



THE SOLAR SYSTEM  
FROM THE ORIGIN OF ALL THINGS TO THE BEGINNING OF LIFE

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Front picture © Jakob Lautrup

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The Solar System  
from the Origin of All Things to the Beginning of Life

**GEOLOGISK MUSEUM**

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## Introduction

In our everyday life we never give it much thought. Our society is such an intricate part of our lives that we forget how incredibly isolated our civilization here on Earth actually is. Astronauts often tell us that it was not until they saw Earth from space, that it dawned upon them how unique our planet is. The purpose of the Geological Museum's new exhibition is to put Earth in a cosmic perspective. Why are we here? How has it all come into existence, and what does it look like in the Solar System – our small corner of the universe? In our everyday life the exploration of the Solar System may seem a bit irrelevant, but if you put on cosmic glasses, the cradle of humanity was in the Solar System. What happened 4.6 billions years ago, which caused a civilization to emerge on the third planet from the Sun, a civilization that is advanced enough to begin reconstructing the chain of events?

Our world is not eternally constant. The universe – as we know it – has not existed for ever and our “small” solar system in the incomprehensible cosmos has only existed for a relatively short time. It developed from a primitive gas cloud to a solar system with planets, comets, asteroids and most inconceivably of all, life evolved on at least one of the planets.

The elements that formed the Earth and especially ourselves have been formed in the interior of a number of stars that were born and died before the solar system was created. In the last phases of these stars' lives matter was hurled back into space – sometimes in connection with explosions of an incomprehensible magnitude. From this it could be used to build up a new star until it eventually was used to build up our own solar system.

From the origin of the solar system until the formation of the oldest rocks on Earth more than 600 million years passed. The only rocks that have been preserved from this important period are meteorites. Meteorites are bits of asteroids and planets that fall on Earth. Only by studying them an insight in how and when our solar system emerged may be obtained. With 550 different meteorites with a total weight of around 25 tons, the Geological Museum has the largest meteorite collection in Scandinavia. These bits from the remote corners of the solar system and from ancient times can tell us a fantastic story of the development of our solar system until the day the meteorite fell through the Earth's atmosphere with a deafening crash. The exhibition tells the story and displays the meteorites that have made

it possible to reconstruct our common origin. The rest of the Geological Museum deals with one of the consequences of this course of events – the development of our planet through the last approx. 4 billion years – including the beginning and evolution of life. It is from this period that we have preserved rocks on Earth. The new exhibition will thus not only tell you about the origin of all things, but will also form a natural introduction to the rest of the museum. Here everything will be staged, the elements as we know them today, will be created and the Earth and the rest of the known objects in the solar system will be built up.

The target audience for the exhibition is – just like the rest of the Geological Museum – the general public. By visiting the exhibition you may get an insight into the whole chain of events from the origin of the universe 13.6 billion years ago to the creation of the solar system 4.6 billion years ago. The exhibition will also offer an insight into the diversity of the solar system as it is today.

The exhibition itself may be experienced on your own during the opening hours of the museum. You may make use of the virtual guides of the exhibition in the form of a number of video screens where Danish scientists will tell you about the parts of the exhibition that are their field of research. You will thus not only get expert tuition on the subject, but will also get a glimpse of Danish research in the field. Outside opening hours school classes may book a free tour with a guide.

This catalogue has been written by a number of Danish scientists. Here you may go deeper into some of the subjects mentioned in the exhibition's videos. The catalogue may be bought or borrowed in the museum, and it will also be possible to get it for free on the Geological Museum's website.



# The Cape York meteorite shower



**A fragment of the iron meteorite Cape York sits in the museum's yard. The specimen, which before cutting weighed 20.1 tons, is called Agpalilik after its place of discovery in Melville Bay, North West Greenland.**



Figure 1. The iron meteorite Savik is hoisted up from the ground. Today it sits in the yard of the Geological Museum. ©V.F. Buchwald.

Figure 2. The author relaxes on the meteorite Agpalilik. The Greenlanders had helped by removing some of the rocks above it. 3. August, 1963. ©V.F. Buchwald.



The story behind the Cape York meteorites is long and complex. There were rumours about meteorites among both scientists and skippers, who at intervals visited Baffin Bay during the 19<sup>th</sup> Century. But it was not until 1894 that the Arctic explorer Robert E. Peary managed to find some solid information. His Eskimo helpers knew of three meteorites, which lay 50 km east of Cape York. Peary recovered them in the late 1890s and sailed the meteorites to New York. They were given the names Ahnighito (31 t), Woman (3 t) and Dog (407 kg), and they are on display today in the American Museum of Natural History in New York.

When Knud Rasmussen and Peter Freuchen travelled across the same areas, in 1913, a young sealer, Qitlugtoq, told them that he knew of another meteorite. It was given the name Savik (3.4 t), and with the help of a government grant, was recovered by engineer Holger Blichert-Hansen, after the First World War, and eventually reached Copenhagen in 1925. Savik is also in the museum's yard.

In 1955 American glaciologists found a smaller meteorite on a nunatak east of the American Thule Air Base. It arrived in Copenhagen in 1956 and was given the name Thule (49 kg). The discovery of so many iron meteorites in Northern Greenland was quite baffling. I received some material from all three meteorites in New York and compared them with Savik and Thule. All were medium octahedrites with around 8% nickel, 0.5% cobalt and a little phosphorus and the rest was iron and sulphur. I suggested the hypothesis that all five meteorites belonged to the same fall, i.e. that a 100-200 tons giant meteor presumably had arrived from the north-west and broke into hundreds of pieces, of various sizes. The smallest pieces had been slowed down the most by the atmosphere and fell in the north-west (Thule), while the largest continued farther and landed in the south-east (Ahnighito). There is approximately a 100 km range between the finding places of Thule and Ahnighito.

By Vagn F. Buchwald

(0.1)



I suggested this hypothesis to Eske Brun (Head of Department in the Ministry of Greenland) indicating that I was interested in visiting Thule to locate the finding places more precisely and perhaps find more, as the hypothesis did not exclude the presence of additional meteorites in the area. With the support of the Ministry I was appointed scientific liaison officer for the summers of 1961 and 1963 at Thule Air Base. In my spare time I searched systematically the ice free areas and located the old meteorite localities, which were recognizable because of the presence of a considerable number of Eskimo basaltic hammer stones. Furthermore I campaigned for further assistance and information among both the Americans and the Greenlanders.

Already in late 1961 this led to the sealer Augo Suerssaq communicating the discovery of a new iron meteorite, Savik II (7.8 kg). It was located within the hypothetical ellipse of impacts and supported my working hypothesis.

During the summer of 1963, I reached by motor boat, the rather inaccessible peninsula of Agpalilik, which was not even on my map; this had not been improved since Lauge Koch's measurements in 1922. Here, on the 31st of July I found the new meteorite Agpalilik, named after its place of discovery. It was almost completely covered by large blocks of gneiss. There was no crater and no Eskimo hammer stones. The fall probably took place more than 2000 years ago when the area was covered by thick ice. A small glacier still remains only 200 m from the locality.

The meteorite must have made a crater in the ice; later, when the ice melted, the iron block was simply deposited among the other stone blocks carried in the ice. This meteorite was unknown to the local Greenlanders and when I told them about the discovery, they were very sceptical. But a few days later we went together to the locality where they helped me free the top so that we could assess its size. The lower part was firmly anchored in the permafrost, a mixture

of gravel, pebbles and ice, which was strong as concrete. We could not do much, but the visible dimensions indicated that the meteorite must weigh at least 15 t.

Home again financial support for the future work should be found and plans made for the excavation and recovery of the meteorite. The Geological Museum, the Carlsberg Foundation and the Greenland Technical Organization all supported the plan, so in the summer of 1964 a small expedition travelled to Greenland. Unfortunately our ship, M/S Elfy North, became ice-bound in Melville Bay, so the expedition had to be abandoned.

The most important work was carried out, however, in 1965. Thanks to the assistance of two helicopters from Thule Air Base, provisions, dynamite and camp equipment could be flown to a camp site only 300 m from the meteorite. Agpalilik was excavated and hauled towards the coast on a prefabricated steel sledge, which slid over a temporary log track. Everything was done by hand as the use of machinery was out of the question in the difficult terrain. We were eight men who worked on the task from the 18th to 28th of August. Then we had to leave the locality because of ice. We sailed south with the cutter Sagfioq towards the trading station at Savigsivik, but we had to blast our way through an extensive belt of new, heavy ice with dynamite.

In 1966 the expedition was abandoned since the LCM landing vessel, which should have collected the meteorite, had its bow port destroyed during a storm on the way to Agpalilik.



Figure 3. The meteorite Agpalilik is excavated. 20 August, 1965.  
©V.F. Buchwald.

