Meteorites, Clues to Solar System History

A family on a camping trip watches a bright light streak across the sky and disappear.

An explorer comes upon a circular crater with rocks scattered around its rim.

Two boys watch a rock fall from the sky and land near them.

A farmer picks up an unusually heavy rock while plowing his field.

A scientist discovers the rare element iridium in a soil layer that marks the end of the age of dinosaurs.

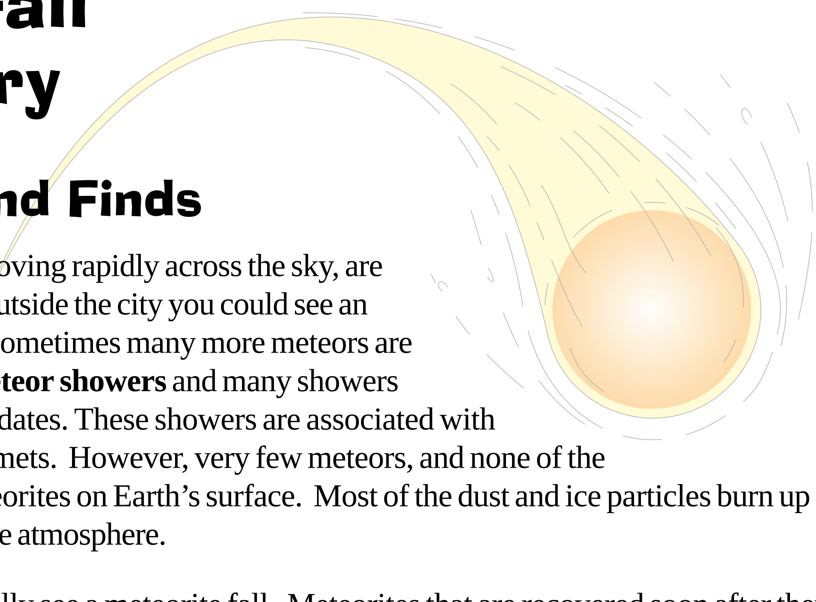
All of these people have discovered possible evidence of rocks from space that passed through the atmosphere and landed on Earth. Sometimes there is little or no evidence of the rock itself; it burned up in the atmosphere or broke up on impact. Other times the rock is all there is, with little evidence of its fiery entry or crash landing. These events all involve the mysteries of meteorites: what they are, where they come from, how they got here, how they affect people, and what they tell us about the solar system. These are some of the questions that are investigated in *Exploring Meteorite Mysteries*.

Brodie Spaulding (age 13) and Brian Kinzie (age 9). *The boys are standing on the lawn where they observed the Noblesville, Indiana meteorite fall on August 31, 1991. (Photo by M. Lipschutz)*

Meteorites are rocks from space that have survived their passage through the atmosphere to land on Earth's surface. Some meteorites are seen or heard to fall and are picked up soon afterward, while most are found much later. Some meteorites are large enough to produce impact craters or showers of fragments, but others are small enough to hold in one hand, and still others are so small that you need to use a microscope to see them. Some meteorites are like igneous rocks on Earth, others are pieces of metal, and others are different from all known Earth rocks. Yet, despite their variety in size, appearance, and manner of discovery, all meteorites are pieces of other bodies in space that give us clues to the origin and history of the solar system.

Noblesville meteorite*. The 0.5 kg (fist-sized) meteorite found by the boys. Inside Noblesville is a gray stony meteorite, but outside it is covered by a dark brown glassy crust.*

Meteorite Fall and Recovery

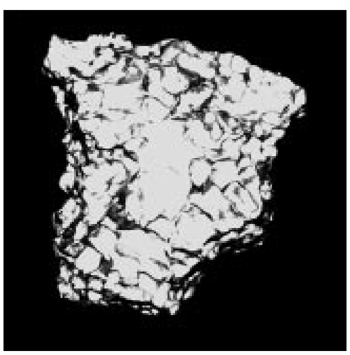


Meteors, Falls and Finds

Meteors, bright streaks of light moving rapidly across the sky, are fairly common. On a clear night outside the city you could see an average of three or four an hour. Sometimes many more meteors are visible. These times are called **meteor showers** and many showers return year after year on the same dates. These showers are associated with comet dust left by long-passed comets. However, very few meteors, and none of the yearly meteor showers, yield meteorites on Earth's surface. Most of the dust and ice particles burn up completely as they pass through the atmosphere.

Only a few people each year actually see a meteorite fall. Meteorites that are recovered soon after they land on Earth are called **falls**. About 900 meteorite falls have been recovered around the world, mostly in the last 200 years. The fall of a relatively small meteorite is exciting, but not dramatic unless it injures a person or damages property. When young Brodie Spaulding and Brian Kenzie observed the fall of the small Noblesville meteorite in August 1991 (see Lesson 1), they saw no bright light and heard only a whistling sound. The meteorite was slightly warm to touch and made a small hole in the ground where it landed.

Falls of large meteorites are rare, occurring only once every few decades, but are dramatic, beginning with the bright streak of light and thunderous noise of a **fireball**. The falls of the Allende stony meteorite in rural Mexico and the Sikhote-Alin iron meteorite in Siberia, Russia, were two recent large falls (see Lesson 15). Both meteorite falls began with bright light and explosions that were seen, heard and felt for great distances. The cover of this booklet shows the Sikhote-Alin fireball as depicted in an eyewitness painting. The fall sites for the two meteorites were soon found. Allende was scattered over a 150 square kilometer area



***Sikhote-Alin meteorite**. This is a fragment from the Sikhote-Alin shower that fell in Russia in February, 1947. It is an iron meteorite that is covered by black fusion crust and indentations like thumbprints from melting during flight through the atmosphere. The Sikhote-Alin irons weighed a total of 23,000 kg, with the largest piece weighing 300 kg.*

***Allende meteorite**. This is a fragment from the Allende shower that fell in Mexico in February 1969. It is a dark gray stony meteorite with black glassy fusion crust. The Allende stones weighed a total of 2,000 kg, with the largest piece weighing 100 kg.*

***Meteor Crater in Arizona**. This 1.2 km wide, 150 m deep, crater was made by a 30 m iron meteorite weighing about 1,000,000,000 kg. Thousands of fragments totaling 30,000 kg of the Canyon Diablo iron meteorite have been found, but most of the meteorite was vaporized by the heat of the impact.*

around the town of Pueblito del Allende. The Sikhote-Alin site was located from the air by its devastation of a forested area. On the ground scientists found over 100 craters of varying sizes. Both meteorites fell as thousands of fragments covering wide areas. The breakup and fall of a large meteorite like Allende or Sikhote-Alin before impact is called a **meteorite shower**. (See Lessons 2 and 3)

The impact of a huge meteorite has never been observed and recorded by people; however, many have been recorded as **craters** in the surfaces where they landed on the Earth or other planetary bodies. Meteor Crater in Arizona is the best known meteorite **impact crater** on Earth. It is about 50,000 years old and well preserved in the arid desert. Many small fragments of the Canyon Diablo meteorite have been found around the crater, but their total mass is only a tiny fraction of the total mass of the incoming meteorite. The force of the impact is thought to have vaporized most of the meteorite. Imagine how powerful that explosion must have been if anyone were nearby to see and feel it!

Studies of numerous observed falls, combined with field and experimental studies of impact craters, give us a general picture of the fall process. Meteorites approaching Earth come in all sizes from microscopic to gigantic. The larger the size, the fewer the number of meteorites there are. Most meteorites approach Earth at speeds of about 20-30 km/sec. They are slowed down by friction with the air as they pass through the atmosphere. The heat produced causes their outsides to melt to glass creating the **fusion crust**. The tiniest rocks and dust burn up as meteors without landing on Earth. Small meteorites like Noblesville are slowed to below the speed of sound. Larger meteorites like Allende and Sikhote-Alin don't slow down much and make sonic booms as they approach Earth at speeds greater than the speed of sound. Even larger meteorites, like Canyon Diablo that formed Meteor Crater, are hardly slowed at all by the Earth's atmosphere and hit the Earth at very high speeds, making large impact craters. No meteorite this large has fallen in recorded history. Most small to medium falls are stony meteorites and most of the larger showers and impact craters are produced by iron meteorites. Iron meteorites are stronger than stony meteorites; therefore, they don't break up as easily in space or as they pass through the atmosphere.

Many meteorites fall to Earth each year, but are not observed. Few of these meteorites are ever found. From photographic records of fireballs and smaller meteors, scientists have calculated that about 30,000 meteorites larger than 100 g fall on the Earth's surface each year. Although this sounds like a huge number, there is very little chance of a meteorite falling on you. Most of these meteorites just go unnoticed because they fall quietly during the night, in unpopulated areas, or in the ocean . However, some meteorites survive exposure at the Earth's surface and are picked up hundreds or thousands of years after they fall.

Identifying Meteorites

Finding a meteorite on Antarctic ice when there are no other rocks around is easy (if you can stand the cold!). Finding a meteorite on sand, a plowed field, or a path or road isn't hard. But finding a meteorite in a thick forest, or picking one out of a pile of Earth rocks is challenging, even for experts. There are many types of meteorites and they are found in all sizes and shapes, but most meteorites have two things in common: Outside they have dark brown or black glassy crusts and inside they contain enough **iron metal** to attract a magnet. The outer glassy crust, of the meteorite, called its **fusion crust**, is produced as the rock is heated by friction when it comes through the atmosphere. The outer part of the rock melts and forms fusion crust that often has flow marks or indentations like thumbprints. The inside stays cool and is usually light gray to black in color, but some may be tan or, if weathered and rusted, brown.

The three major types of meteorites are stony, iron, and stony-iron meteorites. These are easily distinguished by their amounts of iron metal. **Stony meteorites** are mostly **silicate minerals** with less than 25% metal, **iron meteorites** are essentially all metal, and **stony-iron meteorites** are about half silicate minerals and half metal. Iron-rich meteorites can be easily identified by their density; they feel much heavier than Earth rocks. Most stony meteorites have shiny or rusty

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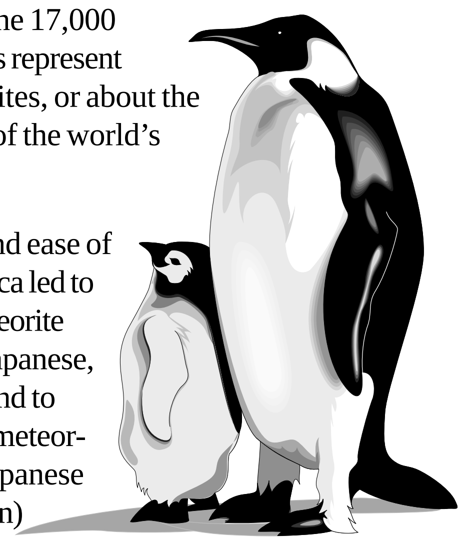
Meteorites that are collected with no visual evidence at the time of their fall are called **finds** and make up the bulk of the world's meteorite collections. Prior to 1970, about 1500 meteorite finds had been collected around the world. The discoveries of numerous meteorites in desert regions in North America, Africa and especially Australia have added hundreds of new meteorites to the collections in the last few years. But the best area in the world for collecting meteorites is the icy desert of Antarctica. In 1969, nine meteorites were found on Antarctic ice by a Japanese field team. Since then about 17,000 meteorite fragments have been found by Japanese, European, and U.S. meteorite collection teams.

Antarctic Meteorites

Antarctica is a special place for collecting meteorites. More meteorite fragments have been recovered there than from the rest of the world combined. Yet because the continent is frozen, remote and uninhabited, not a single Antarctic meteorite fall has been observed. Several factors combine to make Antarctica ideal for finding previously-fallen meteorites. The first is the ease of finding dark meteorites on ice. This aids in recovery of small and sometimes rare meteorites. The ice also helps to preserve the meteorites because they rust and weather away more slowly in cold Antarctic temperatures than in warmer climates. The next factor is the movement of the ice which concentrates meteorites that fell in different places at different times. The meteorites are enclosed in ice and move with a glacier until it comes to a rock barrier and stalls. The meteorites are later exposed at the surface as the ice gradually erodes away. This concentration makes it difficult to tell which meteorites are parts of a meteorite shower, and which are individual falls. All Antarctic meteorites are given separate names although some are later grouped as paired meteorites if data suggest that they came from a single shower. It is estimated that the 17,000 Antarctic meteorite fragments represent about 3,000 separate meteorites, or about the same as the total for the rest of the world's collection. (See Lesson 18)



The concentration process and ease of finding meteorites in Antarctica led to national and international meteorite programs organized by the Japanese, Americans and Europeans, and to yearly expeditions to collect meteorites. The Japanese JARE (Japanese Antarctic Research Expedition)

***Collecting Antarctic meteorites**. This scientist is collecting a meteorite on the ice in Antarctica. The Antarctic ice aids meteorite collection by concentrating many meteorites in some areas, weathering them slowly, and making them easy to see. Scientists live and work in remote, hazardous conditions in order to recover hundreds of meteorites per year.*

program is run by the National Institute of Polar Research (NIPR) in Tokyo. The EUROMET (European Meteorite) consortium is a cooperative program among many European countries with its headquarters at the Open University, Milton Keynes, England. The American ANSMET (Antarctic Search for Meteorites) program is a collaboration among three government agencies: the National Science Foundation (NSF), NASA, and the Smithsonian Institution.

