 1993 (20% of them short-period, with orbits less than 200 years). They reside in two major regions of the Solar System, the Oort Cloud and the Kuiper belt. In 1950, Jan Oort predicted that a huge spherical cloud of perhaps a trillion comets was orbiting the Sun beyond Neptune and Pluto, from 30,000 AU to 50,000 AU away. This cloud is the source of long-period comets, those with orbits of 200 years or more. Oort Cloud bodies may comprise a significant percentage of the mass of the Solar System, perhaps exceeding that of Jupiter. The cloud is referred to as a "celestial deep freeze," being so distant from the Sun. These comets can be dislodged from stable orbits because of their relative proximity to earth's nearest neighbor star, Alpha Centauri, and other "close" stars.

In 1951, Gerard Kuiper predicted the existence of a belt of comets beyond the orbit of Neptune. Their existence was confirmed in 1992 through charge-coupled device (CCD) technology and telescopes at Mauna Kea. They occupy a disk-shaped or flat plane region just past Neptune's orbit, about 30-50 AU from the Sun and possibly further out. The innermost edge of the Kuiper belt is taken to be the orbit of Neptune. These are called trans-Neptunian comets. The total mass of Kuiper belt objects is perhaps 100 times that of the main asteroid belt. They are small icy bodies covered by organic soot, turned reddish from exposure to solar radiation.

Kuiper belt comets are believed fairly new to this region of the Solar System, as they would have been disturbed from their orbitals through long periods of proximity to the jovian planets. Where they originated is unclear. Following the 1992 discovery of one Kuiper belt object (with a 138 year orbit), five objects were located in 1993 (one has a 291 yr orbit), 12 in 1994, 14 in 1995, and 4 or more in the first part of 1996, bringing the total of known Kuiper belt objects at least to 36. The calculated size of these comets ranges from 96 to 389 km. There are an estimated 35,000 objects with diameter greater than 100 km, and there may be 100 million comets in orbit with 20 km diameters, although this is as yet unconfirmed. An estimated 60,000 objects are equal to or greater in size than Halley's Comet. Chiron, with a diameter of 170 km, is largest known of these. Some consider Neptune's moon Triton, Pluto (2300 km diameter), and Pluto's moon Charon (1100 km diameter) to be the largest Kuiper belt objects, disturbed in their former cometary orbits. If a tenth planet aptly dubbed Planet X exists, it may also have been diverted from the Kuiper belt.

Oort Cloud and Kuiper belt comets, well-preserved remnants of the solar nebula, give us a glimpse of the Solar System's formation and early evolution. Their study is a rapidly evolving field in astronomy. In addition to the above comets, six objects are known which orbit between Jupiter and Neptune. They include 2060 Chiron (an active comet with recognizable coma) and 5145 Pholus. These are transition comets, formerly of the Kuiper belt and now on their way to becoming short-lived members of the inner Solar System.

VI. THE METEORITES AND METEOR CRATERS (WHY CAN'T THE REAL EXTRATERRESTRIALS GET ANY RESPECT?)

Meteorites are small objects of extraterrestrial origin pulled to Earth from near-Earth trajectories, penetrating the atmosphere, and landing on Earth's surface. Their existence has been known through recorded history, but their Solar System origins have been recognized only for a century. The term "meteoroid" is used for any small object moving through the Solar System and capable of intersecting Earth's orbit. If a meteoroid enters Earth's atmosphere, it is termed a meteor, or "shooting star." If it lands on Earth's surface, it is then called a meteorite. Meteorites which have an observed entry and which are recovered shortly thereafter are falls. Meteorites discovered by chance some time after their fall to Earth are finds.

Several decades of meteorite study have produced a classification scheme which groups meteorites on the basis of their physical appearance and composition. Current classifications recognize that meteorites exhibit primary (nebular) properties relating to their original locations and processes of formation, and secondary properties caused by events of their later histories. The three broad classes of meteorites are the stones, stony-irons, and irons.

The stone meteorites are extremely diverse in their chemical and physical properties. The two types of stones are chondrites and achondrites. Chondrites are aggregates of different component materials. They contain chondrules, silicate mineral assemblages 0.1 to 1.0 mm large contained in glass or crystalline, bead-shaped structures. The chondrules, which are found in essentially no other rock types, have been partially or totally melted. Chondrites closely mirror the composition of the Sun but have lost the volatile gases (mainly hydrogen and helium) present in the Sun.