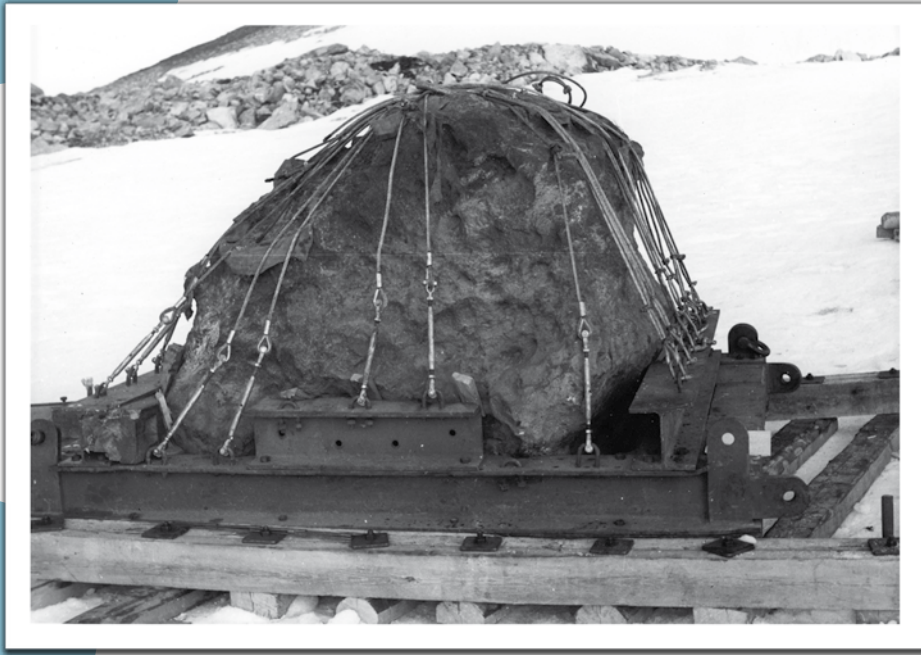


Figure 4. Agpalilik was transported to the coast on a prefabricated steel sledge, which is still in the yard of the Geological Museum supporting the meteorite. 23. August, 1965.  
© V.F. Buchwald 23 august 1965.

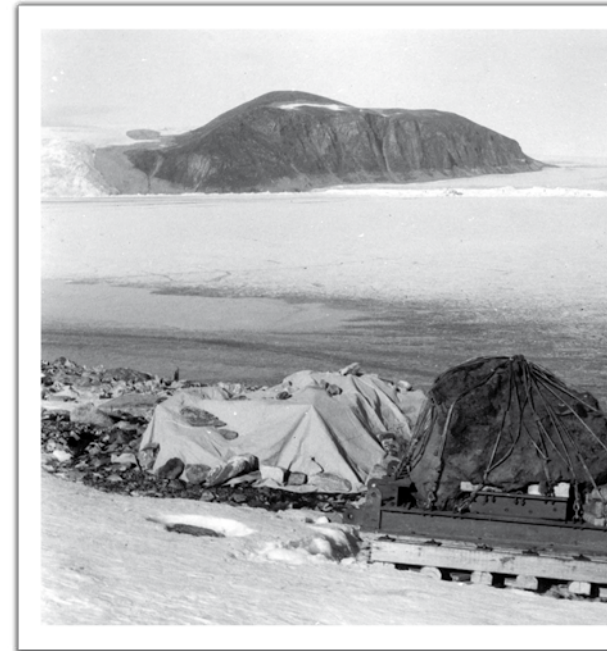


Figure 7. Here the ice is blasted with dynamite in order to make a passage through the ice. 28. August, 1965.  
©V.F. Buchwald.



Finally in August 1967 Captain J.E. Leo managed to bring his 3700 t coaster M/S Edith Nielsen into the ice-filled bay, where the meteorite was located. In a hectic drive, working round the clock for 60 hours, we succeeded in hauling the meteorite, on its sledge, aboard the landing vessel borrowed from the Americans. This then sailed to the Edith Nielsen, which using its strongest derrick, swung the meteorite sledge on board. In September of that year Agpalilik was unloaded in Copenhagen, attracting considerable attention. The meteorite weighed in, on one of the scales in the harbour, at 20,140 kg for the meteorite and 1,000 kg for the sledge and associated wires.

In 1970 the meteorite, together with its sledge, was transported to Gråsten by the Engineering Regiment, where a stone mason cut off one fourth of the meteorite. A slice weighing 560 kg was liberated for exhibition. Each of the two cuts took 200 hours with a cord saw. A corner piece of 560 kg was also cut off. It is presently on loan to the Tycho Brahe Planetarium, and other pieces have been cut for research and exchange with other museums. In this way the Danish meteorite collection has expanded and become one of the best in Europe.

Polishing and etching with dilute nitric acid has exposed the characteristic Widmanstätten-structure, "Heaven's own trademark". The structure is impossible to copy; it is estimated to have formed during slow cooling from a high temperature at a rate of approximately  $1^\circ$  per 10,000 years. At a temperature of  $1000^\circ\text{C}$  Agpalilik was one giant single-crystal of some 2 m, the largest single-crystal of metal ever known. On the cutting surfaces are seen parallel inclusions of the nonmagnetic iron sulphide troilite,  $\text{FeS}$ ,

which marks the vertical orientation of the small asteroid, of which Agpalilik and Cape York originally were both part.

The Cape York meteorite shower, with an extension of over 100 km and including 12 known large specimens, weighing a total 58 of tons, is the world's largest. Another interesting aspect is that numerous pieces of nut-sized meteorite fragments served as knives together with harpoon and arrow heads for the Greenlanders, for more than 1000 years. They carried the small pieces to Woman and Savik, using them as anvils while they hammered the meteorites into shape by means of tough basaltic hammers which they had also brought along. Archaeologists have found dozens of knives and harpoon heads at settlements both in Greenland and as far away as in Hudson Bay. Many of the finds are on exhibit in the National Museum and in the Greenland Museum in Nuuk.



Figure 5. Agpalilik on its steel sledge, ready for shipment to Copenhagen. 27. August, 1965. ©: V.F. Buchwald.



Figure 6. The cutter Sagfiq. The expedition had to blast its way out through the ice with dynamite. 28. August, 1965. © V.F. Buchwald.



Figure 8. The author standing in front of the Agpalilik meteorite. Part of the meteorite has been cut away. March 2006. ©GM marts, 2006





Chapter (1)

From Big Bang to the creation of the Solar System



# Where do the elements come from?

By Uffe Gråe Jørgensen

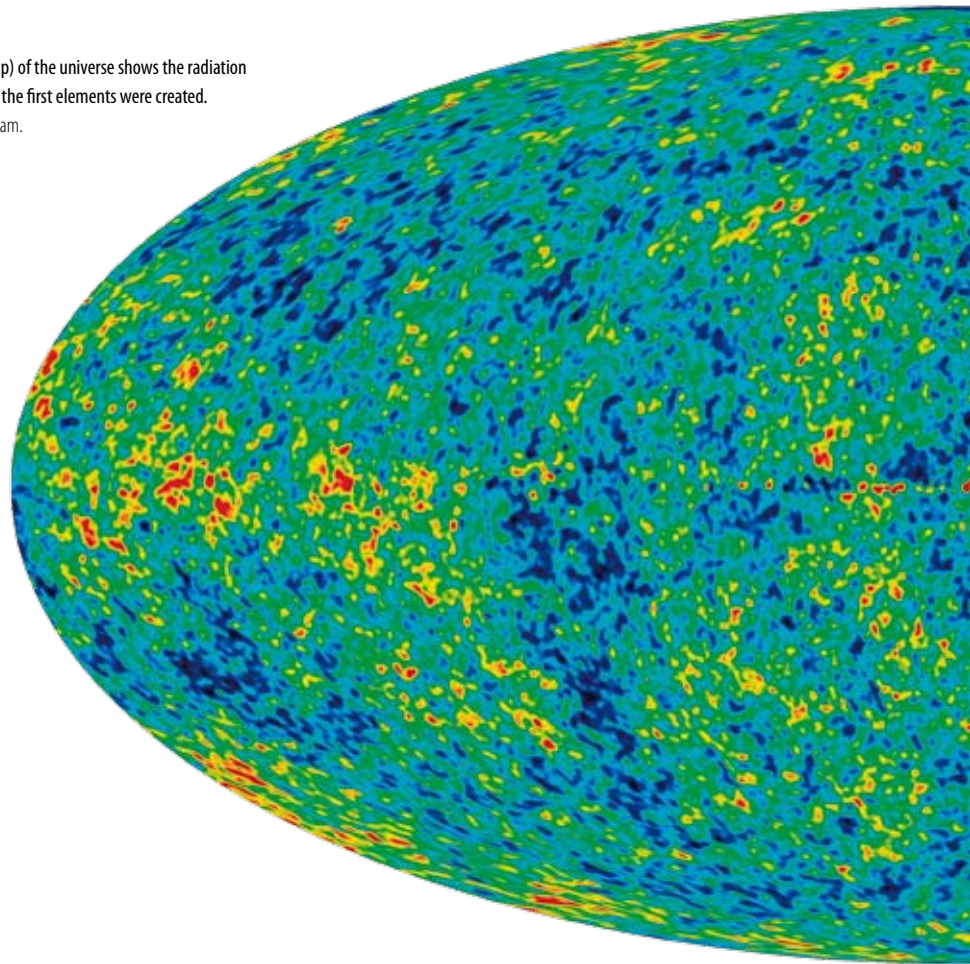
## 14 billion years ago there was nothing!

It was not only the Earth and the Solar System, the forests and the lakes, the stars and the clouds that did not exist. There was no matter, no space and no time. It is very difficult to imagine and science has still only some very vague ideas of how everything was created from nothing.

What we do know is that approximately 13.6 billion years ago everything that exists today in the universe was concentrated in an extremely small area – maybe as small as a pinhead. There was nothing around it. From this incredibly compact and hot, minute area the whole universe was created.

One can imagine the very early universe as a soup of energy. There were no molecules and atoms. No elements. Only extreme heat. Very quickly the universe cooled off and expanded. Today the universe is inconceivably large, but on the other hand space has become immensely cold. Figure 1 shows a map of the temperatures of the universe measured all round the sky. By and large the temperature is  $-270^{\circ}\text{C}$  in all directions, but very small variations in temperature reveal some of the most important details about how the universe looked just after it was created.