In Antarctica, meteorites are concentrated on ice fields near mountains, especially the Transantarctic Mountains. The sites are far from the few coastal research stations or from the South Pole station. The weather is extreme, with sub-zero temperatures and high winds to make life hazardous. Teams of scientists spend one to two months in this frigid environment collecting meteorites. They travel to these sites by helicopters or cargo planes, drive around in snowmobiles, and live in special polar tents. They must take almost everything they need to survive because Antarctica provides only air, frozen water and refrigeration. Despite these hazardous conditions, the teams have been highly successful in collecting meteorites. During approximately twenty years of collection, American expeditions have returned over

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metal flecks visible inside: almost no Earth rocks have iron metal. A few stony meteorites have no metal and are very similar to Earth rocks; these can be recognized by their glassy fusion crust. Stony meteorites are the most abundant (94%) among falls and irons are uncommon (5%). However, irons make up about half of all finds, except in Antarctica. Stony-irons are rare (1%) among both falls and finds.

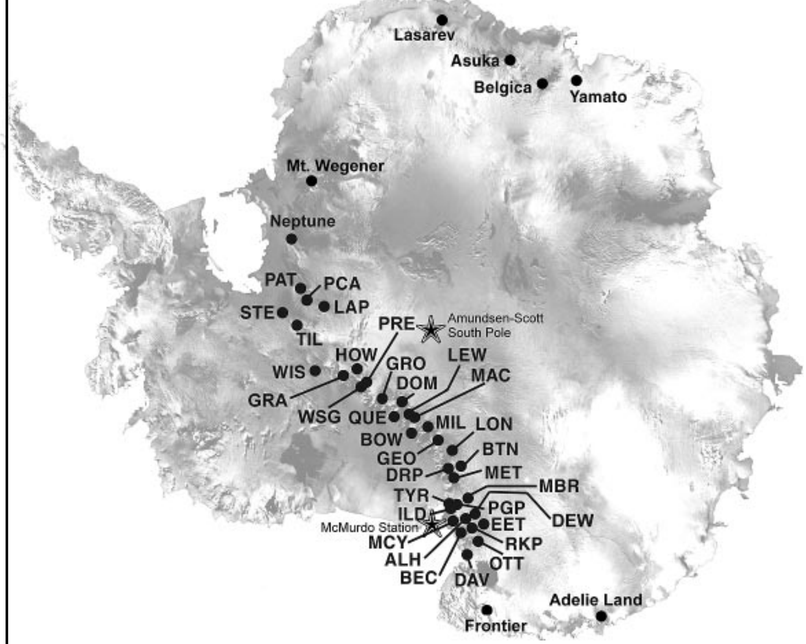
The only way to be sure if a rock is a meteorite is to have it examined and analyzed by an expert. If you have a sample that might be a meteorite, you should contact a meteoriticist, geologist or astronomer at a local science museum or university. Alternatively, you could contact a national meteorite curation center at NASA Johnson Space Center in Houston or the Smithsonian National Museum of Natural History in Washington, DC.

***Antarctic ice cave**. A member of the U.S. meteorite collection team is standing outside an ice cave in Antarctica.*

Naming Meteorites

Noblesville, Allende
Sikhote-Alin
Canyon Diablo
Gibeon, Brenham
ALH90411, EET83227

Meteorites are named after the nearest town (Noblesville, IN) or post office so their names are often picturesque. Because meteorites have been found the world over, the list of meteorite names looks like a geography lesson. When meteorites are found far from towns, they may be named after their county of origin (Sioux County, NB), or after a nearby river (Calkalong Creek, Aus.), lake (Carlisle Lakes, Aus.) or other geographic feature (Canyon Diablo, AZ). In deserts where many meteorites are found in areas with few towns or geographic names, meteorite names include both a geographic area and sample number. For example, Acfer 287 is from the Sahara Desert in Algeria and Camel Donga 005 is from the Nullarbor region in Australia. In Antarctica, where thousands of meteorites have been collected in yearly expeditions, the names include the geographic area, year of collection and sample number. Geographic areas are often abbreviated using one to four letters. Thus ALH90411 stands for sample 411 collected in 1990 in the Allan Hills area of Antarctica. The names, locations and find dates of meteorites in the disks are given in the Meteorite ABC's Fact Sheet on page 29.



Antarctic meteorite locations. *Meteorites are found mostly along the 3,000 km Transantarctic Mountains that diagonally cut the continent. These sites are remote from the U.S. research stations South Pole and McMurdo (indicated with stars).*

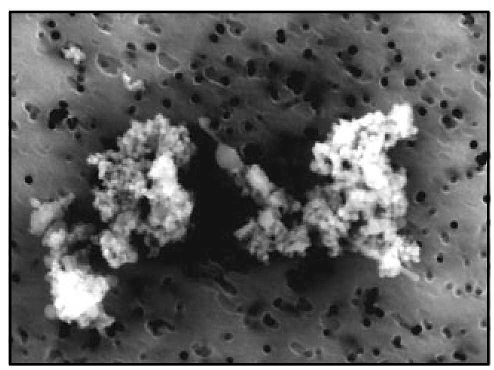
8,000 meteorite fragments, and Japanese over 9,000. In only three expeditions Europeans found 530 meteorites.

Meteorite Curation

Scientists in museums and universities around the world are responsible for the **curation** of non-Antarctic meteorites. Curation includes classifying new meteorites, storing them, and distributing them to scientists for study. When the three Antarctic meteorite collection programs began bringing back hundreds to thousands of meteorite fragments per year, each program set up its own facilities to do curation. Each of these facilities has special clean labs because Antarctic meteorites are less contaminated by Earth's environment and pollution than other meteorite finds. Meteorites are stored in clean cabinets, sometimes in a dry nitrogen gas, and handled and examined in glove box cabinets or lab benches with filtered air. The first task of the curators is to classify new meteorites and announce them to research scientists. Scientists then send requests for samples to study. In response, the curators take small pieces of each requested meteorite and distribute them to the scientists. Finally, the curators store the meteorites in clean environments to preserve them for future studies.

Meteorite curation. *This is the meteorite curation facility at NASA's Johnson Space Center in Houston, Texas. It is operated by the same group which curates the Apollo lunar samples. A companion facility is at the Smithsonian National Museum of Natural History in Washington, DC.*

Cosmic dust collection. *NASA collects cosmic dust in collectors mounted on aircraft that fly in the stratosphere.*



Interplanetary dust particle. *This fluffy aggregate of grains was collected by NASA high in the atmosphere. It consists of a variety of minerals loosely held together. It is sitting on a metal surface with holes in it.*

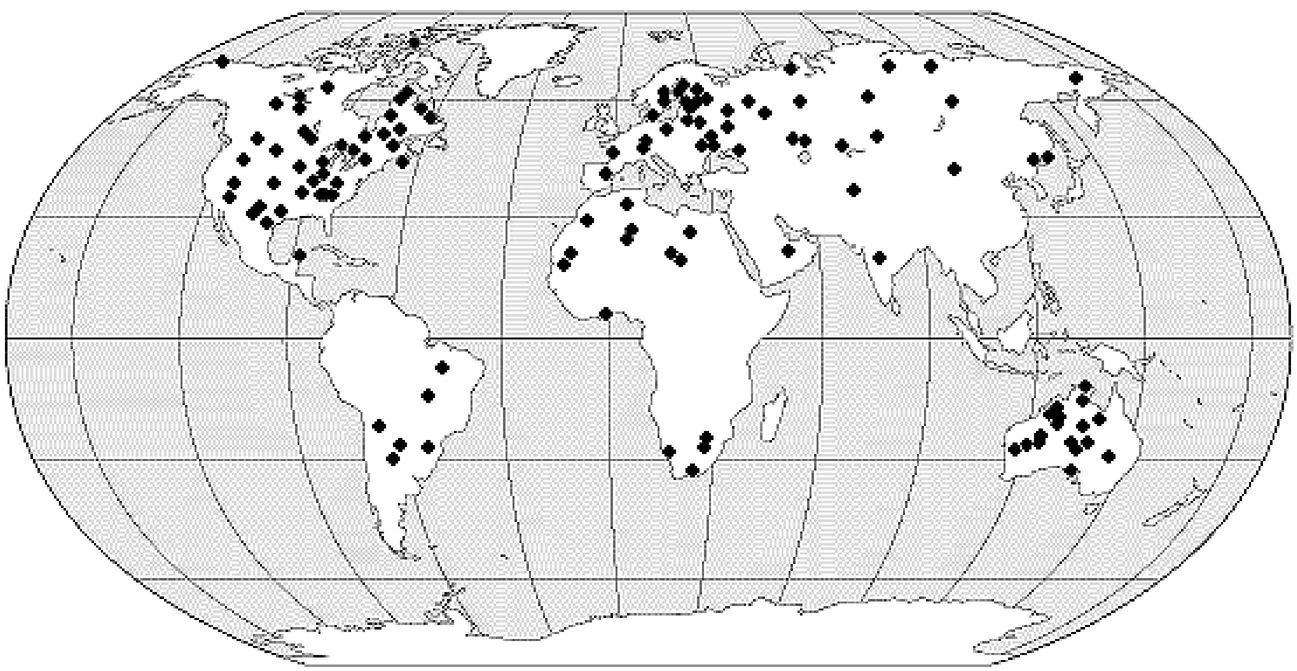
Micrometeorites

The smallest objects approaching Earth are **cosmic spherules** and **interplanetary dust particles** (IDP). They are called **micrometeorites** because they are so small that a microscope is needed to see them. Because micrometeorites are small and have very large surface areas compared to their masses, they radiate heat rapidly and are not melted as they pass through the atmosphere. Cosmic spherules are droplets less than a millimeter in size that are found in deep sea sediments and Antarctic and Greenland ice. EUROMET has an active micrometeorite collection program with a curation facility in Orsay, France. IDPs are micrometer-sized irregular aggregates that vary widely in composition, mineralogy and structure. NASA collects IDP's in the upper atmosphere using military airplanes with collectors attached under their wings. The collectors are opened upon reaching high altitudes and closed before returning to the ground. This ensures that only high altitude particles are collected. Some of these particles are man-made space debris, others are ash from Earth's volcanoes, but many are interplanetary dust. These IDP's are curated at NASA Johnson Space Center in a lab adjacent to the Antarctic meteorite curation lab. NASA curators describe, announce and distribute the IDP's which are studied by scientists around the world.

Impacts and Craters

Impact as a Planetary Process

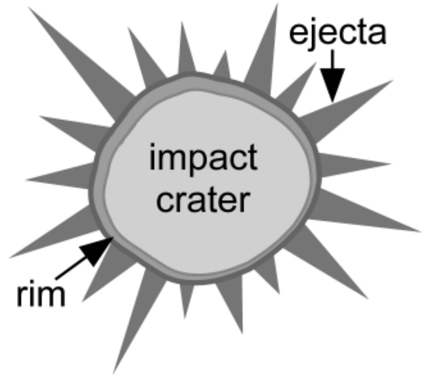
One of the most significant discoveries from NASA's exploration of the solar system is the importance of meteorite impact as a planetary process. Images of the Moon, Mercury, Mars, asteroids, and the moons of the outer planets show surfaces covered with impact craters. The recent Magellan radar images of Venus revealed both craters and volcanism on that cloud-covered planet. The view of the whole Earth from space shows little effect of impact. However, from photos taken in orbits closer to Earth, scientists have identified a number of circular impact features. Meteor Crater in Arizona is the most familiar example of an impact crater. It is relatively small, young, and well preserved compared to most impact craters. Many of these craters are old; some craters are partly-filled circular lakes; others are heavily eroded. Various types of craters are illustrated in the companion slide set. A map of terrestrial impact crater locations shows that they are scattered around the Earth.