Chondrites are divided into nine main classes. The H, L, and LL chondrites, called ordinary chondrites, are the most abundant meteorite type found. The CI, CM, CO, and CV chondrites have high carbon contents and are called carbonaceous chondrites. CI and CM carbonaceous chondrites have hydrated clay-silicate sheets. EH and EL chondrites are enstatite chondrites, high in this mineral.

Achondrites are rare among the meteorites. They are igneous rocks or are derived from igneous rocks. They are highly altered from the original nebular material, due to their cooling histories, melting, metamorphism, and shock. They differ considerably from the Sun in composition. Three of the more common types of achondrites are called eucrites, diogenites, and howardites. Three other achondrites, the shergottites, nakhlites, and Chassigny (known as the SNC meteorites), are believed to have originated on Mars. They have generated great scientific interest in recent months. The achondrites also include unclassified breccias, or aggregated fragments of coarse, angular rocks. The stony-irons are mixtures of stony material and metal. One type, the pallasites, consist of iron-nickel alloy networks with rounded olivine nodules. Irons are pieces of metal, iron-nickel alloys with minor amounts of carbon, sulfur, and phosphorus. They are the meteorites which best fit the popular image of what a meteorite is.

Irons consist of two phases, one called kamacite which is low in nickel, and one called taenite which is high in nickel. The majority of irons, collectively called octahedrites, have an octahedral arrangement of kamacite with interspersed taenite. A characteristic structure within these irons is the Widmanstatten structure, which resembles a crystalline material or is suggestive of frost on a window. “Shock-twins” are another feature of these meteorites. The irons are classified on the basis of their content of the elements gallium, germanium, and nickel. Most common are IAB, IIAB, IIIAB, IVA, and IVB irons.

Other aspects of meteorite structure and composition used in classification are degree of oxidation of iron and isotopic proportions of oxygen 16, 17, & 18. Classification attempts to separate meteorites on the basis of their origins and methods of formation. Secondary properties include metamorphism (here, one considers paleotemperatures and cooling histories), shock, aqueous alteration, and brecciation. Shock effects on meteorites are particularly important because the collisions of parent bodies and impact bodies that produced the shock features also are responsible for sending these objects on an Earth-intersecting trajectory.

Of all the meteorite types, the chondrites are most similar to the Sun in composition, least altered through their histories, considered the best indicators of the early conditions of the Solar System. They formed in the solar nebula. To the extent that there are different types of chondrites, it is a reflection of the different nebular processes at work during formation of the Solar System. The nine chondrite groups and their subgroups may be samples of different regions of the nebula. They give us our closest readings of the age of the Solar System, about 4.56 billion years old.

Approximately one dozen recovered meteorites match nearly identically the chemical makeup of martian rocks studied during the unmanned Mariner satellite visits to Mars. These meteorites (the SNC meteorites referred to above, and dated to 1.3 billion years ago) are recognized as ejecta from asteroidal collisions with Mars. One meteorite of martian origin, called ALH84001 after the Allan Hills locality in Antarctica where the rock was found in 1984, now has been determined to have a “shock age” of 4.0 billion years. A dozen meteorites from our Moon, matching rocks collected on the Moon during the six manned Apollo landings there, have reached Earth in similar fashion, having been knocked off Moon’s surface.

Meteor craters of Earth’s Moon have been observed through recorded time and recognized as structures formed by collision impacts for decades. Meteor craters on Earth were suspected of having extraterrestrial origins just since the latest 19th century. Craters of the other terrestrial planets and those of the larger jovian satellites have become known to us through space exploration of the past several decades. There is an extensive literature on known and suspected meteor craters on Earth. The first meteor craters considered to be of proven extraterrestrial origin were Meteor Crater (also called Barringer Crater) in northern Arizona (studied beginning in 1891 by Albert Foote and subsequently studied exhaustively by Daniel Barringer during the period 1902-1929), the Odessa crater in Texas (1921 discovery), the 13 Henbury craters in central Australia (1931 discovery), the Wabar craters in Saudi Arabia (1932 discovery), the Haviland crater in Kansas (meteoritic fragments first discovered in 1885), the Campo del Cielo craters of Argentina (deduced in 1933), the Kaalijarv craters of Estonia (they have yielded meteorites for centuries), the Boxhole meteor crater of central Australia (1937 discovery), the Wolf Creek crater of western Australia (1937 discovery), the Aouelloul crater of Mauretania, West Africa (ca. 1951 discovery), and the Ungava-Quebec crater (Chubb Crater) of Canada (1943 discovery).

