Meteorites: Helping the Search for the Origins of Life

Editor's Introduction | The study of meteorites is helping us understand the processes and materials that shaped the earth and the solar system. Recent space missions, and the analysis of meteorites from the Moon, Mars and the asteroid belt, have led scientists to question the possible evolution of life on other planets. How is a meteorite formed, where do they come from and how do they arrive on earth? Monica Grady, the head of the Petrology and Meteoritics Division in the Department of Mineralogy at The Natural History Museum, discusses these questions and more.

Our local star, the Sun was formed out of a nebula, a rotating and turbulent cloud of gas and dust. As the cloud rotated faster, it collapsed and flattened into a disk with the Sun at its centre. Within the disk, dust grains joined together to form bigger and bigger bodies, eventually, some 4,560 million years ago, producing the planets and their satellites, plus comets, asteroids and the host of other minor bodies that make up the Solar System.

NASA/JPL/Caltech

Photomontage of eight of the nine planets in the Solar System.

The four inner planets (Mercury, Venus, Earth and Mars) are mainly made from rock. Then follow the giant planets Jupiter and Saturn (composed mainly of gas) and the outer planets Uranus and Neptune (gas plus ice). The outermost planet, Pluto, and its satellite Charon, are small compact icy bodies that have an affinity with a disk-like array of similar objects known as the Kuiper Belt. Approximately 35,000 Kuiper Belt objects orbit the Sun at the distance of Pluto (5,913 million km or ~ 40 AU; 1 AU is the mean Earth-Sun distance, approximately 150 million km) and beyond. When objects from this belt are dislodged by gravitational perturbations, they might enter the inner Solar System as comets, although many comets are presumed to emanate from the cold outermost reaches of the Solar System, where ices could condense. The icy bodies that produced comets are now thought to inhabit a spherical region of space extending to ~ 50,000 AU, called the Oort cloud. Like the planets, comets orbit the Sun and they have been described as "dirty snowballs," a mixture of partially melted ice and dust. Each time a comet approaches the Sun, some of the ice melts, and streams away from the central portion, or nucleus of the comet, carrying with it some of the dust. This expanding cloud of gas and dust gives rise to a comet's characteristic appearance of a head and a tail. Each time the comet draws near to the Sun, more of the ice and dust is lost, and the dust eventually becomes spread out along the entire orbit of the comet.

NASA

Halley's Comet, as photographed on March 8, 1986, by W. Liller, Easter Island.

Between Mars and Jupiter, at a distance of approximately 450-700 million km at the hiatus between rock and gas in the Solar System, lies the Asteroid Belt, the source of most meteorites. There are several thousand asteroids, the largest of which, named Ceres, is ~ 914 km across (for comparison, Earth has a diameter ~ 13,000 km, and Moon ~ 3,500 km). Asteroids are rocky, metallic or carbonaceous bodies. They are material remaining after the planets formed: Jupiter's gravitational pull prevented the bodies from joining together to form a single planet. Occasionally, influenced by Jupiter, the orbit of an asteroid is altered such that it might collide with another, and break up. Images of asteroids obtained recently by the Galileo probe show that many have cratered surfaces, indicating that collisions are frequent. Fragments of disrupted asteroids fall to Earth as meteorites, dating from the formation of the Solar System, and comprise the only source of primordial material available for study. Although the Earth and other planets were also formed 4,560 million years ago, none of the original material remains: it has been removed by bombardment or erosion, or recycled through geological activity. It is only by studying meteorites that we can learn about the processes and materials that shaped the Solar System and our planet.

Meteorites are divided into three main types (stone, iron and stony-iron), reflecting their composition. These provide evidence about events that have occurred as the Solar System formed and evolved. 96 percent of meteorites are stony, made up of the same silicate minerals (olivine, pyroxene, plagioclase) as many terrestrial rocks.

The stony meteorites are sub-divided into chondrites and achondrites. The former are meteorites that have remained unmelted since formation of their parents, whereas the latter are igneous rocks, like basalts, that formed from melts on their parent bodies. As a consequence of the melting process, achondrites are chemically differentiated and as they are the oldest known basalts in the Solar System, their study has allowed insight into early magma genesis, the nature of the source material from which they crystallised and processes of condensation and accretion.

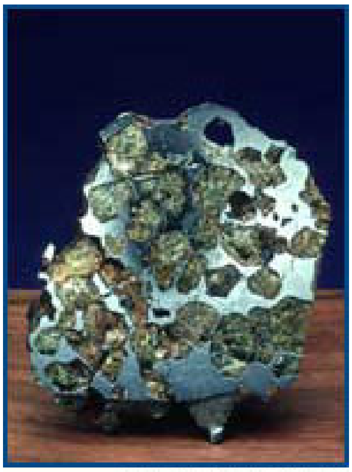
In contrast, chondrites retain a chemical signature close to that of the original material from which they aggregated. Although they have not been melted, they do contain materials that were once molten. Chondrules were then produced by rapid cooling of droplets of molten stone. Collisions between clumps of dust grains during early formation of the Solar System produced these meteorites and so represent the materials from which it grew. In addition to chondrules, chondrites contain organic compounds such as amino and carboxylic acids and complex hydrocarbons, or elemental carbon. Meteorites like these, together with the ice- and organics-rich comets, probably brought volatile materials to the newly formed Earth, and helped establish its atmosphere and oceans. Without them, there would be no life on Earth.