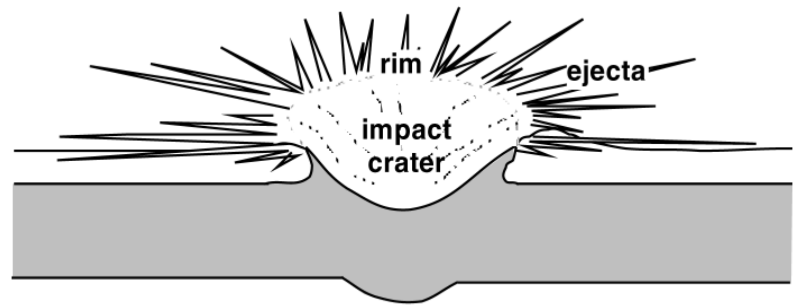


Terrestrial impact craters. *This map shows locations of 140 impact craters which have been identified on Earth. The craters range in size from under 1 km to over 200 km across and in age from recent to 2 billion years old. The clusters of craters in eastern North America, Europe, and Australia are due to both stable geologic environments and active crater search programs.*

Field and Laboratory Studies of Impacts

Recognizing impact craters and understanding how they form require a combination of field geology and impact experiments. The experiments define the speeds of impacting objects, structures of craters, and types of rocks formed in the impact process. Field studies of well-exposed craters provide "ground truth" for experiments and help define crater structure and the nature of rocks modified by impact. The speed of the impacting object (about 20-30 km/sec) is greater than the speed of sound in air. The object produces a sonic boom as it passes through the atmosphere and an explosion crater when it impacts. The diameter of the crater is about 10 times larger than that of the impacting object while the crater depth is about 1/10 the





***Crater cross sections**. This diagram shows two views of a typical impact crater. The left view shows the circular crater with its rim and scattered ejecta. The right view shows that the rim is above and the crater floor is below the original surface. The ejecta are thickest closest to the rim.*

crater diameter. These numbers vary with the speed, size, mass, and angle of approach of the impacting object, and with the nature of the target rocks.

Finding a circular crater is not sufficient to identify it as an impact crater because there are also volcanic craters. Although their size ranges overlap, impact craters tend to be larger than volcanic craters. Their structures also differ. A volcanic crater's floor is often above the surrounding surface, while an impact crater's floor is below the surrounding terrain. Thus a fresh impact crater is circular, with a raised rim and a lowered floor. Impact craters are also surrounded by rocky material thrown from the crater, **ejecta**. The best proof of an impact crater is associated meteorite fragments; after that, the next best indicator is the nature of its rocks. They are broken, distorted or even melted by the shock of the explosive impact. Much of the ejecta outside the crater is broken pieces of various rocks mixed together to form a **breccia**. The rocks inside the crater are also breccias which are highly shocked and sometimes melted. The original bedrock below the crater is shocked and fractured. (See Lessons 6 and 7)

Catastrophic Impacts

Looking at the surface of the Moon we see craters ranging in size from tiny to gigantic. The largest basins are the dark, roughly circular mare that are filled with solidified basalt. Such large impacts must have had a major affect on the whole Moon. Studies of lunar rocks returned by the Apollo missions showed that the giant impacts happened about 3.9 billion years ago (see companion volume *Exploring the Moon*). Studies also showed that the breccias formed by impact on the Moon are rich in some metals that are abundant in meteorites, but rare in rocks on the surfaces of the Moon and Earth. Iridium is one such metal that is common in meteorites. Its discovery in the K/T boundary soil offers an explanation of a catastrophic Earth event.

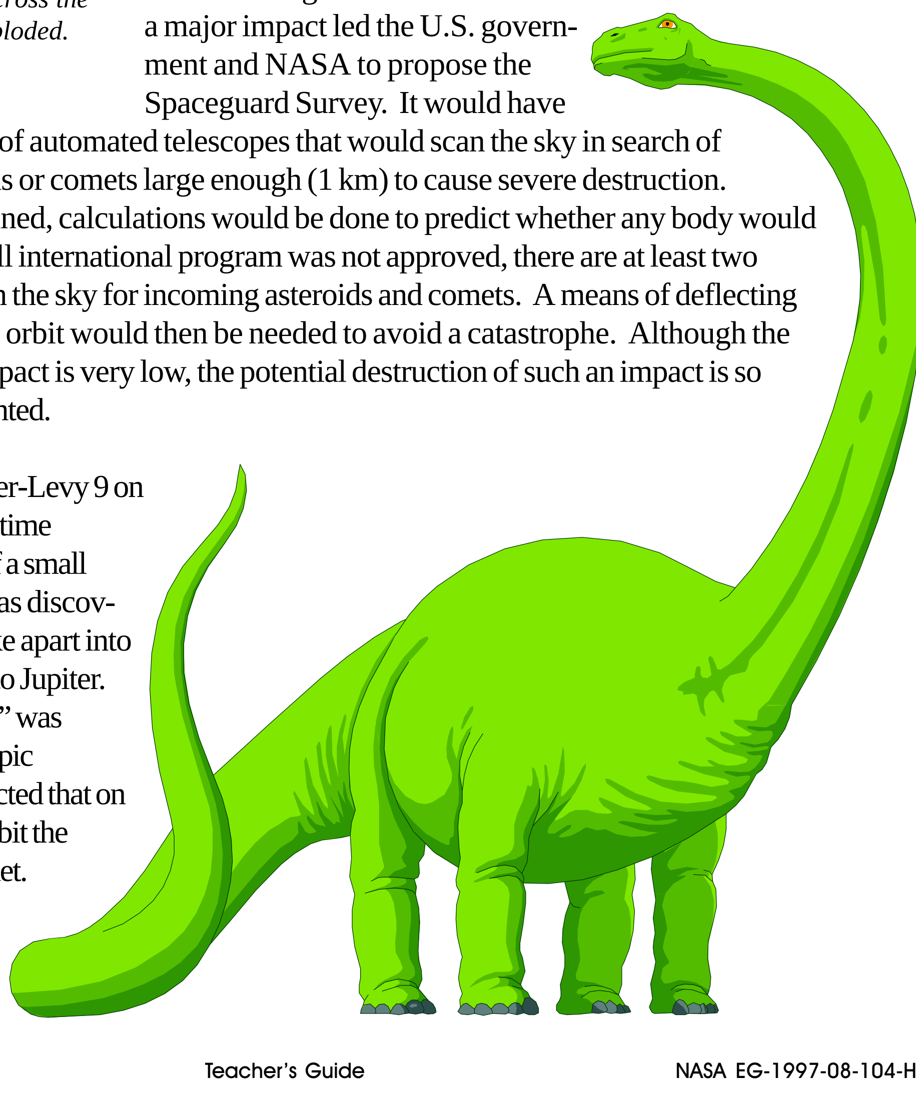
***Aristarchus.** The lunar crater Aristarchus is about 40 km in diameter. It is one of the most studied craters on the Moon.*

The K/T boundary is the layer of soil that marks the end of the Cretaceous (K) period and beginning of the Tertiary (T) period of geologic time. It occurred 65 million years ago when three-fourths of all species of life on Earth became extinct. Other time boundaries in earlier periods also mark extinctions of many species. Geologists have tried to understand the causes of these mass extinctions, suggesting perhaps major changes in climate. In 1980 geologists discovered that this layer is surprisingly rich in iridium. They suggested that the iridium was from a giant meteorite that impacted the Earth throwing a tremendous volume of dust into the atmosphere. While the immediate effects of the impact would have been regional, the effect of the dust in the atmosphere could have been global. The climate might have been changed drastically for some time after the impact. For years the impact hypothesis seemed plausible, but there were no terrestrial craters with the right age and size to have caused these changes. Recently, geologists found a 65 million year old buried crater that is over 200 km across on the Yucatan Peninsula in Mexico. It, possibly in combination with other craters the same age, might be the “smoking gun” of the K/T mass extinctions (see Lesson 14).

The Tunguska Impact. *In 1908 the biggest meteor in recorded history shot across the Tunguska River in Russia and exploded. (Credit: Smithsonian Institution)*

It is only natural to ask when the last large impact occurred on Earth and whether another one could occur soon. Meteor Crater was made by the impact of a large meteorite 50,000 years ago. Although it is a relatively small crater, it would have caused major destruction in a city, had there been any in existence at the time. Two medium-sized impacts occurred this century in Russia, Tunguska in 1908 and Sikhote-Alin in 1947 (see Lesson 15). The Tunguska explosion was large enough to have caused significant destruction if it had happened near a city.

The threat of global devastation from a major impact led the U.S. government and NASA to propose the Spaceguard Survey. It would have been an international network of automated telescopes that would scan the sky in search of all Earth-approaching asteroids or comets large enough (1 km) to cause severe destruction. Once their orbits were determined, calculations would be done to predict whether any body would impact Earth. Although the full international program was not approved, there are at least two smaller programs which search the sky for incoming asteroids and comets. A means of deflecting the asteroid or comet out of its orbit would then be needed to avoid a catastrophe. Although the probability of a devastating impact is very low, the potential destruction of such an impact is so great that precautions are warranted.



The impact of Comet Shoemaker-Levy 9 on Jupiter in July 1994 was the first time scientists predicted the impact of a small body on a planet. The comet was discovered in March 1993 after it broke apart into 22 fragments as it passed close to Jupiter. The orbit of this “string of pearls” was determined by continued telescopic observation. Calculations predicted that on its next pass through Jupiter’s orbit the fragments would impact the planet. Because of the predictions, the whole world watched and waited, while thousands of

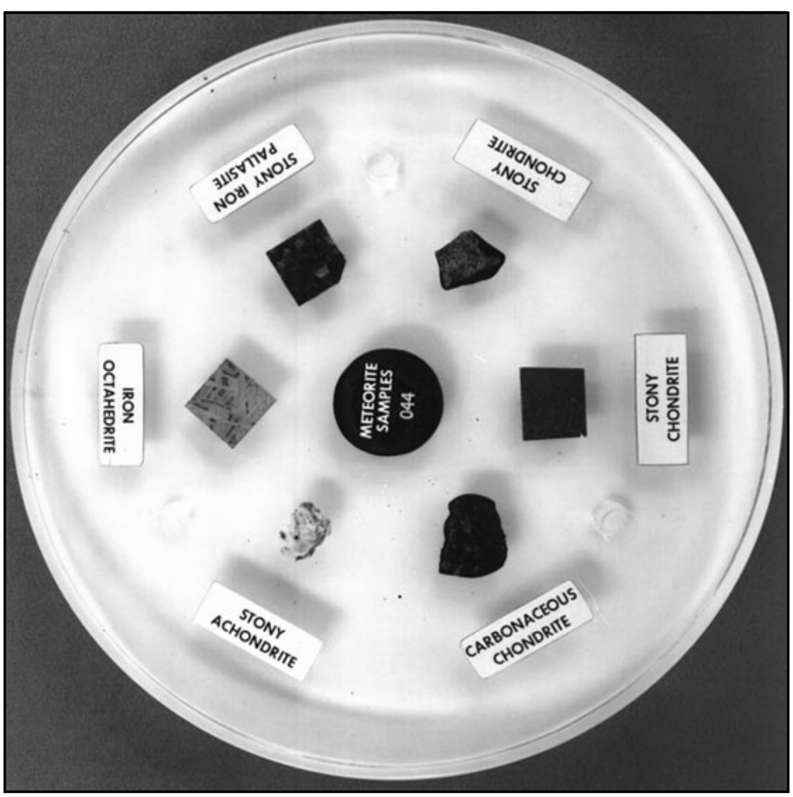
Comet Shoemaker-Levy 9 approaching Jupiter*.* *This picture is a composite of photographs taken by the Hubble Space Telescope. The "string of pearls" is the broken pieces of comet Shoemaker-Levy 9 which were photographed during the approach to Jupiter. The collisions in July 1994 were the first predicted impacts of an asteroid or comet on a planet. (Credit: Space Telescope Science Institute.)*

telescopes were aimed at Jupiter as the fragments of the comet impacted the planet on schedule. The views from the Hubble Space Telescope and from the Galileo spacecraft were even better than from large Earth-based telescopes. The successful identification of the comet and prediction of its impact allude to the potential capabilities of the Spaceguard Survey.