Figure 1. This map (W-map) of the universe shows the radiation from the Big Bang, when the first elements were created.  
©NASA/WMAP Science Team.



## The elements emerge

One minute after the universe was created, it had expanded and cooled off sufficiently so that particles of the nuclei of atoms began to precipitate out of the "soup". These were the protons, neutrons and electrons. All elements are built of protons, neutrons and electrons – and nothing else. After only one minute all the ingredients of all the elements were in place, but billions of years would pass before they became the many elements we know around us today – the building blocks of the whole physical world that surrounds us.

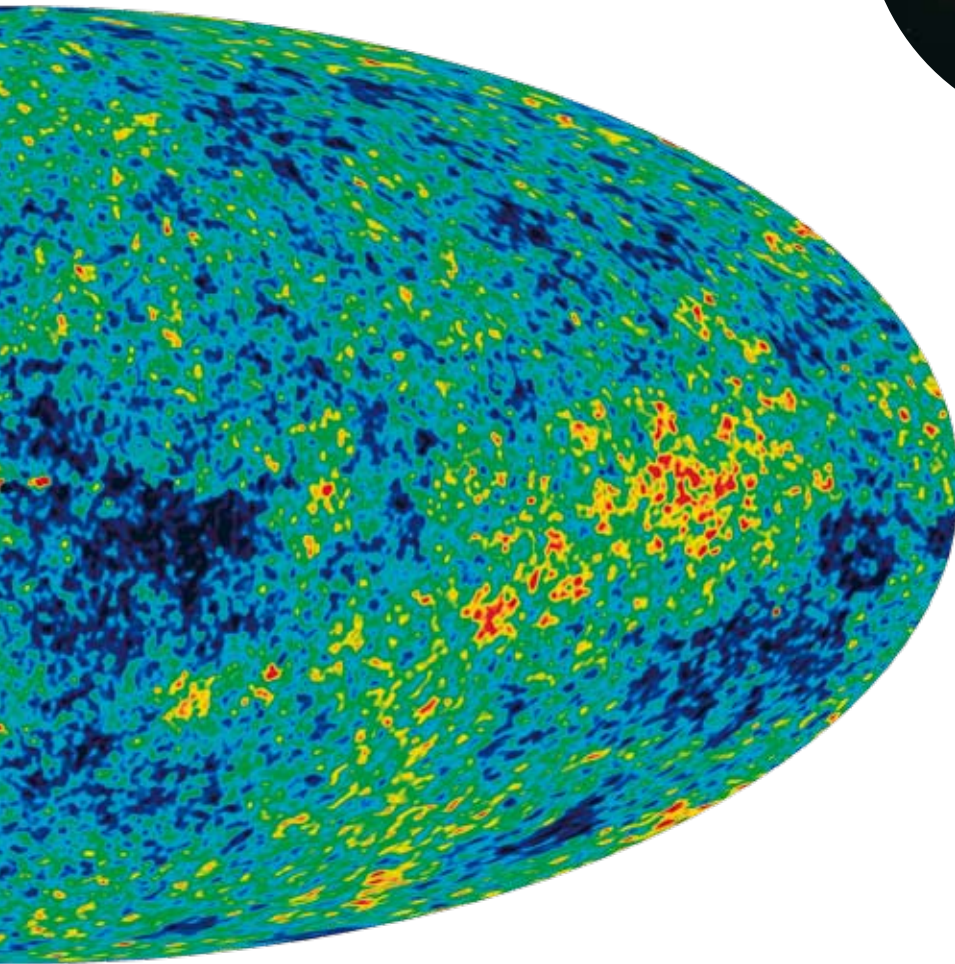
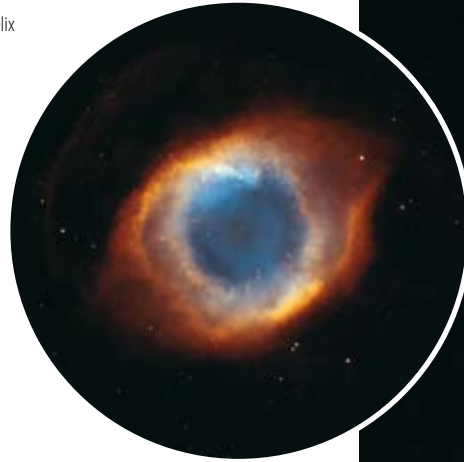
An element is the same as an atom. The simplest atom is Hydrogen consisting of one proton and one electron. Hydrogen was thus present in the

universe already one minute after its creation. It is no wonder that more than 90% of all atoms in the universe are Hydrogen atoms.

The next element in the series is Helium consisting of two protons, two neutrons and two electrons. The elements differ from each other by their numbers of protons. The protons and the neutrons of an atom form together the nucleus of the atom. The electrons circle around the nucleus, just like the planets circle the Sun. All the elements have the same number of electrons as protons.

In order to construct elements heavier than Hydrogen, protons and neutrons must combine together into larger lumps, the heavier nuclei of

Figure 2. The planetary nebula Helix. Here elements, that have been created in a star like the Sun over billions of years, are blown out into our galaxy. © NASA/NOAO/ESA the Hubble Helix Nebula team, M. Meixner (STScI) og T.A. Rector (NRAO).



atoms. It was once thought that all the elements we know in nature might have been formed by protons and neutrons colliding during the first hours and days of the universe, while it was still very hot and very dense. Observations and experiments have, however, shown that the proto-soup of the universe only created Hydrogen and Helium and the three rare elements Lithium, Beryllium and Boron. This is mainly due to the fact that neutrons are unstable. When it moves freely in space, i.e. is not within an atom, a typical neutron converts into a proton in approximately 10 minutes. Thus there was only about 10 minutes available at the beginning of the universe to form the elements. After that there were no more neutrons available.

Figure 3. The Tycho Brahe supernova, which is one of the places where new heavy elements are formed. ©Max-Planck Institut fuer Extraterrestrische Physik, Garching b. Muenchen, Germany

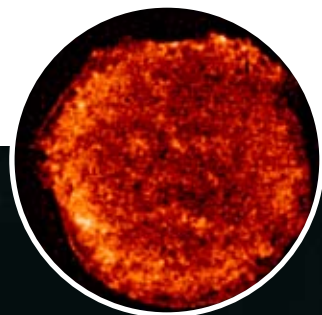
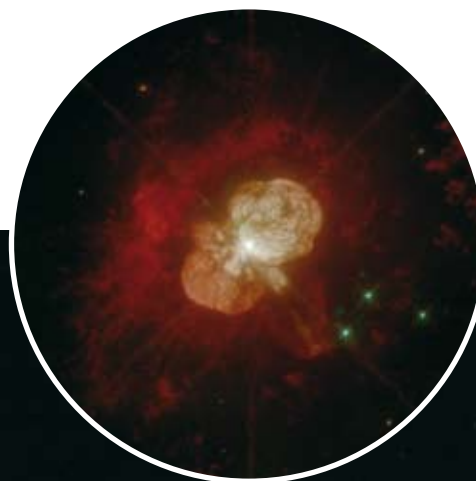


Figure 4. Another supernova is brewing. Here we see the star Eta Carinae, now very unstable, and will soon be a new supernova that will create new elements for our galaxy. © J. Hester/University of Arizona/NASA



## Stars as element factories

The proto-universe only created the five lightest elements. The rest of the elements have been formed during billions of years, deep inside stars. At the end of a star's life, the newly formed elements are blown into space with the space between the stars slowly growing richer and richer in heavier elements such as Carbon, Oxygen, Iron, Gold, Lead, Uranium etc.

Stars are gigantic, controlled fusion power stations that create energy for their light by "burning" (i.e. fusing) light elements into heavier elements. It is the same energy source that powers a Hydrogen bomb or a fusion power station. (when we get one built one day). During the major part of a star's life they obtain their energy by converting Hydrogen to Helium. In this way we get still more Helium in the universe, and still less Hydrogen, but so far no Carbon and Iron etc.

Towards the end of their lives the stars become so hot internally that Helium can be converted further into carbon and nitrogen and in some cases into oxygen, neon, aluminium, etc. up to and including iron. When matter becomes iron, no more energy can be gained by further fusions. If the star is of sufficient size, still larger internal areas will become iron. Ultimately when such an enormous bubble of iron vapour (actually "iron plasma") is created internally in the star, the iron nuclei can no longer withstand their own weight. At that point something rather remarkable happens. The iron nuclei break down under their own weight and become neutrons

again. The neutrons collapse towards the centre of the star and eventually form a small neutron lump, a neutron star, with a diameter of only 10 kilometres. Every cubic centimetre of its matter weighs a billion tons. The formation of a neutron star releases so much energy that all the rest of the star is blown into space. This is what we observe as a supernova explosion.

## Exploding stars

In the supernova explosion, matter that the star has created during millions of years, is blown out. Astronomers estimate that practically all the Oxygen, Fluorine, Neon, Sodium, Magnesium, Aluminium, Silicon, Phosphorus, Sulphur, Chlorine, Argon, Potassium, Calcium, Scandium, Titanium, Vanadium, Chromium, Manganese, Iron, Cobalt, and Nickel that are present in nature are "waste products" from the nuclear processes that have made the large stars shine throughout their lives.