Chondrites also contain tiny grains of dust that came from stars other than the Sun. These grains are diamonds (only 3 nm across) and silicon carbide (or carborundum). Their interstellar origins have been inferred from the isotopic compositions of nitrogen and the noble gas xenon trapped within the diamond lattice, and released when the diamond is burnt in the laboratory. The diamonds were blown from the surfaces of neighbouring stars, and carried on the stellar wind into the collapsing dust cloud that formed the Solar System. From these grains, we learn that the Sun did not grow in isolation.

The second large division of meteorites, the irons, are made dominantly from iron metal, typically with 5-15 wt. percent nickel. These formed during extensive melting processes on the parent bodies from which they originated. The heat source for melting iron meteorites was often the result of impacts, although for many the probable decay of short-lived radioactive isotopes, such as Al, was the cause. Iron meteorite parent asteroids were sufficiently large to permit heat buildup and retention, which allowed reduction reactions to occur within the parents. Iron-nickel metal, produced from the reduction of silicate minerals, migrated under gravity to the centre of the parents, forming a core, whilst the less dense remaining silicates rose to the surface, forming a crust. Iron meteorites are the closest physical analogy we have to the material which forms the

Earth's core.

The third meteorite type is the stony-irons: a mix of stone and metal. The pallasite sub-group of these very rare meteorites, composed of almost equal volumes of stone and iron, have one of the most beautiful of appearances, produced from the intergrowth of iron-nickel metal with olivine. Pallasites were also formed by melting in their parent, and represent an intermediate stage between iron meteorites and differentiated silicates, a snapshot of material from the core/mantle boundary of the body.


The Natural History Museum

A polished piece of pallasite (stony-iron meteorite), about 8 cm across.

In addition to meteorites from the Asteroid Belt, there are currently eighteen known meteorites from the Moon. These can be compared directly with samples brought to Earth by the Apollo and Luna missions between 1969 and 1976. The surface of the Moon is covered in craters caused by impacting bodies. If the impactor arrives with the requisite velocity and on a favourable trajectory, then the force of the impacts will be sufficient to eject material from the surface with a velocity great enough to overcome the Moon's gravity and be launched into space. Subsequently the material goes into orbit in interplanetary space, and some of it eventually lands on the Earth as a meteorite. In the same way, rocks have come to us from Mars and there are currently seventeen known meteorites that have been ejected by impact from its surface. We know they come from Mars because they contain gas from Mars's atmosphere trapped within them. Studying meteorites from Mars permits us to learn about the past events on this neighbouring planet, when it had a thicker atmosphere and could support running water, even though the surface of the planet now seems to be dry. The study in martian meteorites of organic compounds and of salts produced by the action of water has demonstrated that these contain information that might shed light on the possible evolution of life on Mars.


The Natural History Museum

Iron- and magnesium-bearing minerals inside the Nakhla Martian meteorite.

This question has fascinated scientists and philosophers ever since the astronomer Galileo thought he could see oceans on the surface of the Moon. We know now that we have to look further afield than our harsh atmosphere-less partner in seeking for life other than in our own oasis of biology. Fortunately, recent space missions have indicated that there are several possibly habitable niches within the Solar System.

With a supply of liquid water and the presence of carbon, nitrogen and oxygen, given sufficient energy and a stable environment, it is possible that organisms could evolve. The most likely places to look for life are the bodies that have all these essential ingredients: Mars, the Galilean satellites of Jupiter, and to some extent, Saturn's giant satellite Titan.

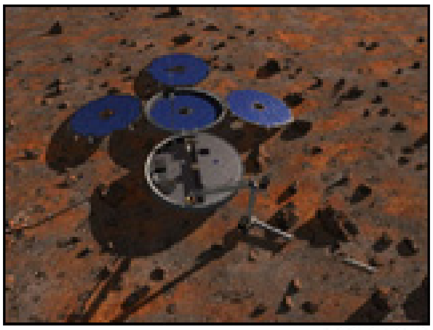
Water ice is present in the polar ice caps on Mars, however, the surface temperatures only exceed 0°C during summer at the equator and atmospheric pressure is too low for water to be stable at the martian surface. Evidence that liquid water flowed across the surface in the past is cut deep into the surface in the form of valleys and channels scoured by floods. The water was generated from permafrost (the thick ice layers under the surface) melted by underlying magma. Although Mars probably no longer has active volcanoes, sufficient residual heat might allow water to occur at depth in the crust, providing an energy source for simple organisms. Analyses of sandstones from the Dry Valleys region of Antarctica show that bacteria and algae can survive in conditions of harsh, dry cold, and provide a valuable analogy for potential micro-organisms on Mars.