Today, nearly 150 major meteorite craters have been identified on Earth. A dozen or so craters are of considerable size, measuring at least 50 km in diameter and up to 185 km in diameter. Chicxulub crater in the northern Yucatan of Mexico has a diameter of 170 km, but some researchers believe the full dimension of the hidden crater is 300 km in diameter. Our ability to look for and locate impact craters on Earth has developed in part through efforts of the space program. Satellite remote sensing work and the use of gravity anomaly and magnetic surveys continue to disclose new candidates for meteor craters. For example, U.S. Geological Survey research conducted in 1994 disclosed an inner basin and an outer rim of a proposed meteor crater buried 300-500 meters under Chesapeake Bay, caused by an impact event dated at 35.5 million years ago. The existence of a string of three impact craters 12 kilometers wide in Chad was announced by a NASA Jet Propulsion Laboratory scientist and her colleague in March 1996.

Earth's meteor craters are lost through time by erosion, covered by younger rocks, or hidden in ocean basins. Impacts are well documented by presence of craters, melt rock, shock features, and high-pressure minerals. A main problem is the uncertainty in dating the impacts. A one kilometer diameter meteorite striking Earth would liberate energy equivalent to tens of billions of tons of TNT, millions of times the energy of the Hiroshima atomic bomb.

VII. IMPACTS OF COMETS AND ASTEROIDS WITH EARTH (DO THE DIRTY SNOWBALLS SPELL DOOM?)

The Earth collides with and accretes about 10,000 tons of dust particles per year as it orbits the Sun. This dust ranges in size from 10 microns to 1 millimeter, and it is identified as the fragments of comets and asteroids. Deposition in the oceans of the world has been documented by the Deep Sea Drilling Project. This material is obviously a significant source of material to Earth's biogeochemical processes.

Each year dozens of asteroids are discovered through improved telescope techniques. Many of these asteroids are determined to have Earth-crossing orbits. Given enough time—thousands or tens of thousands or millions of years—some of these asteroids are predicted to collide with Earth. In March and early April of this year, for example, we experienced the spectacular passage of a comet (Hyakutake) to within 9 million miles of Earth.

Asteroids pose a greater danger to life on Earth than do comets. Collisions in the main belt are common events. Asteroid fragments are thrown to the farthest reaches of the Solar System or toward the inner Solar System—the terrestrial planets and the Sun. Comets have much greater orbital speeds than do asteroids, and they too produce cataclysmic collisions with Earth. Some, such as Halley's Comet, orbit the Sun in the opposite direction from the Earth, thereby enhancing the magnitude of impact with Earth. The 1908 explosion of a small comet or asteroid over the Tunguska River region of Siberia resulted in the devastation of more than a thousand square kilometers of forest. This was a small event compared with the total range of possibilities for collisions. Large asteroids enter the inner Solar System every 10 million years and persist for as long; those 1 km diameter and larger pose the greatest risk to life (1000-2000 are in near-Earth orbits; these collide with Earth once every 300,000 years). Perhaps 100,000 Near-Earth Objects (NEOs) of 100 meters diameter come inside Mars' orbit today.

Oort Cloud comets can be dislodged from their orbits by Alpha Centauri and other nearby stars and enter into highly elliptical, planet-crossing orbits, leading to possible collisions. Kuiper belt comets far from the jovian planets can reside there for billions of years, while those closest to the jovian planets will have their orbits disrupted and be ejected from the Solar System sling-shot fashion or drawn to the inner Solar System.

Neptune's gravity slowly erodes the inner edge of the Kuiper belt at 40 AU, pulling comets into the inner Solar System. Comets may persist in near-Sun orbits for 500 orbits before exhausting themselves; when exhausted, they may resemble or become asteroids. Collision of a comet or asteroid with Earth would result in global disruption: nuclear winter, large dust clouds exploding into the atmosphere and obscuring the Sun, prolonged darkness, subzero temperatures, violent windstorms, enormous fireballs, ejection of rocks and steam into the atmosphere, shock of the Earth's crust, resultant earthquakes; volcanic activity, global tsunamis, total darkness lasting for months, acid rainfall, settling of dust and creation of a several centimeter layer of sediment over the Earth's surface, and extinction of a very large percentage of species. Several of the bibliographic references give detailed accounts of the potential effects a collision would have on climate and life.