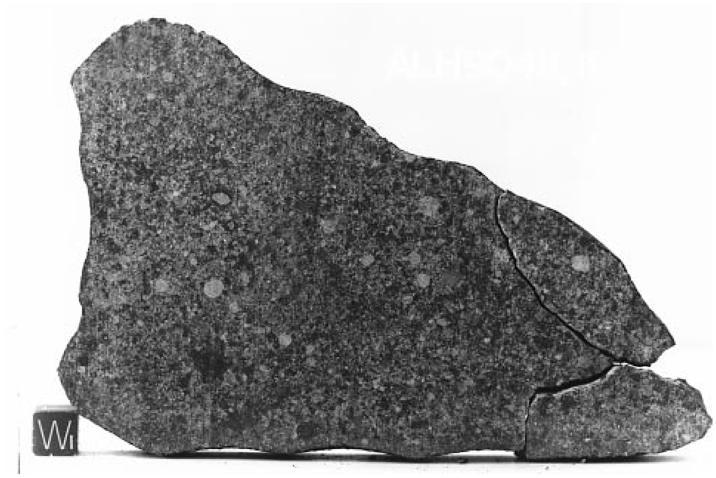
Meteorite Classification and Formation

Classification

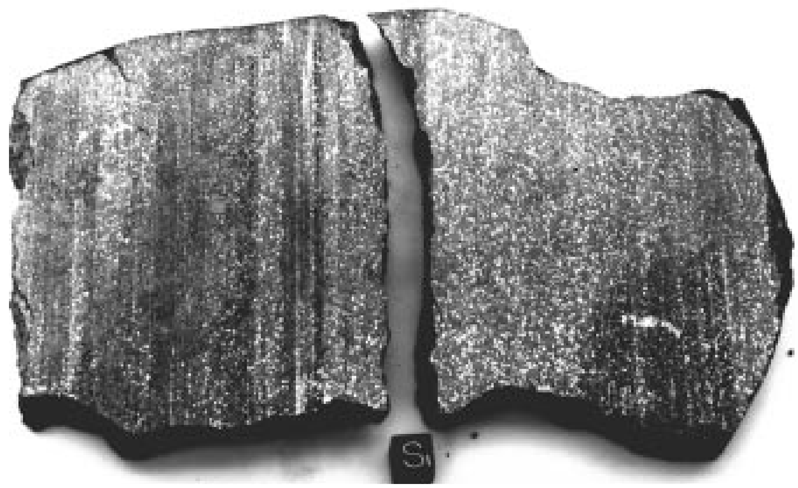
Meteorites are rocks that are made up of a variety of **minerals**. Minerals are naturally occurring crystalline materials composed of elements in defined proportions and structures. The most common minerals in meteorites are listed in the Meteorite ABC's Fact Sheet on page 29. Most meteorite minerals are similar to those occurring in Earth rocks, but a few of the rarer minerals are found only in meteorites. Different types of meteorites have different types and proportions of minerals and different compositions. Therefore, meteorites are classified by their mineralogy and **composition**. As



Meteorite Sample Disk. *The meteorite sample disk contains six different meteorite samples. See page iv for more information on using this disk in the classroom.*



***ALH90411 chondrite**. This stony meteorite is chondrite A in the meteorite sample disk and accompanying lithographs. This sawn surface shows an irregular texture with round chondrules, broken fragments, and a little dark rusted metal. ALH90411 is a low iron chondrite and is not metamorphic.*

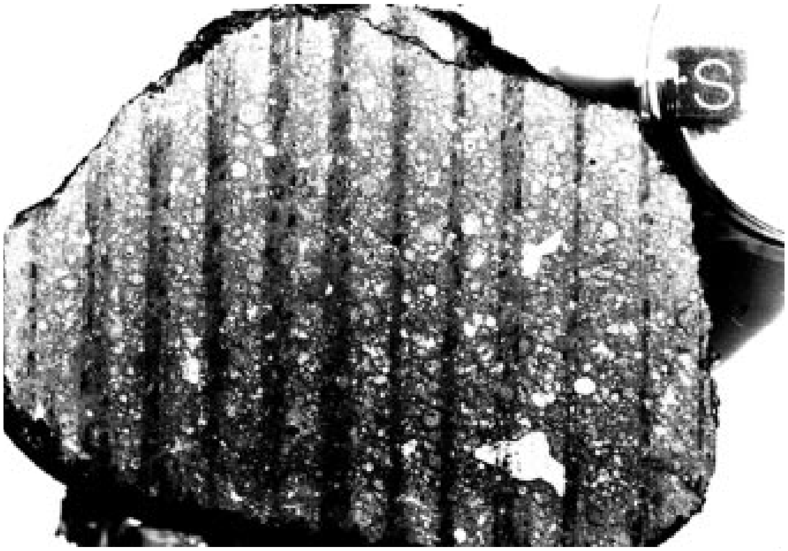


***LEW87030 chondrite**. This stony meteorite is chondrite B in the meteorite sample disk. It has a more uniform texture than ALH90411 and indistinct chondrules (vertical streaks are saw marks). It also has lots of shiny metal. LEW87030, like Noblesville, is a high iron, metamorphic chondrite.*

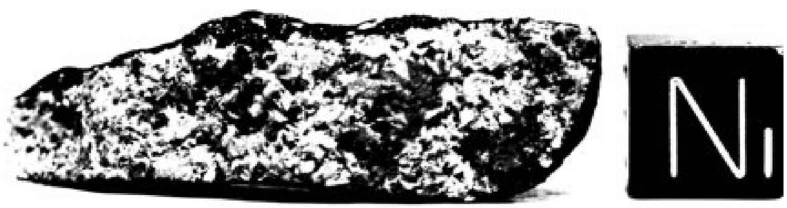
discussed in the section on identifying meteorites, the simplest classification of meteorites into **stony**, **iron**, and **stony-iron** types is based on the amount of iron metal and **silicate minerals** in the meteorite. It is relatively easy to tell whether a sample has little metal, is mostly metal, or is about half metal and half silicate minerals. This can be determined by looking at the amount of metal and silicate minerals in the sample's interior and by hefting it to feel its density because iron metal is about twice as dense as silicate minerals.

Each of the three major types of meteorites shows considerable variability and is further subdivided based on mineralogy and composition. Meteorite **classification** is complex because of the diverse possibilities. Meteorites represent many different rock types and probably come from different bodies in the solar system. However, after detailed studies, some meteorites of different types appear to be related to each other and possibly come from the same solar system body. A simplified listing of meteorite types is given in the Meteorite ABC's Fact Sheet.

Stony meteorites are divided into **chondrites** and **achondrites** based on whether they contain small round balls of silicate minerals called **chondrules**. Chondrites contain chondrules and achondrites do not. Chondrites are the most abundant type of meteorites, making up nearly 90% of both falls and Antarctic meteorites. Chondrites are divided into several classes, including **ordinary chondrites**, the most common, and **carbonaceous chondrites**, perhaps the most interesting because of their potential to tell the earliest history of the solar system.



***ALH84028 carbonaceous chondrite**. This stony meteorite has a highly irregular texture with distinct round chondrules, white inclusions, and little metal in a dark carbon-bearing matrix (vertical streaks are saw marks). It is a carbonaceous chondrite similar to Allende, the carbonaceous chondrite in the meteorite sample disk.*

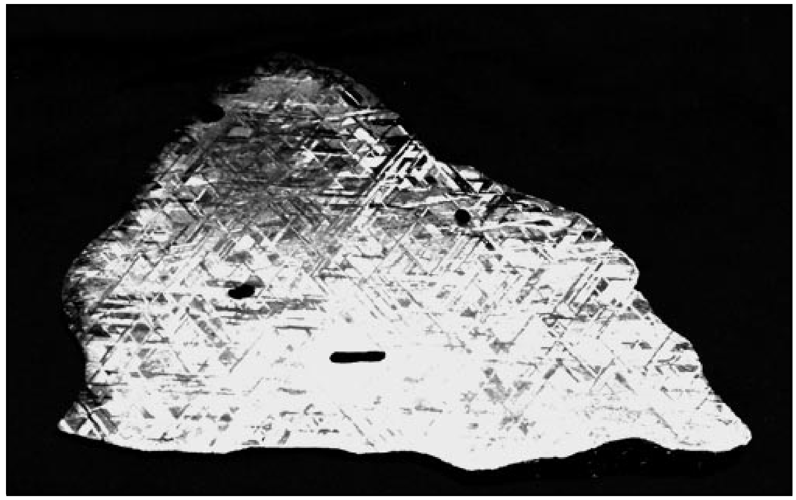


***RKPA80224 basaltic achondrite**. This stony meteorite contains no chondrules or metal and is an achondrite. Basaltic achondrites consist of feldspar (white mineral) and pyroxene (dark mineral) and are similar to basalts that formed from lavas on Earth and the Moon. This sample has an igneous texture showing that it crystallized from a melt. Other basaltic achondrites have the same mineralogy and composition, but are breccias containing broken rock fragments. The achondrite in the meteorite sample disk, EET83227, is a basaltic achondrite breccia.*

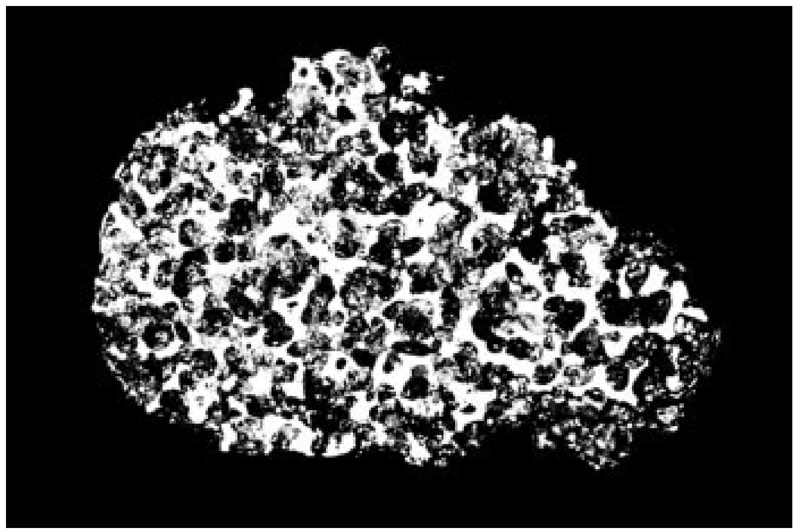
Ordinary chondrites consist of variable amounts of metal and chondrules in a matrix of mostly silicate minerals. The silicates are mostly olivine and pyroxene, with minor feldspar. Further subdivisions of ordinary chondrites are based on the amount of iron metal and the variability in composition and texture. Some are high iron chondrites, others are low or very low iron types. Chondrites which have distinct chondrules and variable mineral compositions have not been heated since they formed and are non-metamorphic chondrites. Metamorphic chondrites have indistinct chondrules and constant mineral compositions and have been changed since their initial formation.

Carbonaceous chondrites are a very special meteorite class because they are the most primitive meteorites and they contain water and **carbon compounds**. These chondrites consist mostly of the silicate minerals olivine and pyroxene or clay minerals that formed from them by weathering. Carbonaceous chondrites contain very little metal, but contain unusual inclusions, and 2-20% water in their clay minerals. The carbon occurs in elemental form as graphite and occasionally diamond, and in **organic molecules** which range from simple molecules to **amino acids**, the building blocks of DNA and life. Carbonaceous chondrites show variations in composition and degree of metamorphism and weathering.

Achondrites are the second most abundant type of meteorites (8%) and many are similar to igneous rocks on Earth. Achondrites are divided into several classes, of which the most abundant is **basaltic achondrites**, and the most unusual is **planetary meteorites**. The basaltic achondrites are actually a family of three distinct subclasses that are grouped together because they appear to be related to each other. The most common are pyroxene-feldspar igneous rocks similar to basalts on Earth. Many of these basalts were broken up by impacts so that the meteorites are breccias made up of basalt fragments. Another type consists mostly of pyroxene and may have formed by accumulation of minerals sinking in a magma. The



***Gibeon iron meteorite**. This photo shows a sawed surface which has been etched with acid to reveal the criss-cross Widmanstatten pattern. The Gibeon iron meteorite in the sample disk and the Sikhote-Alin meteorite have fine intergrowths of iron-nickel metals.*



***Brenham stony-iron meteorite**. This stony-iron meteorite consists of yellow-green olivine crystals surrounded by iron-nickel metal. It is a cumulate stony-iron and is used in the meteorite sample disk.*

third type are complex breccias made up of fragments of the other two types. These meteorites formed by impact mixing on the surface of a parent body.