C. J. Gilbert, British Antarctic Survey

A magnified picture of the surface of a sandstone boulder from the Dry Valleys of Antarctica.

In 1996, features within the ALH 84001 martian meteorite were interpreted as nanofossils. This report had followed on from the discovery of organic carbon within the meteorite, and led to a resurgence of interest in the possibility of life on Mars. Tiny fossil bacteria have now been identified on one of the several martian meteorites and similar organisms have been discovered living at depth in the Earth's crust. Unfortunately, there is no consensus on the interpretation of the features in ALH 84001: many scientists believe that the nanofossils are artefacts. It has also been shown that fossilisation processes proceed much more swiftly than had been thought, even at the low temperatures of the Antarctic, thus it is possible that the meteorite might have become contaminated with terrestrial materials.

Although the martian meteorites have provided much information on the environmental conditions on Mars, they have not provided conclusive evidence that life has either existed on the planet in the past, or is still present today. In 2003, the European Space Agency (ESA) will launch the *Mars Express* mission, comprising an orbiter and the *Beagle2* lander. On board will be a fully integrated package designed to search for the chemical traces of past (and present?) life on Mars, by examining surface and sub-surface soil and rock samples and the atmosphere.



Beagle 2

The *Beagle 2* lander showing its solar outspread and its instrument arm being deployed.

Other possibilities exist further from Earth. Europa is the smallest of the Galilean satellites, with a radius a little under that of the Earth's Moon. It orbits Jupiter at a distance of ~ 600,000 km, sufficiently close for the satellite to be heated by the tidal forces of Jupiter's gravitational attraction. Most of the information and images that we have of Europa have been acquired by the recent Galileo mission, giving a fairly accurate picture of Europa's bulk density, surface composition, magnetic properties and appearance. Its density (~ 2.97 gcm) implies a silicate body, but with a significant water ice content. Recent models based on gravity and magnetic data have suggested a differentiated structure for Europa, comprising a metallic core, overlain by a silicate mantle, covered by a crust of water ice.

The icy crust appears to be ~ 150 km thick, with a possibly layered structure, with a substantial sub-surface salt-rich ocean beneath a thinner shell of water ice. If there is indeed a sub-surface liquid ocean on Europa, then the heat source that keeps it liquid is likely to come from the complex interplay of the orbiting Galilean satellites with Jupiter. Both Io and Ganymede exert minor tidal influences on Europa, in addition to the much larger tidal effect emanating from the parent planet itself. There has been much speculation that Europa's ocean might be heated from the bottom upwards, by hydrothermal vents analogous to those found on the deep ocean floor of the Earth. Study of the sub-surface inland Lake Vostok beneath the ice of the Antarctic plateau is being employed as a pathfinder case study prior to the future exploration of Europa and its ocean.


NASA

A closer look at Chaos on Europa

Meteorites are not delivered to Earth from Europa and the search for life on this icy satellite will have to be achieved by space probes. A first step will be taken by the proposed NASA Europa Orbiter which will measure the depth of the ice and any water ocean with a radar echo-sounder.

Titan, the fifteenth moon of Saturn, is its largest satellite and has an atmosphere 1.5x as thick as the Earth's, composed mainly of nitrogen and methane with minor amounts of more complex organic molecules.


NASA/ESA

Artist's impression of Titan's surface.

Although there is no suggestion that Titan is suitable to harbour life, the atmospheric composition and surface conditions are sufficiently primitive that they have been taken as possible analogues to the conditions extant on the early Earth, prior to development of the biosphere. Hence understanding the atmospheric and surface processes on Titan is key to understanding the processes that led to the evolution of life on Earth. As a result, Titan is the target of *Huygens*, an ESA-led probe (part of the joint NASA-ESA *Cassini-Huygens* mission to the Saturnian system, scheduled to arrive in December 2004), which will descend for several hours through Titan's atmosphere. The probe will acquire images, measure the elemental and isotopic composition of the atmosphere and record its environmental conditions right down to its crash--or splash--landing on the surface.

Books:

Title: Origins of Life : From the Birth of Life to the Origin of Language
Format: Hardcover
Author: Maynard Smith, John; Szathmary, Eors
Date: 01-MAY-99
ISBN: 0198504934

Title: Earth
Format: Paperback
Author: Jonathan I. Lunine Illustrated by Cynthia J. Lunine
Date: 10-DEC-98
ISBN: 0521644232

Title: From the Beginning
Format: Paperback
Author: Katie Edwards, Brian Rosen
Date: 01-JAN-00
ISBN: 0565091425

Title: Meteorites
Format: Paperback
Author: Robert Hutchinson, Andrew Graham
Date: 01-JUN-00
ISBN: 0565091581

Title: Search for Life
Format: Paperback
Author: Monica Grady
Date: 01-MAR-01
ISBN: 0565091573