VIII. EXTINCTION AND THE FOSSIL RECORD (WHY DID THE DINOSAURS DIE?)

All species of life on Earth are faced with the inevitibility of extinction, either through evolution into new life forms or replacement by successful competitors. Average duration of species is estimated to be between one and 10 million years. Compilations of family, genera, and species extinctions over the past 590 million years (the Phanerozoic) suggest that approximately 40% of all losses occur as a background extinction level of less than 5% of contemporary life forms. 55% of extinctions occur at a higher, "pulsed extinction" rate, and only 5% of all extinctions occur during mass extinction events, when at least 60% of all life forms disappear quickly, as evidenced by the fossil record.

Using the percentages shown above, paleontologists recognize seven major mass extinction events occurring during the Phanerozoic (which is divided into the Paleozoic, Mesozoic, and Cenozoic). They are the Early Cambrian, Late Ordovician, Late Devonian, Late Permian, Early Triassic, Late Triassic, and end-Cretaceous extinctions. The greatest of these occurred 250 million years ago at the end of the Permian, when 96% of marine organisms died out. The causes of the Permian extinction are still being sought. Less severe but still considerable was the mass extinction occurring 65 million years ago at the boundary between the Cretaceous and Tertiary. Best known as the period of extinction of the dinosaurs, the K-T extinction also included the disappearance of 63-77% of all species, among them many marine foraminifera and land plants in western North America and eastern Asia. Two groups which survived the extinction were the flowering plants and the small mammals.

Of the major mass extinctions, there is strong evidence of extraterrestrial causes for two of these sudden interruptions in the history of life. Crater ages and mass extinction dates correspond for the Devonian extinction of 368 million years ago and the 52 km diameter Siljan crater. The Chicxulub crater of the Yucatan corresponds perfectly with the Late Cretaceous extinctions of 65 million years ago. A third mass extinction, that of the Late Triassic 210 million years ago, has a possible fit with the 100 kilometer Manicouagan crater in Canada.

The first persuasive evidence for an extraterrestrial cause for the K-T extinctions came with the 1980 discovery of a one centimeter layer of clay (initially found in northern Italy, and subsequently in nearly 100 sites around the globe) containing iridium, a platinum-group metal which is extremely rare in Earth's crust but comparatively abundant in meteorites. The iridium is believed to have been laid down by the impact of a 10 km diameter asteroid, the resultant formation of a global dust cloud from the impact, and settling to Earth's surface of the iridium carried in by the asteroid. This "Alvarez" hypothesis of asteroid extinction, named for research team leaders Luis and Walter Alvarez, now is widely accepted as the best explanation for the K-T extinction.

The study of impact craters on Earth indicates that impact events have been common over geological time scales and that some of these impacts potentially have been catastrophic. Tables comparing crater diameters with their frequency of occurrence on Earth and average time intervals of occurrence indicate that 150 km diameter craters occur every 100 million years, 100 km craters every 50 million years, 50 km craters every 6 million years, and 10 km craters every 10,000 years. Only the largest of these craters would account for a mass extinction.

After the asteroid extinction proposal was made, a widespread search was undertaken for possible places on Earth where evidence remained of a huge asteroid impact. The probable site of this collision of Earth with an asteroid 65 million years ago has been located in the Yucatan Peninsula. The crater was detected belowground through identification of magnetic anomalies which describe a pattern of four concentric circles, and at ground level by distributions of cenotes (limestone sinkholes), on the Yucatan landscape. Cenotes correspond closely with magnetic anomalies.

IX. CODA: LIFE ON MARS (DOES THE RED PLANET RESPIRE?); PANSPERMIA (IS SOLAR SYSTEM LIFE LIKE A SEXUALLY TRANSMITTED DISEASE?)

On August 6, just as the curriculum units in this Teachers Institute volume were going to production, news broke of the first persuasive evidence of life elsewhere in the Solar System, and by extension, elsewhere in the Universe. A team of scientists from NASA'a Johnson Space Center and Stanford University announced that they had detected probable microfossils in a martian meteorite. Meteorite ALH84001 was found in Antarctica in 1984 and was classified at that time as a rock sample most likely from the Main Asteroid Belt. A 1994 publication of data on mineralogical analyses and radioisotopic studies of oxygen in the rock revealed, however, that the most likely origin of the meteorite was the planet Mars. The age of the ALH84001 meteorite is determined to be 4.0 billion years, while the 11 other known martian meteorites have dates of 1.3 billion years old. This unique antiquity of the ALH84001 meteorite led to intensive examination of the meteorite and to the discovery of tubular, bacteria-like forms and further evidence of biological activity (polycyclic aromatic hydrocarbons and calcium carbonate deposits).