Planetary meteorites are a recently recognized class of achondrites which include both lunar and martian meteorites. They are igneous rocks and breccias that formed from igneous rocks. Their compositions and mineral proportions range widely. Some are basalts that crystallized as lavas. Others are cumulates, rocks that formed by accumulation of minerals floating or sinking in magmas. These include lunar anorthosite breccias which formed by feldspar floating (see companion volume *Exploring the Moon*) or martian cumulates which formed by pyroxene and olivine sinking. More lunar and martian meteorites have been found in Antarctica than in the rest of the world.

Iron meteorites, which make up only 5% of meteorite falls, consist almost entirely of iron-nickel metal with variable amounts of sulfides and occasional inclusions of silicate minerals. Iron meteorites usually consist of two distinct iron-nickel minerals, kamacite (high iron) and taenite (high nickel) which are intergrown to form a criss-cross Widmanstatten pattern which can be seen when the sample is etched lightly with acid. Irons are subdivided both by the texture of this intergrowth and by the composition of trace elements in the metal. However, the textural and compositional subdivisions do not correlate well. Some groups of iron meteorites may be related to basaltic achondrites.

Stony-irons, which are the least abundant major type of meteorites (1%), include both cumulate and breccia varieties. The cumulates consist of metal and the silicate mineral olivine, where the olivine grains are large and surrounded by metal grains. The metal and silicates formed by slow cooling of heavy phases from a melted body. The metal and silicate grains in the stony-iron breccias are usually much smaller than in the cumulates, and the texture is a complex mixture of broken fragments imbedded in matrix. The silicate fragments are similar to those in basaltic achondrites. Both cumulate and breccia stony-irons may come from the same bodies as basaltic achondrites.

Meteorite Research

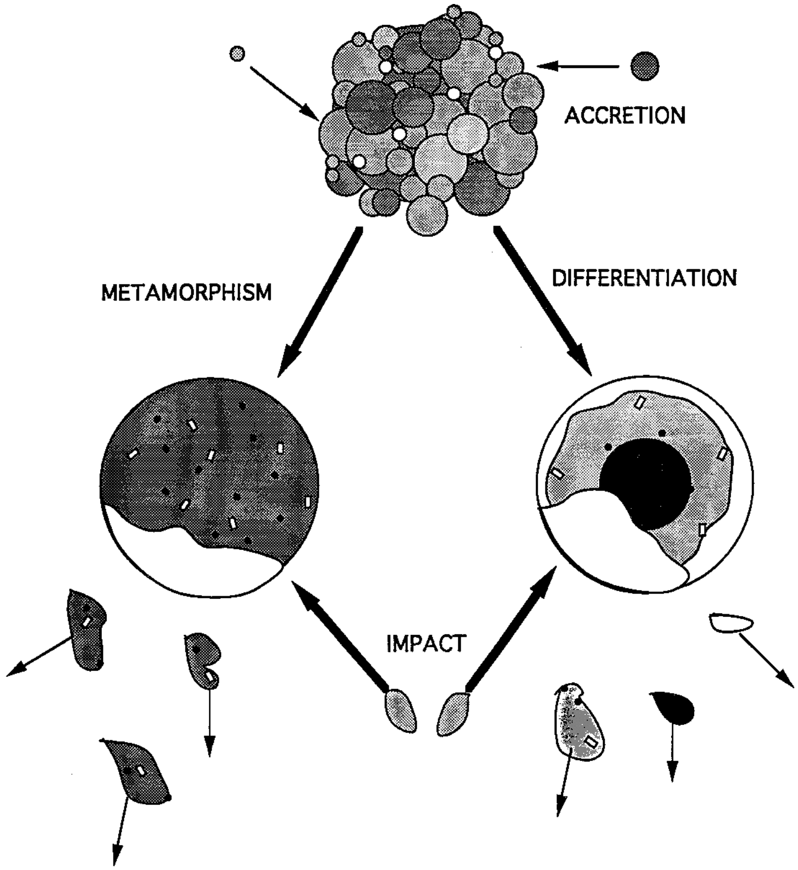
Many different types of science are involved in the study of meteorites, their formation and their sources. Meteorite research bridges the gap between geology, the study of Earth's rocks and landforms, and astronomy, the study of the Sun, planets, moons, and stars in space. **Planetary geology** is a new science which began when we were first able to study the Moon and other planets up close. Planetary scientists study the planets and other bodies in the solar system using photographs and chemical or physical data collected from flyby and orbiting spacecraft or robotic landers: Voyager, a flyby craft, explored the outer planets; the orbiter Magellan focused on Venus; Viking studied Mars with both orbiters and robotic landers. The Apollo missions to the Moon provided the only chance so far for humans to walk on another planetary body, to study the landforms, and to bring rocks back to Earth for detailed analyses (see companion volume *Exploring the Moon*).

Meteoriticists are scientists who study meteorites. They may be trained in geology, chemistry, physics, or astronomy because all these fields are needed to understand meteorites and their relationships to bodies in the solar system. Meteoriticists often work in teams so that specialists in several different fields contribute to the research. Mineralogists study the mineralogy and textures of thin slices of rock; chemists analyze rocks for their elemental and isotopic compositions and determine ages; physicists measure physical properties such as magnetism.

To learn about the relationship of meteorites to planetary bodies, astronomers try to match meteorites with possible sources. Planetary geologists study impact craters on Earth, the Moon and planets to understand the impact process. Other scientists do not study meteorites or planetary bodies directly, but do experiments in laboratories to simulate the processes of meteorite formation or impact. NASA funds most of the research on meteorites that is done in the U.S. through grants to investigators at universities, industry, and government laboratories.

Meteorite research*. This scientist is working at a scanning electron microscope. With this instrument the scientist can look in detail at the mineralogy, composition, and physical structure of meteorites.*

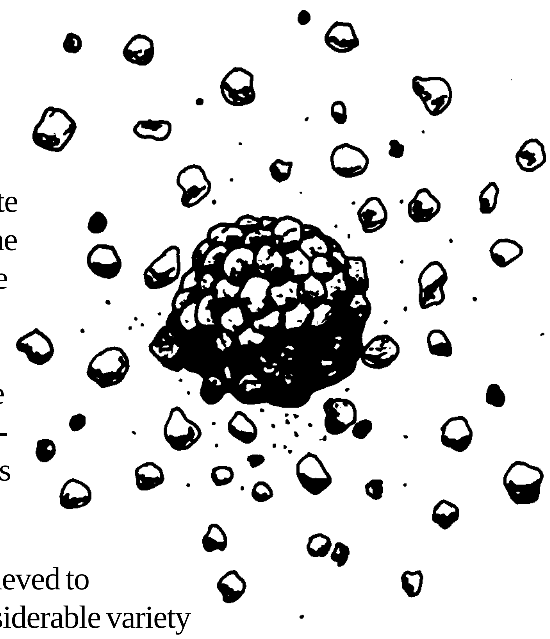
***Processes of meteorite formation**. This diagram illustrates several meteorite formation processes. The first processes are condensation from a gas to a solid (not illustrated) followed by accretion of small particles to form an asteroid or planet. When the accreted body is heated, it is modified by metamorphism or differentiation. Even if heating is not enough to melt the body, it may undergo metamorphic processes which make the texture and mineral compositions more uniform. If heating melts the body, it may undergo differentiation: Metal separates from the silicate melt and sinks under the influence of gravity to form the core. Silicate minerals crystallize and heavy minerals, like olivine and pyroxene, sink to form the mantle, while light ones, like feldspar and some pyroxene, float to form the crust. Volcanism (not illustrated) brings basalts to the surface to add to the crust. Weathering (not illustrated) alters the surface rocks through chemical or physical changes. Finally, impacts on a variety of bodies break off fragments that may fall to Earth as meteorites.*



Formation Processes

The processes of meteorite formation have been identified by comparing studies of meteorite mineralogy, composition and ages with those of Earth and Moon rocks, and experimental results. On Earth, rocks form by **igneous, metamorphic** and **sedimentary** processes**,** but the continued action of these processes has erased all evidence of Earth's initial formation. Meteorites bear evidence of the history of the solar system from its initial formation to recent volcanism and impacts on Mars. Chondrites are primitive objects formed at the beginning of the solar system and changed by metamorphic and sedimentary processes. Achondrites, irons, and stony-irons are differentiated objects formed by igneous processes and changed by impacts and metamorphism. Evidence for these processes is listed on the Solar System ABC's Fact Sheet on page 31. Many of the details of the processes are not fully understood — hence meteorite research continues — but enough is known to present a general story of meteorite formation.

The evidence for the primitive nature of chondrites is found in their ancient ages, Sun-like compositions, and unusual minerals and textures. All chondrites are 4.5-4.6 billion years old. They are the oldest rocks in the solar system and are used to date the beginning of the solar system. Chondrite compositions are very similar to that of the condensable part of the Sun without the gaseous elements, H and He. Carbonaceous chondrites are most similar to the Sun's composition because they contain volatile components such as water and carbon compounds. Chondrites tell us about formation of solid bodies from the cloud of gas and dust called the solar nebula. Carbonaceous chondrites contain stardust and white inclusions. Stardust is composed of minerals such as diamond and silicon carbide which are thought to have formed in a red giant star before our Sun was formed. The white inclusions consist of unusual minerals which were the first minerals to condense from a gas in the formation of the solar system. This **condensation** is the first stage in solar system formation. The gases in the solar nebula gradually condense as it cools to produce the minerals found in meteorites, first the white inclusions, then silicate minerals. Chondrules are melted and crystallized spheres of silicate minerals which are thought to have formed by flash heating as the solid matter in the solar system condensed.



Accretion is the physical process of building up chondrites and planetary bodies by collecting together smaller pieces of unrelated materials such as chondrules, white inclusions, stardust, and volatile components. The variations in chondrite mineralogy and composition show that there were areas in the early solar system with different compositions or temperature and pressure conditions. Inverse variations in the amount of iron in metal versus iron in silicate minerals suggest that there were variations in oxidation state for different chondrite types. Variations in volatile contents suggest that the volatile-rich carbonaceous chondrites accreted at lower temperatures than volatile-poor ordinary chondrites. (See Lesson 10)

The organic compounds in carbonaceous chondrites are believed to have formed very early in solar system history. There is considerable variety in organic compounds in carbonaceous chondrites, from simple molecules to amino acids, but apparently none were formed by living organisms. The evidence for this is in the symmetry of the organic compounds which are found in both right- and left-handed forms in meteorites, while similar compounds formed by living organisms on Earth are found only in one form. (See Lesson 12)

After condensation and accretion, most chondrites were changed by **metamorphism** and **weathering**. Heating of originally heterogeneous chondrites to temperatures below their melting points caused the mineral compositions to homogenize and chondrules to fade into the matrix. Heating of carbonaceous chondrites allowed their water to weather the olivine and pyroxene silicates to clay minerals. This was the first weathering in the solar system, an Earth-like sedimentary process that took place near the beginning of the solar system.

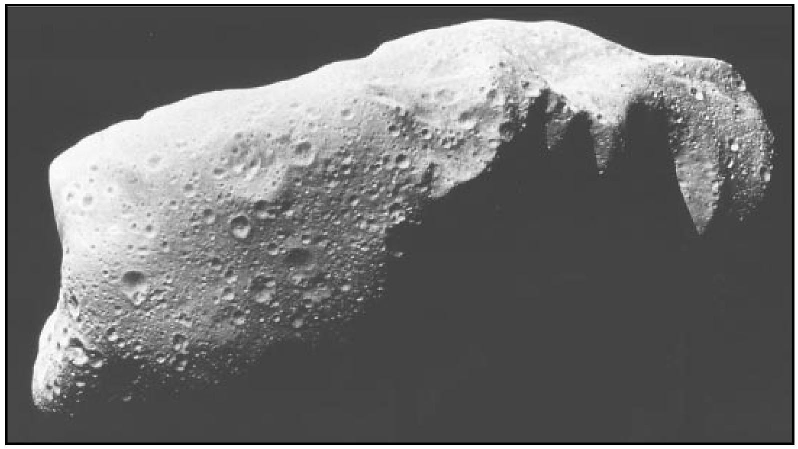
Differentiated meteorites (achondrites, irons, stony-irons) have compositions very different from those of the chondrites or the condensable part of the Sun. However, if their compositions are recombined in the relative proportions in which they fall to Earth, the average differentiated meteorite composition is a lot closer to chondrite composition. Most differentiated meteorites are also ancient rocks 4.4-4.5 billion years old, nearly as old as the primitive chondrites. The only exceptions are planetary meteorites which have ages ranging from 180 million years through 4.5 billion years. Although many differentiated meteorites are breccias broken and mixed by impacts, it is apparent that most are rocks that originally crystallized from melts and formed by igneous processes.