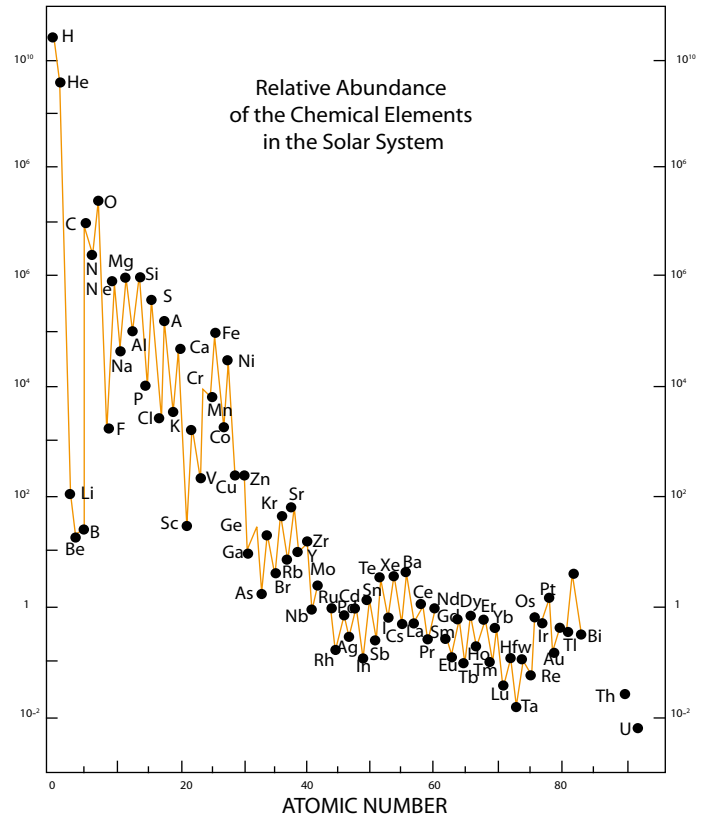
During the actual supernova explosion, large numbers of newly formed neutrons are blown out through the gasses of the star. During this process iron especially will be altered to very heavy elements. No energy is gained from these processes, but they use up some of the energy contained in the explosion. For example, the heaviest element in nature, uranium, is formed by iron absorbing the energy-rich neutrons

from the explosion. When radioactive uranium on Earth decays over billions of years and heats up the Earth's crust, it is correct to state that remnants from the enormous energy reserves of the supernova explosion in fact keep the Earth's crust warm. Also elements such as Gold, Platinum, Osmium, Selenium, Europium and Xenon are formed in this way. All these elements originated from exploding stars.

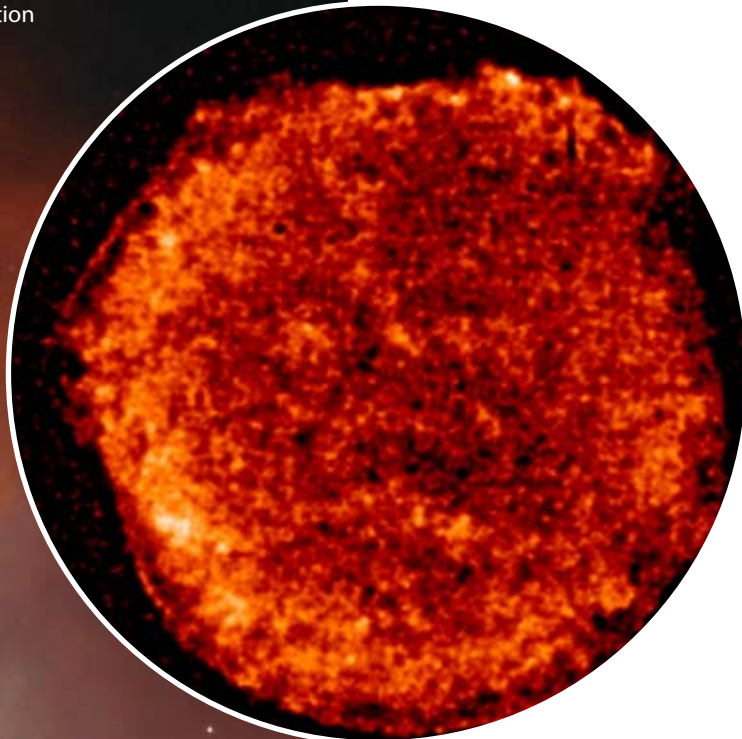
Only the largest stars of all, however, will become supernovae. Stars that are born with less than 8 times the mass of the Sun will only generate elements up to the atomic weights of Carbon and Nitrogen. After this nuclear combustions stop. Their interior will never be warm enough for carbon to transform to oxygen, neon, magnesium, etc. and further to iron. On the other hand most, maybe all, Carbon and Nitrogen in nature were derived from combustions in the "smaller" stars – i.e. those, that like our own Sun, will never become supernovae.

During a curious series of "mini-explosions" close to the end of the lives of the relatively small stars, streams of newly formed neutrons are created. These neutrons differ in their energy levels from the neutrons in supernova explosions. Thus they create different heavy elements than those involved in supernovae explosions. Around two-thirds of all elements heavier than iron are created here – Barium, Lead and Strontium, among others.

Figure 5. Abundances of the various naturally occurring elements in our solar system.  
 ©: Geologisk Museum.



Smaller stars never explode, but blow themselves up dramatically at the end of their lives. In approximately 7 billion years the Sun will be as large as the Earth's present-day orbit around the Sun. At this time the Sun will become what is called a red giant. A million billion of tons of matter will be expelled from the Sun every second during this phase of its life. This matter will be enriched in Carbon, Nitrogen and Lead together with many other substances that were created in the interior of the Sun during its lifetime. Maybe the heat from these enormous gas masses will then vaporize the Earth, and our earthly remains will be expelled with solar matter into interstellar space, eventually becoming new stars and planets in Nature's eternal construction of more and more complex forms of matter.



# Meteorites contain genuine stardust

By Anja C. Andersen

(1.2) In 1987 we were able to extract a well-preserved secret from the carbonaceous chondrites: They all contain small amounts of dust that were not formed in the Solar System, but were already present in interstellar dust before the creation of the Solar System. The dust appears to have originated in long-dead stars, giving astronomers a unique chance to study stardust directly in the laboratory.

## Carbonaceous chondrites

All stars, including our own Sun, were formed from interstellar clouds in the galaxy. These clouds (figure 1) contain gas and dust and they are constantly being enriched with material from old stars that are losing their outer layers or exploding as supernovae (Chapter 1.1). Previously it was thought that the Solar System had been formed from a homogenous mass because the matter had been so thoroughly mixed and strongly heated. Thus all previous traces or characteristic properties that could be traced back to the stars, that had contributed gas and dust to the Solar System, had been erased (Chapter 1.3).

More recently, however, it appears that part of the original interstellar dust has survived unchanged during the formation of the Solar System. This interstellar dust is found in small amounts in certain types of meteorites that have only changed slightly during the formation of the Solar System, the carbonaceous chondrites (Chapter 3.3). The carbonaceous chondrites have, by and large, the same elemental composition as the cloud that became the Solar System (figure 2).

Around 5% of all meteorites are carbonaceous chondrites, but until 1969 there were less than 100 kg of carbonaceous chondrites extant in the various museums around the world. In 1969 two giant pieces of carbonaceous chondrite fell like manna from heaven. One near the town of Allende in Mexico, the Allende meteorite (meteorites were formerly named after the nearest post office), and one near the town of Murchison in Australia. Murchison weighed 82 kg and Allende was estimated to have been around 4 tons, 2 tons of which have been collected. Allende exploded in the air and was spread over a large area, thus smaller pieces are occasionally still found. 1969 was also the year when the Americans were highly focussed

on the forthcoming moon landings. Many laboratories were thus well prepared to analyse stone material from the Moon. These dust-free laboratories and all the equipment that was intended to ensure that the lunar rocks were not contaminated by terrestrial material were, however, also available for the analyses of the two meteorites. In the analysis of the Murchison meteorite 74 different amino acids and some nucleotide bases were found, which we know with certainty were not caused by terrestrial contamination.

Figure 3. The planetary nebula IC418. In the middle is seen the core of a star which has become a white dwarf. Around it is seen all the material, that the star has flung out during the last phase of its life. The Sun will also evolve into a planetary nebula in about 5 billion years. ©NASA and The Hubble Heritage Team (STScI/AURA).

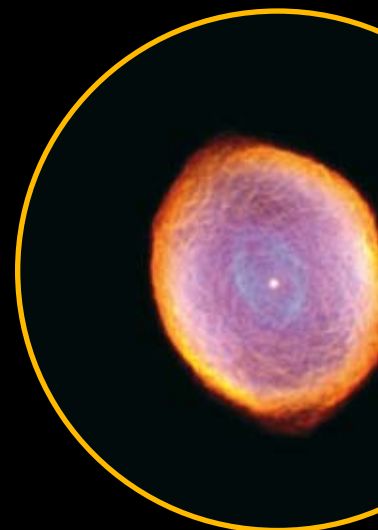
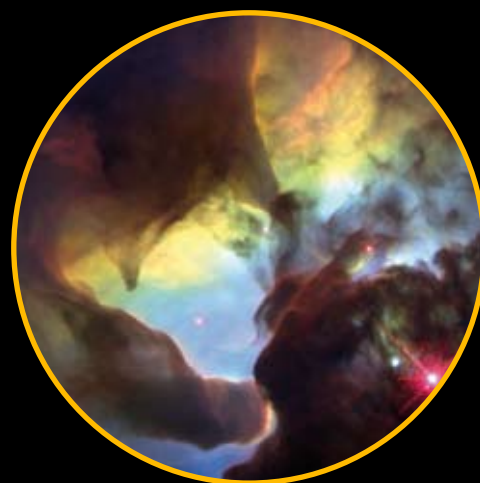


Figure 1. Interstellar cloud (Lagoon Nebula). The nebula consists of gas and dust and occurs in our own galaxy, the Milky Way, at a distance of 5,000 light years from the Sun. New stars are formed in clouds like this. The picture was taken by the Hubble Space telescope. © A. Caulet/ST-ECF,ESA/NASA.