The announcement of possible life on Mars was described by President Clinton as "stunning." In the past days, discussion has focused on the reliability of the description of fossils in the meteorite. Additional information has become available from NASA about the Galileo space probe of Jupiter's satellite Europa, considered to be the next best bet for past or present extraterrestrial life. That discussion is chronicled in the newspaper files available as part of the classroom materials of this unit. Debate will be carried out in the professional meetings and journal publications to come. Debate will center on the environmental history of the meteorite (its primary and secondary properties), on the microfossil forms and their evidence of cellular structure, cell division, and colonial life, and on the validity of associated organic materials of biological origin. We will arrive at answers to questions generated by study of this and other meteorites through the process of scientific investigation and discourse. The larger debate will be about the possible ubiquity of life, in our Solar System and throughout the Universe. Is panspermia, in the narrow sense the natural innoculation of Earth by extraterrestrial life and in the larger sense the cosmic spread of life, a scientific idea finally to be taken seriously? Regardless of the debate's eventual outcome, discovery of possible life on Mars will have a profound impact on the American space program in the years ahead, giving far greater impetus for broadening the search for life on Mars and returning rocks from Mars to the Earth.

Thus, the asteroids and comets giveth, and they taketh away. In being identified as having brought to the newly accreted Earth sufficient quantity of water to establish a moist atmosphere and extensive oceans, they are credited with establishing the conditions on Earth which made the evolution of primitive life possible. Through early planetary history and the Late Heavy Bombardment, they delayed this perhaps-inevitable evolution of life. With cessation of steady cataclysmic collisions, life did arise naturally and spontaneously on Earth and perhaps elsewhere in the Solar System. The exchange of life forms among planets and satellite bodies, still very much a matter of conjecture, would have been mediated by the collisions of asteroids or comets with planets or satellites. To borrow the analogy from the ecology of bees and flowering plants, asteroids and comets have acted, in effect, as flying penises. There has not yet developed a scientific literature questioning the supposed common origin of all life on Earth with the suggestion that Earth has received over time one or more new infusions of life from other Solar System refugia of life. This is certain to develop as we learn more about the potential for or reality of life on Mars, on Jupiter's Europa, or elsewhere in the Solar System. Finally, the asteroids and comets have played a role, whether occasional or repeated, in the major starts and stops of the evolution of life. They have not been associated with all mass extinction events, and their relation to pulsed extinction and background extinction is as yet undetermined. The subject of their potential role in future diversification and attenuation of life should be of interest to those who ask, what is life? where is life found? where does life come from? why is life so diverse? how does life change? why do some living things become extinct?. . . and, what directions will life take in the future?

CLASSROOM ACTIVITIES AND SAMPLE LESSON PLANS

Lesson Plan #1. SLIDES FOR THE CURRICULUM UNIT.

I have taken my own slides of Yale Peabody Museum collections and Mayan astronomical observatories in the Yucatan. I continue to gather color images of Solar System objects from NASA. Part A. Yale Peabody Museum of Natural History. Rudolph Zallinger Great Hall mural, "The Age of Reptiles". 1-3. Cretaceous volcanoes. 4. *Tyrannosaurus* . 5. *Struthiomimus* . 6. *Edmontosaurus* 7. *Triceratops* 8. detail of *Triceratops* . 9. *Ankylosaurus* . 10. *Pteranodon* . Peabody Museum Great Hall fossil specimens. 11. *Edmontosaurus* skull. 12. *Edmontosaurus* pelvic girdle. 13. *Monoclonius* skeleton 14. *Monoclonius* skull. Part B. YPM Meteorite collection. 1. Wethersfield II Meteorite. 2. Roof of Wethersfield house through which the Wethersfield II meteorite crashed. 3. path of Wethersfield II. Part C. Chichen Itza Mayan/Toltec ruins, Yucatan Peninsula. 1-4. The Castillo. 5. Chacmool figure at Temple of the Warriors. 6. Frederick Catherwood lithograph of the Castillo. 7-10. The Caracol (Observatory). 11. Temple of Jaguars. 12. Toltec Ball Court. 13. Temple of the Warriors. 14-16. Sacred Cenote. 17. Mayan scene on paper. Uxmal Mayan ruins. 17-18. Pyramid of the Magician.

Lesson Plan #2. YALE PEABODY MUSEUM OF NATURAL HISTORY, MUSEUM WORKSHEET.