The suite of differentiated meteorites is evidence of early **differentiation** on asteroids (and planets) into **core**, **mantle** and **crust**. Heating of the body to above the melting temperature allowed separation of iron and silicate melts and later separation of crystallized minerals. Iron meteorites represent the core of the asteroid which formed by slow cooling from an iron melt to produce the intergrown iron-nickel minerals. Stony-iron cumulates come from the core-mantle boundary where iron melt surrounded olivine silicate minerals. Basaltic achondrites are mostly from the crust of the asteroid, with cumulates possibly from the upper part of the mantle. Basaltic achondrites flowed as lava onto the surface, just like basaltic lavas produced by **volcanism** on the Earth, Moon, and Mars. Finally, breccias of basaltic achondrites and stony-irons represent the soil and rocks at the surface of an asteroid where various rock types are broken and mixed by **impacts**. (See Lesson 11)

Meteorite Sources

Meteorites from Asteroids

Meteorites are "rocks from space," but there's a vast area of space out there. Our Sun is just one of billions of stars in the Milky Way galaxy, which is one of billions of galaxies in the universe. Luckily, we don't have to search all of outer space for the sources of meteorites because scientists think that meteorites come from our own "backyard," from the **asteroids, comets**, moons and planets in our solar system (see Solar System ABC's Fact Sheet).

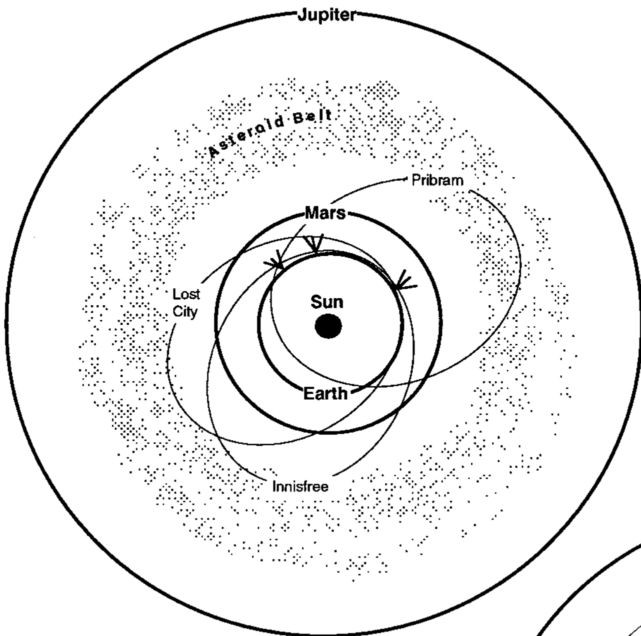


***Asteroid Ida**. This photograph of 52 km asteroid 243 Ida was taken in 1993 by the Galileo mission. The asteroid is a rocky body that is irregular in shape and covered with impact craters.*

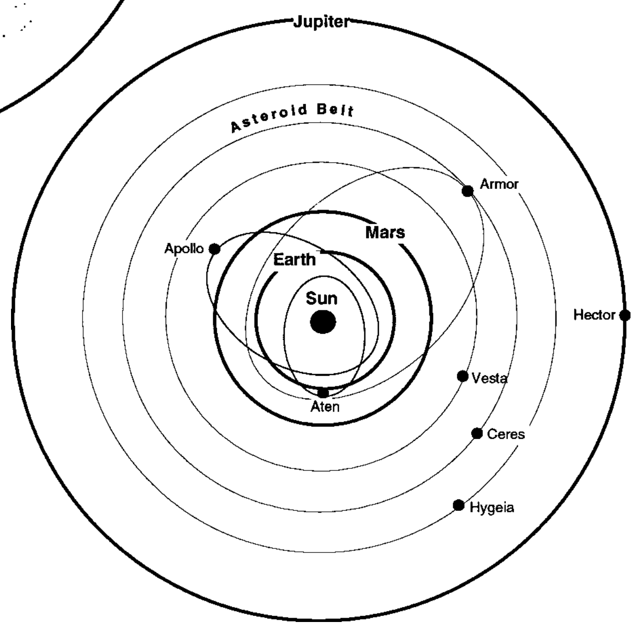
Most meteorites appear to come from asteroids, the small (diameter less than 1000 km) rocky bodies that orbit the Sun in the region between Mars and Jupiter, but are mostly concentrated in the **asteroid belt** between 2.2-3.2 AU (astronomical unit, the mean distance between the Earth and Sun). The evidence that most meteorites come from asteroids is based on comparison of meteorite and asteroid **orbits** and mineralogies. Three meteorites have been observed photographically as they approached Earth. It was possible to calculate the orbits of the Innisfree, Lost City, and Pribram meteorites from a series of timed photographs. These are all elliptical orbits that extend from Earth back to the asteroid belt. (See Lesson 4)

Asteroids are so small and far away that telescopes on Earth see them only as points of light. Astronomers find asteroids by studying telescopic images and looking for the objects that move compared to the stationary star field. Long exposure photographs show a background of stars as bright spots with a streak of light from an asteroid caused by its movement across the sky. To calculate the orbit of an asteroid, one must measure its position at several different places and times, but it is not necessary to follow it through an entire orbit. Asteroidal orbits are ellipses rather than circles (see Lesson 4), but most orbits are not too far from circular and therefore stay within the asteroid belt and do not cross the orbits of the planets. A few asteroids, such as Aten, Apollo, and Amor, have highly elliptical orbits that cross the orbits of Earth or Mars, while others like Hector are in the orbits of Jupiter or beyond. Gravitational interactions with Jupiter, and impacts between asteroids in the belt may break them up and send the resulting fragments into planet-crossing orbits.

Ceres, the largest asteroid (almost 1,000 km) was the first asteroid found in 1801. Since then over 6,000 asteroids have been catalogued. Most asteroids are very small, only three are larger than 500 km, and only about 25 are larger than 250 km. All of the Earth- and Mars-crossing asteroids are smaller than 30 km. Our first close up look at asteroids was provided by the Galileo spacecraft that flew by and photographed asteroids Gaspra in 1991 and Ida in 1993. Both are irregular masses of rock, seemingly broken and covered with impact craters. Phobos and Deimos, the moons of Mars, look very much like asteroids in size and shape. The next planned asteroid encounters are part of the NEAR mission. It will fly by asteroid Mathilde in summer 1997 and orbit and map asteroid Eros in 1999. The Solar System ABC's Fact Sheet gives information for twenty asteroids in order of distance from the Sun. It gives examples from each of the groups of planet-crossers and several of the larger asteroids that populate the asteroid belt.



***Meteorite and asteroid orbits**. Orbits of meteorites and asteroids compared to those of Earth, Mars and Jupiter. (Top) The orbits of three meteorites, Innisfree, Lost City and Pribram, were calculated from series of timed photographs taken as each meteorite fell to Earth. (Bottom) Orbits of seven asteroids are shown. The three closest to the sun, Aten, Apollo and Amor, are elliptical and cross the orbits of Earth or Mars. The next three, Vesta, Ceres and Hygeia, are in the asteroid belt where most asteroids are found. The last one, Hector, is in Jupiter's orbit, but spaced far enough from the planet that it does not impact Jupiter.*



Astronomers study different types of asteroids using the brightness and color of light they reflect. This is called **reflectance spectroscopy**. Asteroids are divided into several classes (indicated by letters) based on their overall brightness and reflectance spectrum. E asteroids are very bright, S and M asteroids are moderately bright, and C and D asteroids are dark. U asteroids are unusual and varied. E, M, and U asteroids are rare, while S and C asteroids are common. The asteroid belt appears to be zoned, with most of the S asteroids in the inner part of the belt, C asteroids in the central to outer belt, and D asteroids only in the outer belt. (See Lesson 5)

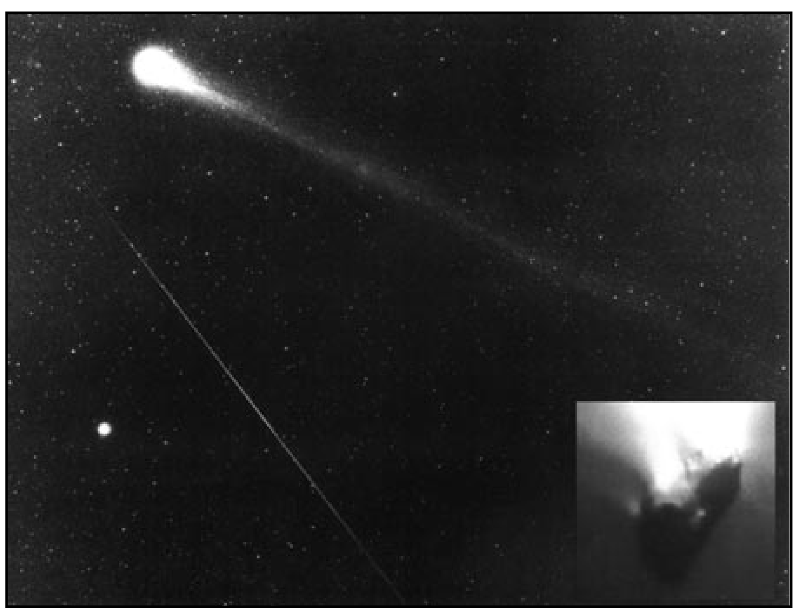
The spectrum of reflected light at different wavelengths is caused by the mineralogy on the surface of the asteroid. If we have reflectance measurements of appropriate mineral and rock standards, we can determine the mineralogy of an asteroid by matching it to that of the standards. In this way we find that E asteroids are rich in iron-free pyroxene, M asteroids are rich in metal, C and D asteroids are rich in carbon, S asteroids are mixtures of metal and silicates, and Vesta, one of the U asteroids, is made of basaltic rock. When compared to meteorites, fairly good matches between asteroid and meteorite classes are found. E asteroids match a special class of achondrites, M asteroids match irons and stony-irons, Vesta matches basaltic achondrites, C and D asteroids match carbonaceous chondrites. However, S asteroids are not a very good match for ordinary chondrites. Also, there is a problem that the most abundant type of asteroid in the inner asteroid belt does not match the most common type of meteorites. Our knowledge of the relationships between asteroids and meteorites is still incomplete. Nevertheless, there is a general relationship between meteorites and asteroids, and a zoning in asteroid types in the asteroid belt This suggests that asteroids represent the transition in formation from rocky inner planets to volatile-rich, outer planets.

Meteorites from Comets

Comets are small (1-10 km) balls of ice and dust that spend most of their time in the frigid outer solar system, but make spectacular displays when their highly elliptical orbits bring them into the warmer inner solar system. The Sun's heat produces a gaseous coma around the solid nucleus and long tails of gas and dust that can be seen by the naked eye. Periodic comets, like Halley which appears every 76 years, have elliptical orbits centered near Jupiter and Saturn and periods of less than 200 years. Most comets have very long periods (>10,000 y) and have visited the inner solar system only once in recorded history. They have nearly parabolic orbits and spend most of their time in the Oort cloud far beyond the orbit of Pluto. Comets Hyakutake and Hale-Bopp that visited the inner solar system in 1996-97 have periods of 65,000 years and 4,200 years, respectively.

Comets are considered to be the most primitive bodies in the solar system. They are "dirty snowballs" consisting of water, methane and ammonia ices mixed with silicates and a little metal dust. They are thought to have formed in the region around Uranus and Neptune, but were moved to new orbits by gravitational interaction with the planets: Periodic comets we see today were moved inward toward Jupiter and Saturn. Most comets, however, were thrown outward beyond the planets to form the Oort cloud.

Comets are clearly related to periodic meteor showers. Almost all periodic showers occur when Earth crosses the orbit of a periodic comet. Meteors are produced as cometary particles of dust and gas are burned up in the Earth's atmosphere. The Solar System ABC's Fact Sheet lists several comets and their associated meteor showers. The relationship between comets and meteorites is less certain. Since the compositions of comets and interplanetary dust particles are quite similar, comets are thought to be the sources of IDP's. Comet composition is also somewhat similar to that of some carbonaceous chondrites; a relationship with them is possible, although much less certain. Until we have more detailed information on the nature and composition of comets, either from robotic landers or comet sample return missions such as the Stardust mission to comet Wild 2, we will not know with certainty whether comets are the sources of carbonaceous chondrites.