## Creation of the elements

The two carbonaceous chondrites have proved to be crucial for our understanding of the creation of the Solar System, the development of the stars and the formation of the elements.

When the universe was formed 13.6 billion years ago in the so-called "Big Bang", H and He were formed as well as very small amounts of Li, B and Be. All the other elements formed after the "Big Bang" in the interior of stars.

H and He fused together to form new elements in the interior of a star. It depends on the star's mass which elements can actually be formed. Light stars, e.g. the Sun, may form a number of specific elements and when there is no more available fuel, they collapse to white dwarfs and simultaneously they exhale their outer layers, becoming a planetary nebula (figure 3). In this

way interstellar space is enriched with some of the newly formed elements.

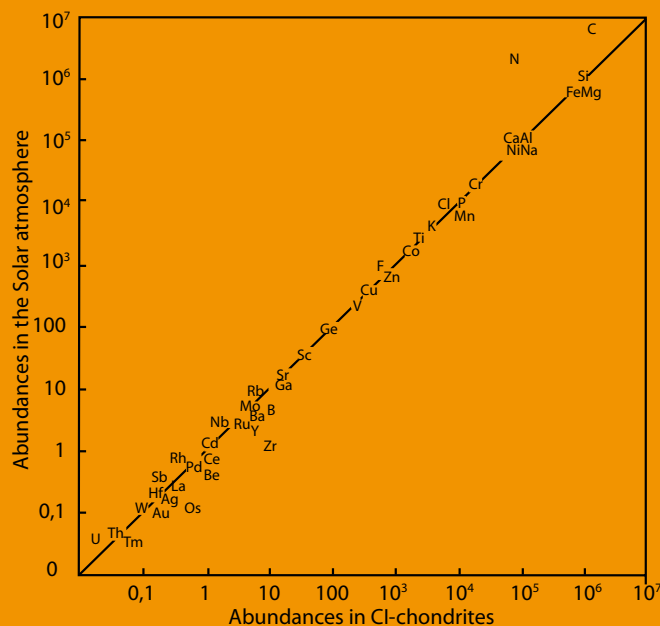
This process happens much faster and much more efficiently in the heavier stars. They live shorter and produce many more different elements than lighter stars. Heavy stars end up collapsing during a supernova explosion (figure 4).

This means that different isotopes were formed in quite specific types of stars. It also means that all the time the Milky Way is being enriched with heavier elements. The composition of the elements in the Milky Way thus differs from when the Solar System was formed approximately 4.6 billion years ago. Clearly its composition will also continue to change in future. The universe will progressively become more and more "contaminated" with heavier elements. Presently the proportion of elements heavier than helium makes up approximately 1% of the total visible quantity of material in the universe.

## Identification of the stardust

When heated to between 400-1000°C, the material from a carbonaceous chondrite releases gas. At most temperatures the composition of its isotopes is the same as the normal composition of the Solar System (figure 2). When the sample is heated, at specific temperatures gas is suddenly given off with a composition that is markedly different from the composition of the Solar System (figure 5). The dust must, therefore, contain minerals that release possible inclusions of gas at given temperatures; the composition of the released gas suggests that the minerals themselves were not formed in the Solar System. Since these minerals were mixed together in a meteorite that has never been restructured since the creation of the Solar System, they were probably mixed with the Solar System nebula during its formation or (more likely) in the interstellar cloud that later collapsed and became the Solar System. These minerals thus represent unaltered stardust, formed outside the Solar System even before the Solar System existed.

Figure 2. Outline of the element abundance in the Sun's atmosphere compared with the element abundance in a specific type of carbonaceous chondrite – the CI-chondrites. The graph is normalized per one million silicon atoms. The fact that the elements fall on a straight line shows that the content of the various elements is the same in the CI-chondrites as in the Sun. This means that the CI-chondrites have not been exposed to any particularly large chemical changes since the Solar System was formed. The content of Hydrogen, Helium, Carbon and Nitrogen is lower in the meteorites as the elements are gaseous and thus escape readily from the meteorites. © GM.



Still cleaner samples of these minerals have been obtained by dissolving the carbonaceous chondrite in acids and bases, removing the sediment or the fluid, separating the dust grains according to size or carrying out similar chemical and physical selection procedures on the material. Through the 1970s and 1980s we moved still closer to the identity of the minerals without ever being able to know precisely the true identity of the dust grains.

After around 20 years of investigation a research group in Chicago finally succeeded in isolating the dust type that contained the characteristic gasses. It proved to be composed of extremely small diamonds of a size of approximately 2 nm, i.e. each diamond consists of approximately 1,200 carbon atoms (figure 6), so in reality it is more diamond smoke than diamond dust!

## The diamonds

It was very surprising that the grains proved to be nano diamonds. On Earth graphite is the most common form of carbon, e.g. soot. So we were surprised to find nano diamonds instead of graphite in the meteorites since the latter is the most common form of carbon in the rest of the universe.

Diamonds are constructed of carbon, but they may contain impurities in the form of, among others, nitrogen, neon, and xenon. The nitrogen atoms may replace the carbon atoms in the diamond's crystal structure, while neon and xenon may sit as single atoms caught in the diamond crystal.

Terrestrial diamonds are formed at high pressure. In the universe, one finds the strongest blast waves in the shock front that is generated after a supernova explosion. Regarding the origin of the small diamonds, the first theory suggested they were formed when small graphite particles met a shock front after a supernova explosion.

However, there were a number of objections to this theory; for example, one would expect to find some graphite in the meteorites, which had escaped the attention of the supernova shock front. The Allende meteorite, which has the highest amount of diamonds per gram, can yield 1 milligram of diamonds per 10 grams of meteorite, but less than one ten thousandth of a gram of graphite is found in the same sample; moreover, the graphite grains are much larger compared with the diamonds, typically 0.3-20 micrometre in diameter. It is not very likely that there were enough supernova explosions in the past to transform all the graphite grains into diamonds.

So a new theory was quickly developed to explain how the diamonds were formed. This theory was based on the fact that industry

had begun manufacturing nano diamonds at low pressure. Diamonds can crystallize in a carbon gas at low pressure as long as hydrogen is present. The presence of hydrogen, in fact, prevents the formation of graphite. So diamonds can be formed where the carbon concentrations are high, while pressure is low. Primarily there are two places in the universe where these conditions exist, i.e. in the outer atmospheric layers of old, cold (~2000°C), red, and carbon-rich giant stars and in the gas of an expanding supernova, which according to the theory will contain a carbon-rich area. From measurements of the diamonds it is not certain whether they are primarily formed in red carbon-rich giants, which is the end phase of a life span of a light star, or in the remains of a supernova explosion which is the end phase of a heavy star. The ratio between the two carbon isotopes,  $^{12}\text{C}$  and  $^{13}\text{C}$ , which we measure in diamonds indicates that they were formed in red carbon-rich giants,

whereas the xenon and neon, which were also measured in the diamonds, are a direct fingerprint from a supernova (and in addition, at least two different supernova episodes). So when we try to understand the formation of nano diamonds in the universe, we must remember that there is probably more than one type of star that is capable of forming diamond dust. This is also logical – considering that a total of 3% of the carbon available when the Solar System was formed have been in the form of nano diamonds.

How large the relative amounts of diamonds, these two scenarios produce will have a great influence on our future understanding of which type of stars are the primary contributors of the carbon atoms that form the building blocks for organic life on our planet.

Figure 4. The supernova remains called the Crab nebula. The nebula is the remnants of a heavy star that exploded 900 years ago. This supernova remnant is located 7,000 light years away in the constellation Taurus. This and other such explosions enrich the universe with heavier elements and newly formed dust particles. © NASA/ESA/ J. Hester and A. Loll (Arizona State University).

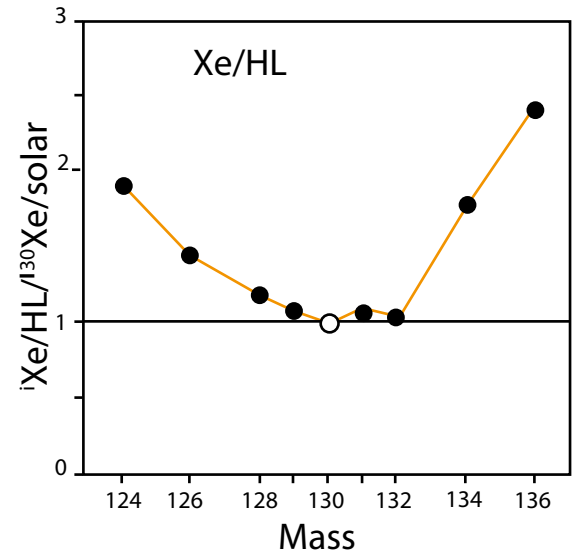


Figure 5. Abundance of xenon gas measured in nano diamonds from the Allende meteorite. The relative abundance has been normalized to the abundance in the Solar atmosphere and set at 1 for Xe130. The Xe124/Xe130 and Xe136/Xe130 ratios in the diamonds are markedly higher than those in the Sun. This difference indicates that the diamonds were not formed in the Solar System, but must be stardust that has survived the creation of the Solar System. © Anders & Zinner, 1993, Meteoritics 28, 490.