The museum has an important collection of meteorites constituting one of the curated divisions of the museum. Two landings between 1st and 3rd floors have displays relating to the meteorite collection. Listed here are display headings with my suggestions for museum worksheet questions. A museum worksheet has been developed; it is not included here due to space limitations.

First Landing: Case #1. A. Distinction Between Meteors and Meteorites. Questions: What is an asteroid, and where do the asteroids originate in the Solar System? Why are fewer than 1% of all meteorites which fall to Earth each year ever recovered? How do comets differ from asteroids? Case #2. A. A Meteorite Lands in Connecticut. B. Stones and Irons C. Weston Meteorite. D. Wethersfield (1982) Meteorite. E. Maps of Craters F. Meteorite Craters. G. Moon and Mars. H. specimens of tektites, pieces of Canyon Diablo meteorite. I. What Meteorites tell Us: 1. time sequence in our galaxy. 2. cosmic abundance of the elements. 3. history of meteoric bodies. Questions: Name some places in Connecticut, the United States, and around the world where we know that meteorites have crashed into Earth. What evidence do we have from other planets and moons of our Solar System that meteorites collide with these larger bodies regularly? What information can be learned from the study of meteorites? Case #3. Detailed Classification of Stony Meteorites. Question: Briefly describe the different types of meteorites that have been recovered on Earth. Case #4 (Wall Display). Connecticut meteorites. Question: Connecticut is the fourth smallest state, and yet there are several meteorites known to have fallen in our state. Name the towns where they have been found. Floor Display. Canyon Diablo Meteorite. Question: Describe the appearance of the Canyon Diablo Meteorite. Second Landing. Case #1. How to recognize a Meteorite. Stone Meteorites/Iron Meteorites. Question: If you find a rock which you suspect is a meteorite, how can you demonstrate that it is not a natural or human-made rock from Earth? Case #2. How Meteorites Weather. Question: Briefly describe the ways in which meteorites weather on Earth over long periods of time.

Lesson Plan #3. CURRENT EVENTS IN ASTRONOMY.

During the preparation of this unit, a number of articles have appeared in newspapers and in popular and professional science journals which relate directly to the subjects of asteroids and comets, earth impacts, and mass extinction events. Review of the Teacher Bibliography and Student Reading List will indicate that *Scientific American* and *Earth* have published particularly timely articles about unit topics. In addition, Connecticut Public Television has recently reaired the 1994 NOVA program, “The Doomsday Asteroid.”

Science is characterized by a progressive extension of our understanding of the world and its processes. I have long felt that science must be taught as an active, organic process of observation, measurement, hypothesizing, experimentation, discovery and theory-building, not as a static discipline. I always allow for the introduction of new material in my teaching. In fact, I plan for this occurrence of “stochastic events” in science news and scientific publications to shape and guide my course curricula. There is no clearer example of the value of current events to a unit of study or a course than the very recent announcement of evidence of ancient life on Mars. The evening news picked up this story of “life on Mars,” and it was developed further that night on ABC News Nightline with Ted Koppel. On August 7, NASA held a major press conference announcing details of the discovery and put the martian meteorite in front of the cameras. The News Hour with Jim Lehrer devoted a lengthy segment to interviews with NASA and Stanford University scientists who conducted the study of the meteorite. Newspapers around the country ran front page coverage of the story. By week’s end, the meteorite went on public display at the Smithsonian Institution.

I include the above material in this unit as an illustration of how the teacher can pick up on current events and give an immediacy to the subject matter. I would further suggest that any science course be taught in such a way that a sizeable percentage of instructional time (let’s say 20%, to make up a value) be devoted to new discoveries and newly developing theories in the discipline. This sort of an approach to science education is totally in keeping with the present national science education reform movement, which places greater emphasis on the process of science and less emphasis (and less time) on the specific blocks of subject matter which have been the mainstay of previous decades of science education. It requires that the teacher seek out information on the latest advances in science, medicine or technology. This may appear to be an insurmountable task for the busy, generalist science teacher—the ongoing and simultaneous study of biology, chemistry, astronomy—all the physical and life sciences—but it's a doable task and one which makes the profession of teaching all the more enjoyable and new. My primary sources of information on the latest scientific advances are the professional journals *Science* and *Nature* , the popular science publications *Scientific American* and *American Scientist* , and the daily newspaper (*New York Times* , *Christian Science Monitor* , and for local flavor the *New Haven Register*). There are other science journals which I review regularly, but the above form the basis for a regular flow of information into the science curriculum. In this fashion, the science curriculum never has a chance to stagnate. To put it in trite terms, a live tree frog or Northern Black Racer snake in the hand is worth a thousand stuffed animals in the science cabinet. I enjoy the search for new and timely information, and my students seem to appreciate it.