Comet Halley*. This photograph of Comet Halley and a meteor, which appears as a streak, was taken on January 7, 1986 at the Mount Palomar Observatory. The inset is an image of the nucleus of Comet Halley taken by the European Space Agency's Giotto spacecraft shortly before closest approach.*

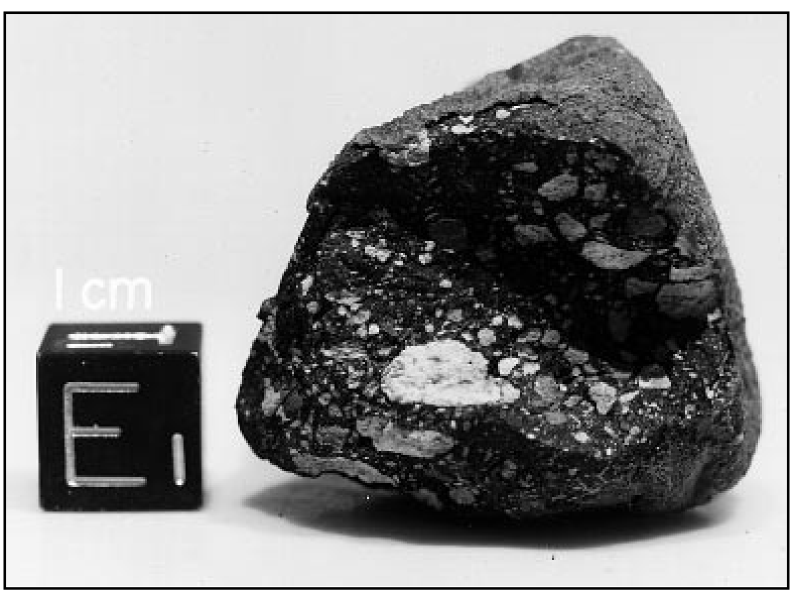
Meteorites from the Moon and Mars

The surfaces of the Moon and the rocky inner planets show many craters caused by meteorite impact. Could some of these impacts have ejected material into space that might later fall to Earth as meteorites? Before the Apollo lunar landings a few scientists thought that meteorites might come from the Moon. But none of the lunar rocks returned by six Apollo missions in 1969-1972 resembled meteorites. It was ten years later when the first lunar meteorite, ALHA81005, was identified in Antarctica. Although not identical to any specific Apollo sample, this achondrite is an **anorthosite** breccia that is very similar to many samples collected in the lunar **highlands** (see companion volume *Exploring the Moon*). Since 1982, a total of fifteen lunar meteorites have been identified. These meteorites include anorthosite breccias from the highlands and **basalts** and breccias from the lunar **mare**.

***Moon**. This photograph of the Moon was taken during the Apollo 17 mission. The light areas are highlands that are covered mainly with breccias rich in anorthosites. The dark areas are maria that are covered with basalt lavas.*

The identification of martian meteorites is a space detective story. Because we have not yet returned samples from Mars we have to rely on what we learned from robotic exploration and our understanding of rocks from the Earth, Moon and asteroids. In 1976 the Viking mission provided our first detailed look at Mars using two orbiters which photographed the whole surface and two landers which analyzed the atmosphere and soil.

The intensive studies of lunar samples and meteorites in the 1970s led to general models for planetary differentiation and evolution. Small bodies like asteroids differentiated early, if at all, and their heat engines died shortly after solar system formation. Hence asteroidal meteorites, including basaltic achondrites, are close to 4.5 billion years old. Larger bodies like the Moon and planets stayed active longer and have



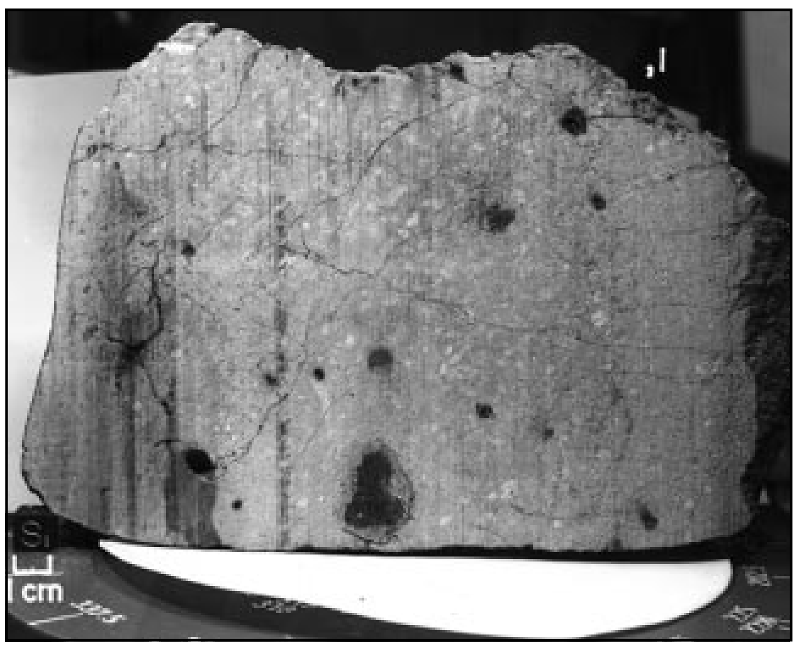
***Lunar meteorite ALHA81005**. This 31 g (ping pong ball-sized) meteorite is a breccia rich in light colored anorthosite fragments melted and mixed together by impacts in the lunar highlands. Other lunar meteorites are dark colored basalts from the mare. The scale is 1 cm across.*

__Mars__. This picture of Mars is a composite made from many photos taken during the Viking mission. The crack across the middle is a canyon as long as the United States. The dark circles at the left are huge volcanoes that are the largest in the solar system.

younger rocks on their surfaces, such as lunar basalts which are 3-4 billion years old. The Earth is obviously still producing igneous rocks today.

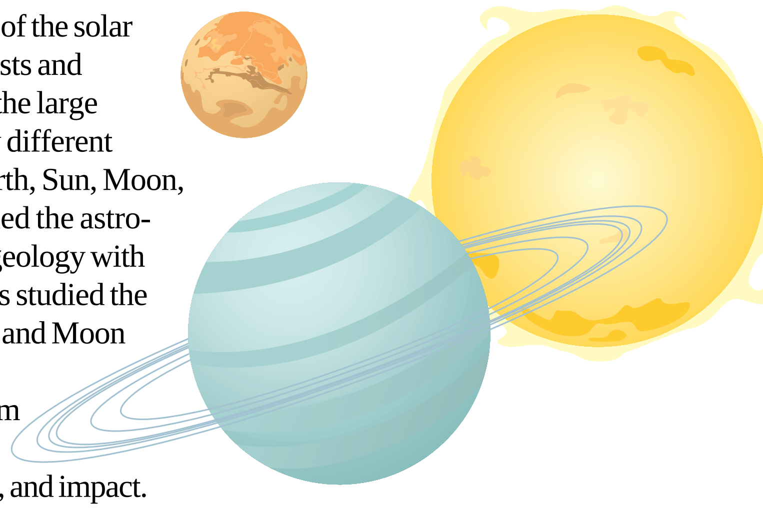
When geochemists discovered the SNC family, a group of achondrites which were 1.3 billion years old or less, they argued that they must be from a body larger than the Moon, perhaps Mars. The absence of lunar meteorites was used to argue that it was not possible to get meteorites off the surfaces of planets. The argument was if you couldn't get meteorites from the Moon with its lower gravity and closer distance, you couldn't get them from Mars. The discovery of first one, and then several, lunar meteorites refuted that argument. The definitive clues to a martian origin were found by comparing the meteorites to the Viking lander measurements. The martian soil had the composition of weathered basaltic rocks similar to the basaltic SNC meteorites. But the real clincher was the discovery that gases in one meteorite, EETA79001, had compositions identical to those Viking measured in the martian atmosphere. The rock actually had martian atmosphere trapped inside. In all there are twelve martian meteorites and all of them are igneous rocks, either basalts or olivine and/or pyroxene cumulates.

__Martian meteorite EETA79001.__ Remains of dark fusion crust, created during high speed entry through Earth's atmosphere are visible.



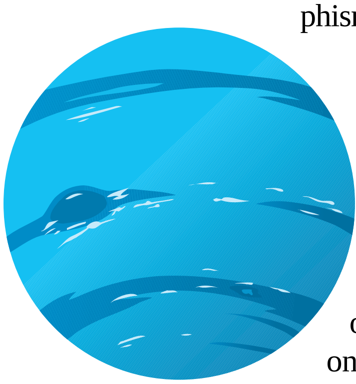
__Martian meteorite EETA79001.__ This 8 kg (soccer ball-sized) meteorite is a basalt similar to, but distinct from, basalts on Earth, the Moon, and the basaltic achondrite asteroid. It has dark glass-lined holes which contain gases with compositions the same as those measured in the martian atmosphere by the Viking lander.

Brief History of the Solar System



Our geological understanding of the history of the solar system has been pieced together by geologists and astronomers based on numerous studies of the large bodies and rocks in the solar system. Many different scientists participated in the study of the Earth, Sun, Moon, planets, asteroids, and comets. Some studied the astronomical bodies with telescopes; others did geology with orbital data and photographs; and still others studied the mineralogy, composition, and ages of Earth and Moon rocks and meteorites. These studies have revealed a series of processes in solar system history: condensation, accretion, differentiation, volcanism, metamorphism, weathering, and impact. These processes have taken place throughout the rocky inner solar system, but the duration and extent of the last four processes depend on the solar system body. Therefore, different bodies and their rocks provide evidence for different processes in solar system history. This evidence is tabulated in the Solar System ABC's Fact Sheet, page 31.

The Earth, Moon and Mars have no evidence remaining of initial planet formation by condensation and accretion. Primitive chondrite meteorites provide the evidence for the beginning of solar system history. Iron, stony-iron meteorites, lunar anorthosites, and seismic studies of Earth's interior structure provide evidence of early differentiation into core, mantle, and crust. Basalts are products of volcanism on all types of rocky bodies. Changes in the original mineralogy and composition of rocks were produced by metamorphism, weathering and impact on various bodies to different degrees.



Dating these events can be done in both relative and absolute ways. Relative dating on Earth is done in layers of rock where the rock on the bottom is presumed to be older than the rock on the top (unless there is evidence that the whole unit is turned over). However, when comparing meteorites or rocks from various planets these relationships are not available so absolute dating must be used. Absolute dating of rocks is based on radioactive decay of some elements with very long half-lives. The process that is dated depends on whether the rock was changed by later processes and how extensive those changes were. For example, if we want to date the initial formation of a meteorite (accretion of a chondrite or crystallization of a basaltic achondrite) the sample should be one that has not been extensively changed by metamorphism or weathering.

A solar system timeline based on dating of many meteorites and rocks from both Earth and Moon is given in the Solar System ABC's Fact Sheet. Like layers in rocks on Earth, the youngest events are at the top, the oldest are at the bottom. Although scientists don't fully understand all of these formation processes, they do know generally what happened and when. Some of these processes took place at about the same time on different bodies in the solar system. Some processes took place once and were finished. Sun and planet formation and initial differentiation are good examples of this. Other processes such as volcanism, metamorphism, and weathering continued over different periods of time on different bodies.

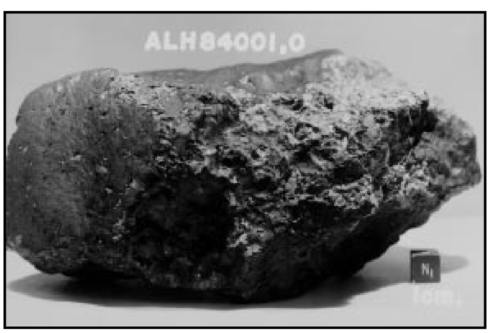
Billions of years ago, the elements which would eventually make up our solar system were produced in other stars. Around 4.6 billion years ago a rotating disk of gas and dust called the nebula formed from these elements. The center of the nebula collapsed under gravity to form the Sun. Slightly later, about 4.55 billion years ago, continued condensation and accretion led to the formation of the planets, moons and asteroids of the solar system. Very soon after their formation the inner planets, Moon and some of the larger asteroids melted and differentiated to produce core-mantle-crust. Basaltic volcanism, metamorphism and weathering took place shortly after the surfaces of these bodies formed. Thereafter the asteroids were geologically inactive except for impacts and the evidence of their early history was preserved.