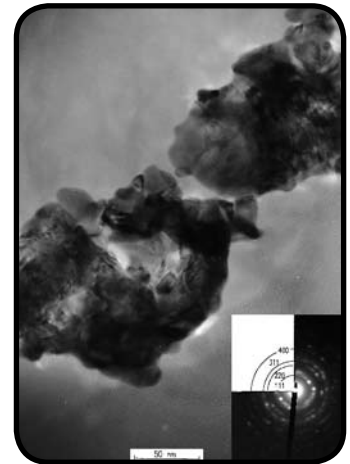


Figure 6. A transmission electron microscope picture of nano diamonds from the Allende meteorite. Each clump contains approximately 1,000 diamonds and each diamond consists of approximately 1,200 carbon atoms. Each clump of nano diamonds is approximately 0.0001 mm in diameter. © A.C. Andersen.

# Formation of a Solar System - from dust to planets

By Martin Bizzarro

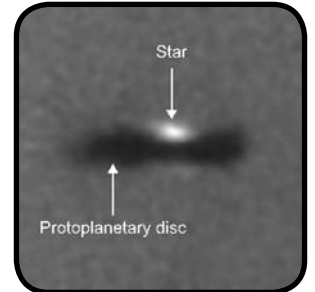


Figure 1. Edge-on protoplanetary disc in the Orion nebula. Image generated by the Wide Field and Planetary Camera 2, Hubble Space Telescope, NASA. © Wide Fields and Planetary Camera 2, Hubble Space teleskopet, NASA.

(1.3)

## A star is born

The sight of a sky filled with stars on a moonless night never ceases to inspire in us a sense of wonder at the beauty and scale of the universe. As seen from Earth, however, most stars seem cold and distant. Yet one star is so blindingly present in our lives that we sometimes forget it is a star. That star is our Sun, consisting mostly of ionized gas and comprising over 99% of the entire mass of the Solar System. But the Sun has not always been as we see it today, surrounded by nine planets. Stars like the Sun form from molecular clouds consisting primarily of molecular hydrogen. When a molecular cloud reaches a critical size, mass, or density, it begins to collapse under its own gravity. As the cloud shrinks, conservation of angular momentum causes the random motions originally present in the cloud to become one coherent rotation. This rotation causes the cloud to flatten out and take the form of a disc - this cloud of dust and gas is known as a protoplanetary disc. Such discs are currently observed in the Orion nebula (Fig. 1), and perhaps provide a glimpse of what our Solar System may have looked like about 4.56 Gyr ago, when our Sun was in its T-Tauri stage. T-Tauri stars are very young stars with masses comparable to that of the Sun, still undergoing gravitational contraction, and characterized by bipolar jets (Fig. 2). The T-Tauri stage lasts approximately 10 Myr, and represents an intermediate stage between a protostar and a low-mass main sequence star

like the Sun. It is during the T-Tauri stage of the Sun that planetary formation was initiated in our Solar System. Starting from tiny dust particles, the asteroids and terrestrial planets formed by collisional aggregation into larger and larger objects. This growth process is generally divided into three stages: (i) aggregation of micron-sized dust to 1- to 10-km-diameter planetesimals, (ii) runaway growth of the largest planetesimals to form planetary embryos, and (iii) aggregation of embryos to form the terrestrial planets.

## Chondrite meteorites and the Solar System's first solids

Chondrite meteorites are traditionally viewed as the most primitive and oldest rocks from the Solar System that are derived from undifferentiated planetesimals, that is, planetesimals that did not melt. In the standard model of early Solar System formation, chondrites are considered to be the first objects to accrete, consisting of dust and debris from the protoplanetary disk (Fig. 3). The careful study of these objects thus provides a remarkable window into the environment, processes and history that accompanied the earliest development of the Sun and planetary embryos.

The major constituent of chondrites are chondrules, millimeter-sized spherical objects that were wholly or partly molten in the young

Solar System, and crystallized in minutes to hours between  $\sim 1800$  and  $\sim 1300$  K prior to their accretion into chondrite parent bodies (Fig. 4). The two major minerals that crystallized in chondrules are olivine and pyroxene. Olivine and pyroxene are also major minerals in the chondrite matrix—the fine-grained silicate material that coats chondrules and other coarse chondritic ingredients and fills the interstices between them.

The other important ingredient of chondrites are refractory inclusions or CAIs (calcium-aluminum-rich inclusions), which are composed almost entirely of crystalline silicates and oxides that are rich in Ca, Al, and Ti and formed above 1300 K (Fig. 5). Not all CAIs were molten when they formed. Like chondrules, some CAIs seem to have experienced multiple heating events, and most exhibit elemental or isotopic evidence that they or their precursors formed by evaporation and/or condensation. The mineral assemblages found in a refractory inclusion typically reflect only a relatively narrow temperature interval. Some rare CAIs contain only corundum, hibonite, and perovskite, which are stable above  $\sim 1650$  K. More common are the CAIs containing spinel, melilite, Ca-Ti-pyroxene, and anorthite, which are stable at  $\sim 1400$ -1500 K. Importantly, the age of the Solar System is currently defined as the absolute age of CAIs, the most recent and precise estimate being  $4.5672 \pm 0.0006$  Gyr, obtained

Figure 2. Bipolar outflows from young stars. These three images provide a dramatically clear look at collapsing circumstellar discs of dust and gas that build stars and provide the ingredients for a planetary system. The pictures also show blowtorch-like jets of hot gas funneled from deep within several embryonic systems and machine gun-like bursts of material fired from the stars at speeds of a half-million km/h. ©Wide Fields and Planetary Camera 2, Hubble Space teleskopet, NASA.

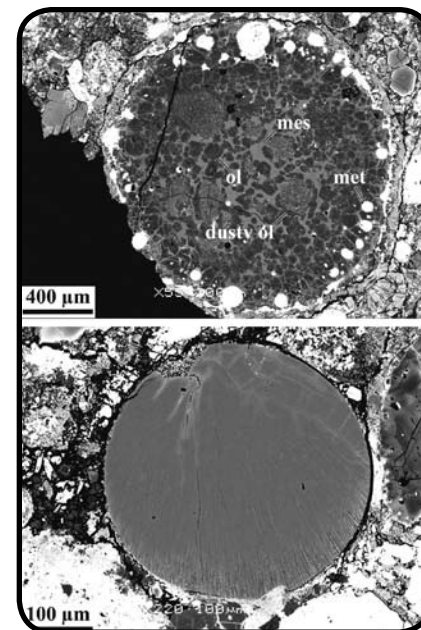
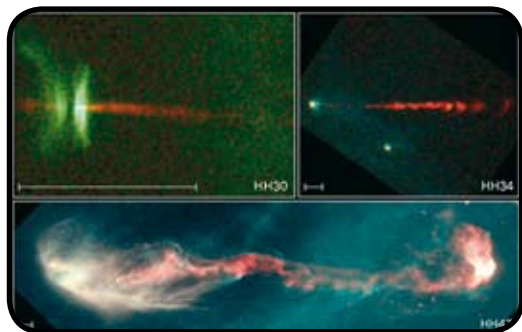


Figure 4. Back-scattered electron images of chondrules from the Allende meteorite. The upper panel shows a porphyritic chondrule composed of olivine (ol) and metal (met) set in a glassy mesostasis (mes). The lower panel shows a chondrule with radially crystallized pyroxene crystals. ©A. Krot.

from the Efremovka chondrite. Understanding where and how chondrules and CAIs formed remains one of the most challenging problems in cosmochemistry.

## Astrophysical settings of CAI and chondrule formation

At present, we must rely on theoretical models to understand the internal structure and evolution of protoplanetary discs. Of particular interest are the temperature estimates within the disc, as these can provide important constraints regarding the astrophysical setting of chondrule and CAI formation. Numerical models suggest that midplane temperatures are 200 to 800 K at 1 astronomical unit (one astronomical unit, or AU, is the distance from the Earth to the Sun) and 100 to 400 K at 2.5 AU from the stars when these are in their T-Tauri stage. These are the regions where Earth and most meteorites and their components may have formed.

CAIs thus formed at temperatures that appear too high compared to midplane temperature estimates inferred for T-Tauri stars. However, because disc heating is caused by the dissipation of gravitational energy associated with the infall of material onto the disc, the disc surface and midplane temperatures should increase with increasing disc mass accretion rate. As such, at the high mass accretion rates typical of

protostars before they enter the T-Tauri phase, radial thermal gradients would have been much steeper, providing temperatures favorable (~1300 K) for CAI-formation within 2 AU of the central protostar.

Another line of evidence comes from the extinct aluminum isotope  $^{26}\text{Al}$ .  $^{26}\text{Al}$  decays to  $^{26}\text{Mg}$  with a half-life of 730,000 years; hence none of the original  $^{26}\text{Al}$  exists today. The majority of CAIs are characterized by large excesses of the daughter isotope  $^{26}\text{Mg}$  relative to other Mg isotopes, for which the most likely explanation is that CAIs once contained  $^{26}\text{Al}$ . The existence of radioactive  $^{26}\text{Al}$  in the early Solar System suggests a source of heat for melting planetesimals, and provides a way of deducing time differences between events. New high-precision Mg isotope measurements of CAIs conducted at the Copenhagen Geocenter indicate that most CAIs from our Solar System may have formed within an interval as brief as 20,000 years. This timescale is inconsistent with the secular evolution of T-Tauri stars, but may be consistent with CAI formation during the infall stage of the protostellar evolution of the Sun.