Lesson Plan #4. ASTRONOMY ON THE INTERNET.

The World Wide Web is a web in the truest sense, websites interconnecting with websites in the most complicated of branching patterns. The subject matter of astronomy is well-represented on the Internet. Here is a sampling of addresses the teacher can use in meaningful and interesting instruction. Topics cover the Earth, the Solar System, space program, asteroids, comets and meteorites. This computer instruction requires 3-4 class sessions. Pick your wave, and ride it in your chosen fashion for so long as you wish. Then hop onto another wave. Potential frustration for the student lies in the limitless possibilities. But, with proper guidance provided by the teacher, this is a very powerful form of instruction. Surf's up!

Websites providing a good starting point for the on-line study of astronomy include the following:

(1) http://mosaic.larc.nasa.gov/nasaonline/nasaonline.html
(NASA's home page);
(2) http://www.gsfc.nasa.gov/hqpao/newsroom.html
(NASA press releases and fact sheets);
(3) http://www.jpl.nasa.gov
(NASA Jet Propulsion Laboratory. Home pages on Shoemaker-Levy 9);
(4) http://www.arc.nasa.gov
(NASA Ames Research Center home page);
(5) http://www.stsci.edu/top.html
(Hubble Space telescope Center);
(6) http://fourmilab.ch/solar/solar.html
(text and photographs on the Solar System);
(7) http://www.c3.lanl.gov/”cjhamil/SolarSystem/homepage.html
(Solar System objects, photos and text;
(8) http://www.mtwilson.edu/Services/starmap.html
(star maps and planetary positions).

These addresses get you into the professional science journals:

(1) http://www.aaas.org/
(American Association for the Advancement of Science, *Science*);
(2) http://www.america.nature.com (*Nature*);
(3) http://www.sdsc.edu/SDSC/Research/Comp_Bio/ESA/ESA.html
(Ecological Society of America, *Ecology*).

Sample Internet surfing session: When giving instruction on the Internet, develop a worksheet which shows the sequence of addresses visited and guides the student through the labyrinth of information. A list of WWW addresses is needed to avoid confusion on the part of the student. Each address below leads directly to the WWW address which follows. Students type:

(1) http://www.arc.nasa.gov/ NASA Ames Research Center home page. Scroll down to NASA K-12 Internet Initiative. "Welcome to Quest, Home of NASA's K-12 Internet Initiative." The Quest mission is "to provide support and services for schools, teachers and students to fully utilize the Internet, and its underlying information technologies as a basic tool for learning."
(2) http://quest.arc.nasa.gov/video1.html This describes the NASA K-12 Internet Initiative Videos. The first video, released in 1993, is "Global Quest: The Internet in the Classroom," "designed to be a general introduction to the enormous positive changes that Internet access can bring to all areas of K-12 education." The second video is "Connecting to the Future," which "provides guidance for schools considering Internet connectivity", and it is co-produced by NASA and the U.S. Department of Education. The third video is "Global Quest II: Teaching with the Internet," which considers "specific uses of the Internet . . . and enhancing [teachers'] favorite curriculum unit[s]." Click on "Reform" to get a list of ways teachers can modify their teaching styles and expand their resources using the Internet. By clicking on "Curriculum" to get "Sci Ed: Science and Mathematics Education Resources." Included here are Astronomy and Space Science, Images and Animations, Views of the Solar System by Calvin Hamilton, The Nine Planets by Bill Arnett, Welcome to Planets (JPL), Atlas of Mars.
(3) http://www.ed.uiuc.edu/ The Learning Resource Server, College of Education, University of Illinois. "LRS is a suite of servers, including Web, Gopher, and FTP servers, that distribute and mediate electronic learning resources created for and by precollege teachers and students, pre-service teachers, education faculty members, and educational researchers."
(4) http://www.ifa.hawaii.edu/images/sl9/ This gives "high-resolution infrared images of the Shoemaker-Levy 9 impact with Jupiter. These images come from the University of Hawaii's 2.2 meter telescope and were obtained with a new infrared camera."
(5) ftp://explorer.arc.nasa.gov/pub/SPACE/GIF/ This long list of ftp addresses includes images of Mars (ftp . . . GIF/mars.gif), See also mercury.gif, saturn.gif, and Earth.gif.
(6) http://www.noao.edu/asteroid/asteroid.html/ National Optical Astronomy Observatories. This

site gives information on Near-Earth Asteroid 1995CR, which “holds the record for closest approach to the Sun. This asteroid was discovered during the dedicated detection program for Near Earth asteroids at the Steward Observatory 0.9 meter telescope on Kitt Peak Mountain. CR1995 crosses the orbits of four inner planets—Mercury, Venus, Earth, and Mars—and is on a highly chaotic and unstable path. Astronomers believe the asteroid will eventually collide with one of these planets or with the Sun, or may be ejected from the Solar System by a “sling-shot” effect. The asteroid, only 200 yards in diameter, will get as close to Earth as 4.5 million miles on Wednesday, February 22, 1995.”