The Moon and inner planets continued to evolve geologically for various periods of time which appear to depend on the size of the body. The record of their earliest geologic history is obscured by this subsequent activity. The oldest Moon rocks, anorthosites, norites and troctolites, date the initial differentiation and first magmas production at 4.4-4.5 and 4.2-4.5 billion years, respectively. The lunar cataclysmic bombardment (discussed in the companion volume *Exploring the Moon*) occurred about 3.9 billion years ago. Mare basaltic volcanism began before 4 billion years and continued until around 2-3 billion years. Geologic activity (other than impact) on the Moon ended long ago.

Our knowledge of the geologic histories of Mars and Venus is extremely limited. The Viking mission to Mars revealed ancient highlands, giant "young" volcanoes, and extensive surface weathering. The samples analyzed by the Viking lander were weathered rocks and soils. The martian meteorites are all igneous rocks most of which have ages of 180 million years (My) to 1.3 billion years. Thus martian basaltic volcanism continued at least to 180 My ago. One martian meteorite is an ancient rock 4.5 billion years old. The Magellan mission remote observations suggest that there may still be active volcanoes on Venus today. We have only very limited analyses of surface samples and no known meteorites from Venus so our information about the geologic history of Venus is woefully inadequate.

Earth is clearly the planet about which we have the most information. However, Earth's current geologic processes (plate tectonics, volcanism, metamorphism and weathering) have hidden the early history by changing the surface rocks. The earliest known Earth rocks are about 4.0 billion years old, although geologists think that Earth history began at 4.5 billion years along with the Moon and asteroids. Earth is clearly still geologically active today.

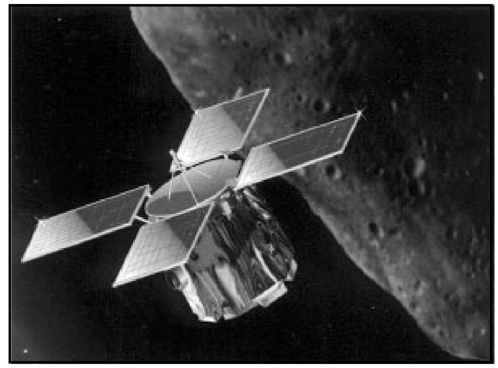
Earth is the only body in the solar system where we know for certain that life began and evolved. The conditions necessary for life as we know it (water, carbon, nitrogen and moderate temperature) are not currently available on any other body; however, there is evidence that Mars was wetter and may have been warmer in the past. The ancient martian meteorite may contain evidence of fossil life from an earlier era. The debate about life in the martian meteorite continues and may not be resolved without martian returned samples. The earliest evidence of life on Earth is dated around 3.7 billion years ago. Life evolved through ups and downs to the present. Periodic mass extinctions changed the direction of evolution. For example, at 65 million years ago 75% of all species died and small mammals took over dominance from the giant reptiles called dinosaurs. Whether the cause of these mass extinctions is a biologic process or the geologic process of meteorite impact is still hotly debated. Nevertheless, meteorite impacts, both small and medium-sized, continue on Earth and other planets at the present.



Martian meteorite ALH84001. *This 4.5 billion year old rock may contain fossil evidence that primitive life may have existed on Mars as much as 3.6 billion years ago.*

The history of our solar system is long and complex. Our knowledge has been gained through various studies in geology and astronomy and related fields. Scientists are still trying to understand the physical and chemical processes in solar system history so the story is not complete. However, the history as we see it involves similar processes occurring at varied times on different bodies. Taken as a whole, it is a fascinating story.

Future Exploration



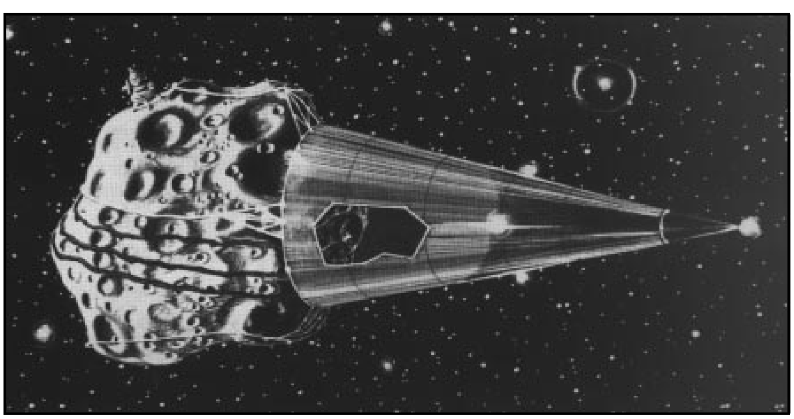
Near Earth Asteroid Rendezvouz (NEAR) spacecraft. *The NEAR mission will rendezvouz with Asteroid 433 Eros in February 1999.*

Further understanding of the history of the solar system is closely linked to the future exploration of space by robotic and human missions. There is still much that we can learn about solar system processes from studies of meteorites and Apollo lunar samples and from telescopic studies of the planets. But think how much more we can learn about planetary bodies with new samples and close-up geologic exploration! The six Apollo lunar landings demonstrated the value of human observation and ingenuity in exploration and returned many documented samples for continued studies. The spectacular results of the Voyager and Viking missions showed how much we can learn about distant planets from robotic missions. Future missions such as the Mars Surveyor orbiter and lander series and the Discovery class missions to the Moon (Prospector), an asteroid (NEAR) and a comet (Stardust) promise exciting discoveries in the next ten years.

Exploration of space has other benefits besides knowledge. It creates new technologies and, perhaps more importantly, it inspires people to excel and to work together. However, space exploration, especially human exploration, is a very expensive business. Not only must the benefits of knowledge, technology, inspiration, and cooperation be high, but the costs must be reduced as much as possible. One of the most effective means of reducing costs comes from using space resources and reusing everything possible.

Asteroidal Resources

NASA has worked on a number of plans for future robotic exploration of the planets, asteroids, and comets and on human missions to the Moon and Mars. The most important expendables for space exploration are energy for transportation and operations and consumables for life support. It takes lots of expensive energy to move a mass of consumables against Earth's gravity. It takes much less energy to move the same mass in lower gravity environments like the Moon and especially asteroids. There is a big advantage in energy, and



Mining an Asteroid*. This is an artist's idea of mining an asteroid to support space exploration. Depending on the type of asteroid, the products might be oxygen, metal, glass, water, organic compounds or several of these resources at once. (Credit: Dennis Davidson)* thereby cost, in using space resources as compared to carrying them from Earth. It may even be advantageous to get resources from one place in space for use in other places.

The closest planetary targets, the Moon, Mars, and asteroids, have little or no atmosphere and surface water, and no known plants for food, but there is abundant energy for operations from solar radiation. Moreover, the rocks and soils can provide many of the elements necessary for space exploration. The rocks themselves are nearly half oxygen, and some also contain water and organic compounds. NASA has developed technologies to extract oxygen from rocks, producing metals or glass as by-products. This oxygen will be used mostly for spacecraft propulsion, but also for astronaut life support. The metals and glass, as well as surface rocks and soil, can be used for building materials and radiation shielding. NASA has also developed methods of growing plants in closed environments, reusing scarce consumables.

The first targets for extended space exploration and resource utilization are likely to be the Moon and asteroids. The Moon is close and relatively easy to get to. Although it doesn't have air, water, or food, we know what it is like, and we could produce oxygen, water, and even food in lunar factories and greenhouses. Ideas for a Moon base are discussed in the companion volume *Exploring the Moon*. Asteroids are such small bodies that their minimal gravity makes it easy to get materials off the surface and into space. In fact it takes less energy to get materials to and from some near-Earth asteroids than from the Moon. The Moon and asteroids could provide test-beds for proving technology to sustain life on Mars or extended space flight.

Asteroids are particularly promising for using space resources because they offer a variety of different resources. Asteroids similar to stony meteorites could provide oxygen for fuel and metal or glass for construction. Asteroids similar to iron meteorites could provide metal, even some precious metals, with very little processing. Perhaps most promising, asteroids similar to carbonaceous chondrites could provide water and organic compounds essential for life support. Mining asteroid resources could become a stepping stone to human exploration of the outer solar system. (See Lesson 17)

Mars Exploration

Mars is the ultimate near-term goal for human space exploration. It is the closest planet that may be habitable by people. Venus, although closer to Earth, has a highly toxic atmosphere

Future mission to Mars. *In the year 2020 Mars exploration will be returning samples from the red planet. (Credit: Pat Rawlings)*

***Exploring Mars**. This painting shows astronauts exploring Mars using a rover for transportation. The astronauts are at the top cliff of a large canyon which is shrouded in mist. (Credit: Pat Rawlings)*

and extremely high temperatures which make it uninhabitable. Mars has a less toxic atmosphere and moderate temperatures. Mars has always intrigued people because some astronomers thought they saw channels suggesting the possibility of intelligent life. Recent geologic studies have shown that all surface features are natural formations, but also confirmed that Mars is the only other planet in our solar system that could once have harbored life of some kind. Although the Viking landers did not detect life in the martian soil, we can't be certain that life doesn't or did not exist elsewhere on the planet. Mars is now cold and dry, but it was not always so. There is evidence that water flowed on the surface in the past. Mars was once wetter and may have been warmer, and more hospitable for life. Several martian meteorites show interaction with martian water. The oldest one, ALH84001, may even have evidence of past life on Mars. The possibility of life and the more habitable conditions make Mars an important target for exploration.

Most of our information about Mars was collected during the Mariner and Viking missions. They were flybys and orbiters that photographed the planet and made geophysical and geochemical measurements, and landers that analyzed the atmosphere and soil composition. Mars' weather is always changing. Wind and dust storms are common and sometimes global. The polar ice caps change with seasonal temperature changes. Major changes occurred some time in the past which made the surface water disappear and the atmosphere decrease. We do not yet understand the causes of these changes.

Mars' geology is also fascinating. Although the planet is much smaller than Earth, the scale of its major geologic features is much larger. Mars' volcanoes are the largest in the solar system, ten times greater than the largest on Earth. Mars' huge canyon, Valles Marineris, is as long as North America is wide! Mars is divided by a global cliff into old cratered southern highlands and young volcanic northern plains. Both the highlands and the plains have been eroded by water and wind. The two Viking landing sites in the plains had soil compositions similar to basalts altered by water. The martian meteorites are all igneous rocks, mostly from the young northern plains, but they contain some minor minerals in cracks and bubbles that are products of alteration by water. There are many questions left unanswered about the geology and climate of Mars. How has the planet changed with time? Why are the northern and southern hemispheres so different? What caused the climate to change drastically so that the surface water and atmosphere disappeared? Is water or ice present at the poles or as permafrost? Is there convincing evidence of life, either living organisms or fossils? These are some of the questions to be addressed by future exploration.

The exploration of Mars is a complicated and expensive endeavor. The trip to Mars takes at least six months when the two planets are closest, which happens every two years. Ideally, Mars exploration will include a combination of robotic and human missions. Robotic exploration is necessary in the early stages to conduct global surveys and investigate potential sites for human exploration. Robotic missions will also test technologies, deliver cargo, and return the first documented Mars samples. Human missions are desirable for detailed exploration of selected sites because people are best at observation, interpretation and problem solving.

Preparation for a human mission to Mars is extensive. The mission would last about three years, including the long trip each way and plenty of time for exploration while waiting for the planets to return to closest approach. This extended mission requires a huge amount of consumables, both for fuel and for life support. The amounts can be reduced to about one third by using Mars' resources. The selected site should be one where water or ice is available for human use. NASA is developing technologies to produce oxygen from the carbon dioxide in Mars' atmosphere. This would be used for breathing, but also to power rovers for exploration and the spacecraft for the return trip to Earth. Astronauts could grow plants for food in greenhouses that recycle CO_2 and other waste components. With habitats for shelter and rovers for transportation, the first Mars outpost could be nearly self-sufficient. It would also be the first step in a permanent human presence on Mars.

Once their basic needs are met the astronauts will spend part of their time on exploration and sample analysis. They will observe geologic formations, collect rocks and soils, and look for any signs of life. In the habitat labs they will do geochemical and biological analyses. Together with their scientific colleagues back on Earth they will attempt to answer some of the questions about the evolution of Mars and its part in the history of the solar system. By exploring the asteroids and planets we may be able to solve some of the mysteries revealed by meteorites.

Mars Habitats. *The joined habitats provide the crew with multiple pressurized volumes for conducting greenhouse experiments, biological research, geochemical analysis of samples, and general crew accomodations. (Credit: Jack Frassanito)*