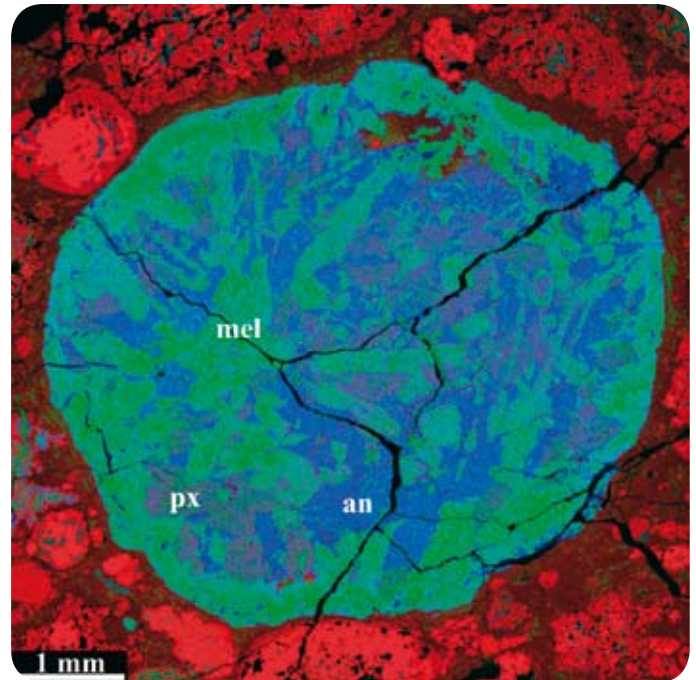
In contrast to CAIs, chondrules have variable excesses of  $^{26}\text{Mg}$  indicating that chondrule formation may have begun contemporaneously with CAIs, and continued for as long as 3 Myr after the birth of the Solar System. Further, the

variations in chondrule properties between chondrite groups and the evidence for recycling has led to a generally held view that they formed by localized phenomena throughout the asteroid belt. The abundance of chondrules in chondrites indicates that they were produced by one of the most important nebular processes in the early Solar System. However, realistic models for chondrule formation have to account for both the necessary high temperature environments as well as the protracted nature of the chondrule-forming process(es). At present, the most promising localized heat sources are shock waves, possibly associated with gravitational disc instabilities and/or planetesimal impacts.



Figure 3. The Allende meteorite ©M. Bizzarro.

Figure 5. Combined x-ray map composed of Mg (red), Ca (green), and Al (blue) of a polished section of the Efremovka meteorite containing an igneous CAI. The CAI consists of pyroxene (purple), anorthite (light blue), and melilite (light green). © A. Krot.



## SAH99555 – a unique basaltic meteorite

In 1999, a team of French explorers led by Luc Labenne discovered a new basaltic meteorite in the desert of North Africa – SAH99555. This unique meteorite belongs to the rare class of achondrite meteorites called angrites. This class of mafic igneous meteorites is named after the meteorite Angra dos Reis (known as ADOR) that fell in Brazil in 1869. Angrites all share a common oxygen isotope fingerprint, and come from a parent asteroid that was apparently extremely depleted in volatile elements and low in silica and rich in calcium. SAH99555 is a fine-grained rock consisting mainly of aluminum-titanium-rich pyroxene, calcium-rich olivine and anorthite.

Conventionally, achondrite meteorites from differentiated planetesimals have been viewed as coming from second-generation (i.e., younger) planetesimals as compared to chondrites from undifferentiated planetesimals. This interpretation is partly based on the presence of CAIs in chondrites, and the fact that two angrites dated in a pioneering study by Gunter Lugmair and Steve Galer in 1992 yielded ages of 4.557 Gyr – while this was then the oldest precise age determined on igneous meteorites it is, in fact, about 10 million years younger than CAIs.

Given the extremely fresh nature of SAH99555, an international team including scientists from the Copenhagen Geocenter attempted to date SAH99555 with two different isotopic clocks. The first clock is based on the decay of  $^{238}\text{U}$  and  $^{235}\text{U}$  to  $^{206}\text{Pb}$  and  $^{207}\text{Pb}$ , respectively. This system provides what chronologists call an absolute lead-lead age for minerals, rocks or meteorites. The results of this work were startling with SAH99555 yielding an apparent age of 4.566 Gyr – apparently just

one million years younger than CAIs. In light of these results, researchers proceeded to search evidence of the short-lived isotope  $^{26}\text{Al}$ , that is, excess  $^{26}\text{Mg}$  similar to that found in CAIs and chondrules.

The former presence of  $^{26}\text{Al}$  in SAH99555 would be of great interest, as it would provide a method of dating angrite formation with respect to CAI formation. Furthermore,  $^{26}\text{Al}$  would have been a potent heat source in the young Solar System, quite capable of supplying enough heat to melt entire planetesimals only tens of kilometers across if they formed very early in the life of the Solar System. Such a heat source provides an ideal explanation as to why such small planetary bodies would have melted.

The results showed that all the angrites have small excesses of  $^{26}\text{Mg}$  as compared to other materials from inner Solar System bodies including the Earth, Moon, Mars and chondrites. The excesses can be used to calculate ages for magmatism on the angrite parent body and yield ages that indicate angrite magmatism is about 3 Myr younger than formation of CAIs, the Solar System's oldest solids. By adding this time difference to the absolute lead-lead age for SAH99555 it is possible to calculate a new age for CAIs – this is ca. 4.5695 Gyr. This age for CAIs is about two million years older than previous determinations and suggests the Solar System might be a little older than previously thought.

A further important implication of the very old age for angrite magmatism relates to the relative age of differentiated and undifferentiated planetesimals i.e., achondrite and chondrite meteorites. This new age for angrites shows that differentiated planetesimals (source of

achondrite meteorites) must be older than undifferentiated planetesimals (source of chondrite meteorites), despite the fact that chondrites are traditionally viewed as the oldest most primitive Solar System rocks. However, the fact that achondrites are older than chondrites makes sense as the widespread presence of heat-producing  $^{26}\text{Al}$  in the young Solar System means that all earliest-formed planetesimals would have melted (making differentiated planetesimals), whereas chondrite parent bodies formed after  $^{26}\text{Al}$  had decayed away to levels insufficient to cause planetesimal melting – some two or three million years after the formation of CAIs.



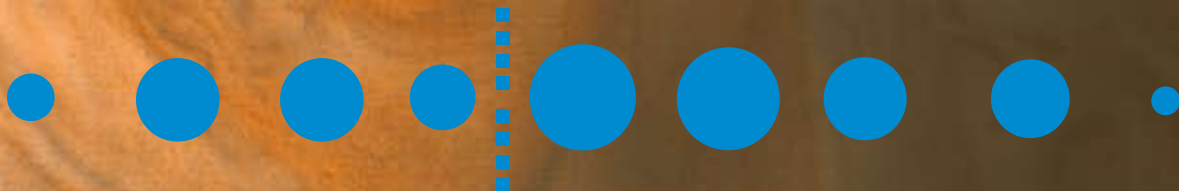
Figure 6. The SAH99555 angrite. Field of view is approximately 5 cm. ©Luc Labenne.





Chapter (2)

# Bodies of the Solar System



# Mercury

By Christine Marwil

(2•1)

Mercury is the planet in our Solar System that is closest to the Sun and also one of the planets we know least about.

Mercury has a very high density, somewhat higher than both that of Venus and Earth. This suggests that an unusually large part of the planet consists of metallic iron. Mercury has a magnetic field just like Earth, so parts of the planet's core must still be liquid. How this is possible when the planet is so small, is not fully understood, but must be due either to the fact that the chemistry of the core is different from that of the Earth, or that the gravitational field of the Sun deforms Mercury when it changes its orbital distance from the Sun. This releases energy in the interior of Mercury and helps keep it partially molten.

Mercury's crust looks a little like the highlands of the Moon, which primarily consists of anorthosite, a feldspar-rich igneous rock. Most likely Mercury's crust was crystallized from a global magma ocean early in the planet's history as is the case on the Moon. It does not appear as if volcanism has played any significant role on Mercury, as it has no clear lava flows on its surface and there are no impact basins filled with lava as on the Moon.

An interesting discovery is that there might be ice in some of the deep craters near the poles. This was probably the last place one expects to

find ice as Mercury is so close to the Sun. On the whole we still know very little about Mercury with any certainty. The knowledge we have is derived from studies of its movement around the Sun, its influence from and on the other planets and the pictures we have of its surface, from telescopes and the Mariner 10 probe.