(7) http://www.noao.edu/education/igcomet/igcomet.html This presents facts on comets, including structure and chemical makeup, historical information and the phenomenon of outgassing of short period comets. The largest known comet, Chiron, has a diameter of 90 kilometers. A comet recipe is presented under the heading, “Making a Comet in the Classroom.” under the address http://www.noao.edu/education/crecipe.html/

(8) http://www.excite.com/Subject/Science/Astronomy and Space/index.html/ This presents the choice of the topic “Solar System” and the subsequent selection of comets, Earth & Moon, planets, Sun, and Overview. Choose “planets”.

(9) http://seds.lpl.arizona.edu/nineplanets/nineplanets/
nineplanets.html/ and the screen “The Nine Planets: A Multimedia Tour of the Solar System by Bill Arnett.” What follows is a wealth of information under a variety of headings and including the tidbits noted here: Asteroid Facts—we know of the whereabouts of 99% of the largest asteroids but of fewer than 1% of the smaller ones; Classification Schemes—Main Belt asteroids, Atens asteroids, Apollo asteroids, Amor asteroids; Trojan asteroids. More About Asteroids—sections include The largest known Near-Earth objects, Near-Earth Asteroid Rendezvous Mission, On-Line asteroid data, and asteroid nomenclature table. Kuiper Belt and Oort Cloud also have sections with interesting information.

(10) http://wwwflag.wr.usgs.gov/wall/ This is the home page for the U.S. Geological Survey, Flagstaff Field Center. It leads you to “Browse the Solar System” and its chart of the Sun, planets, their satellites, and the comets and asteroids. You are advised to “click on a planetary image in the chart below to obtain more information on the selected object.”

(11) http://medicine.wustl.edu/~kronkg/kuiper_belt.html/ for additional historical information on the Kuiper Belt of short period comets. Here it is stated that there are an estimated 60,000 comets in our Solar System equal to or greater in size than Halley’s Comet. Chiron is the largest of the Centaur objects in orbit between Jupiter and Neptune. Pluto may be a Kuiper Belt object which has a planet-like orbit but which in its origins and its structure is planetoidal rather than planetary.

(12) http://www.astro.uva.nl/michielb/maya/astro.html/ The Maya Astronomy Page. It includes sections on the Maya calendar, Maya Astronomy, Maya Mathematics, and a Geographical Orientation.

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CLASSROOM MATERIALS

1. Slide Set, “Asteroids and Comets—Solar System Bodies Linking Astronomy and Ecology.” A collection of color slides covering Yale Peabody Museum of Natural History meteorite exhibits and collections, “Age of Reptiles” mural, Great Hall dinosaurs; a Mayan astronomical observatory and cenotes of the Yucatan peninsula. 2. Videotapes: (a) ABC News, Nightline with Ted Koppel. 1996. Program of August 7, 1996. (b) Connecticut Public Television, The News Hour with Jim Lehrer. 1996. Program of August 8, 1996. (c) NOVA Videocassette, “The Doomsday Asteroid”, 1994. “Join the hunt to scan the skies and earth for evidence that giant rocks from outer space have struck before and will strike again.” WGBH Video, P.O. Box 2284, Dept 9030, South Burlington, VT 05407-2284 Telephone: 800-255-9424 Ext. 9030 or 802-862-8881 Ext. 9030. FACSIMILE: 802-864-9846 Dept. 9030. $19.95 + shipping/handling. 3. Current Events Folder. A collection of recent *Scientific American* , *American Scientist* , and *Earth* articles on asteroids, comets, meteorites, and related subjects having to do with astroecology or biogeoplanetology. Also, a set of *New York Times* , *Christian Science Monitor* , and *New Haven Register* articles reporting on the latest discoveries in this field. At present count, 20 newspaper articles are in the folder, many of them from early August 1996. Folder contains useful Web addresses.

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