On August 3, 2004 NASA sent the space probe Messenger towards Mercury, scheduled to arrive in March 2011. It carries instruments that will give us a much greater understanding of Mercury. If you want to know more about this mission and its results, follow this link:

[http://www.nasa.gov/mission\\_pages/messenger/main/index.html](http://www.nasa.gov/mission_pages/messenger/main/index.html)

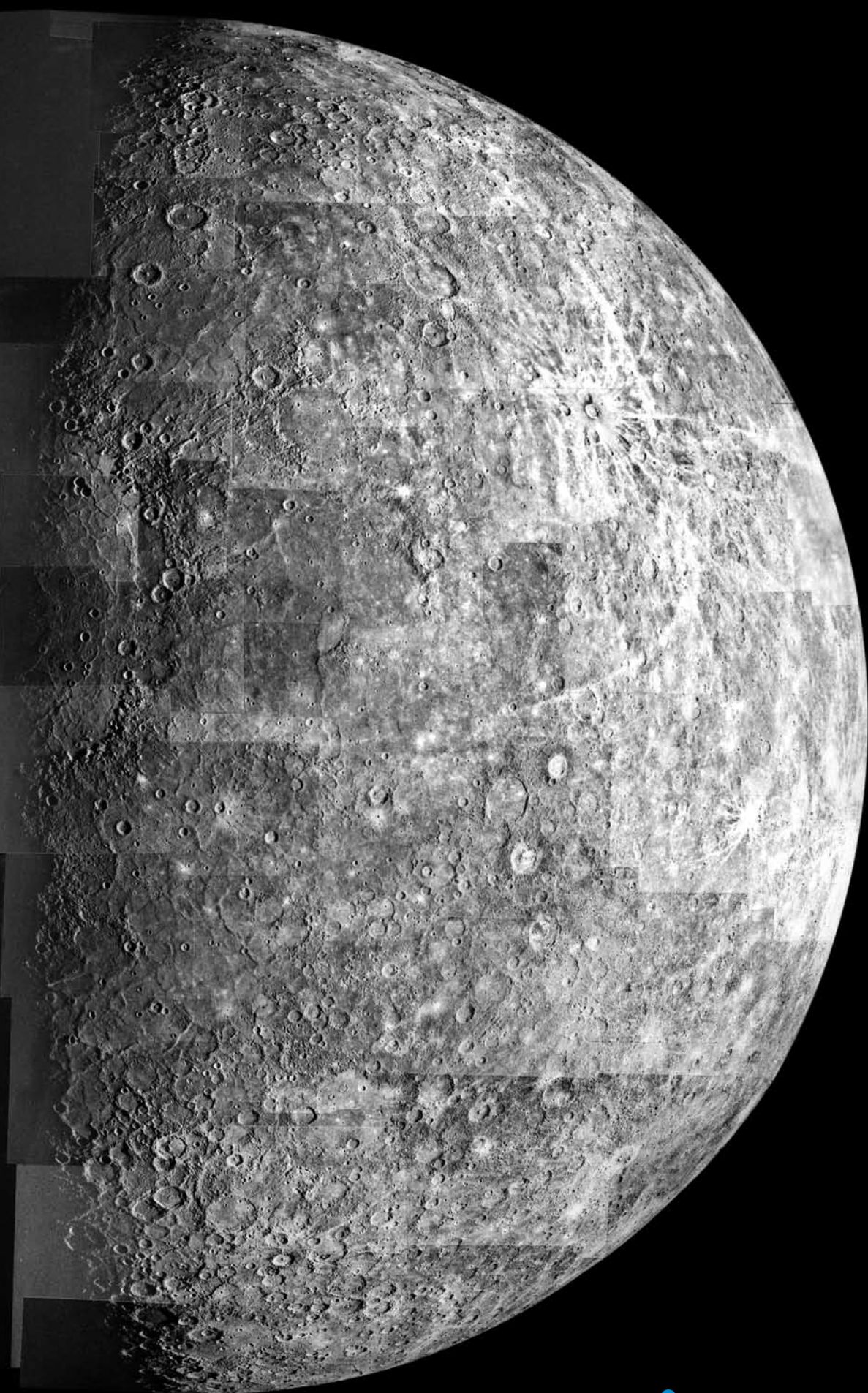


Figure 1. The crater-filled surface of Mercury.  
©NASA /JPL.

# Venus

Figure 1. Here we see Venus as we know it with its dense cloud cover. ©NASA

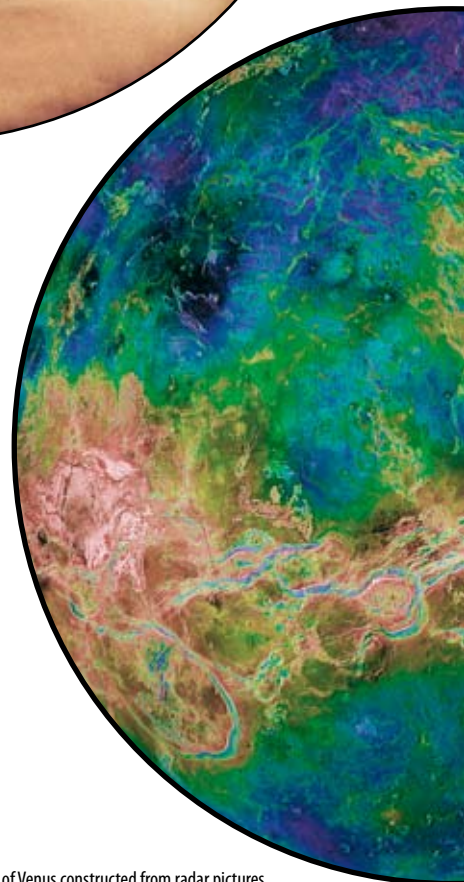
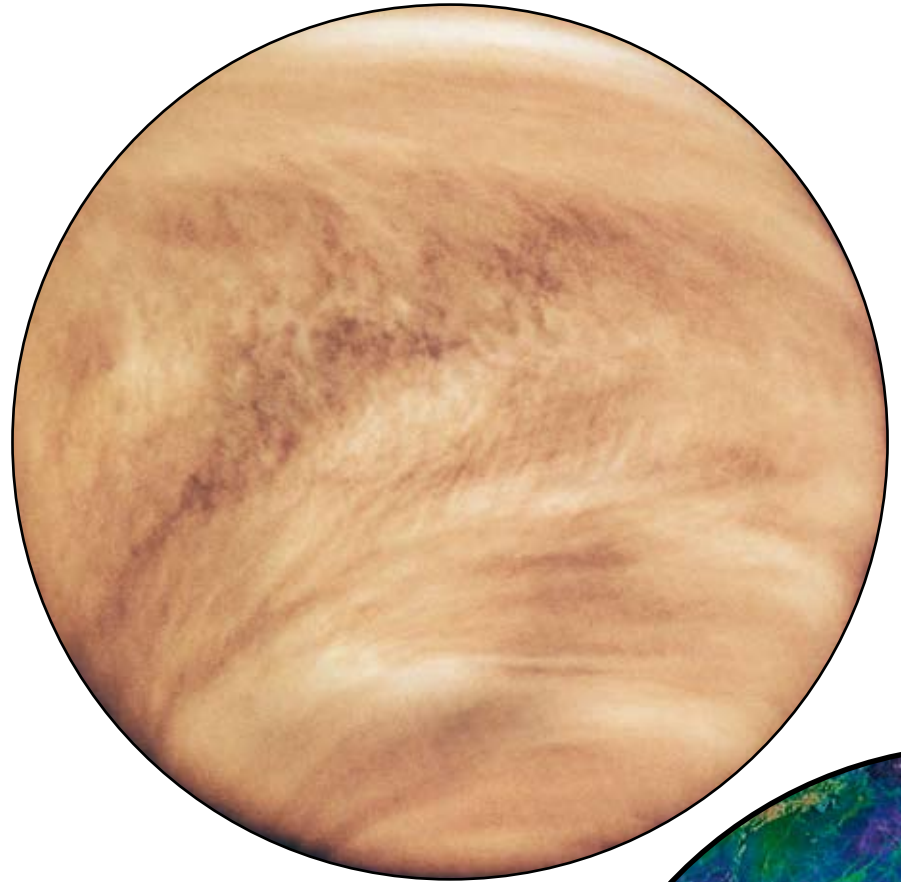


Figure 2. Contour map of Venus constructed from radar pictures. © NASA/JPL-Caltech

By Christine Marvill

(2.2)

The sight of Venus in the evening sky, coloured by the last rays of the setting Sun, is always breath taking. After the Sun and the Moon, Venus is the brightest object in the sky. Venus is slightly closer to the Sun than the Earth and therefore always appears in our skies close to the Sun. That is why it can only be seen in the morning sky just before dawn, or in the evening just after sunset.

## The Earth's twin planet?

As the second planet from the Sun, Venus is also called the Earth's twin planet as it is only a little smaller than Earth and has approximately the same density. It is also the planet that is closest to Earth.

The structure of Venus is also very similar to that of Earth, with an inner metal core, a silicate mantle and a thinner crust. However in contrast to the Earth, Venus does not generate its own magnetic field. This is probably due to the fact that Venus rotates very slowly. Venus also differs from Earth in lacking a moon.

## Clouds of sulphuric acid

Venus has an atmosphere which is approximately 95 times denser than the Earth's, with clouds primarily consisting of sulphuric acid and air mainly consisting of  $\text{CO}_2$ . The air is also very rich in noble gasses such as argon, krypton and neon. The dense atmosphere allows temperatures on

Venus to reach above  $450^\circ\text{C}$ . These are higher than the surface temperatures on Mercury even though Mercury is closer to the Sun. The dense atmosphere, however, makes it impossible to see the surface of Venus from Earth. For many years it was a well-kept secret what was hidden under the dense layer of clouds. In 1975 the Soviet Union succeeded in retrieving data from a probe on the surface of Venus. Previous probes had broken down on their way through the atmosphere because of the unexpected high pressures and high temperatures in the planet's atmosphere. Later the surface was successfully mapped by image-forming radar. All the pictures shown of Venus' surface in this chapter are radar pictures. Surprisingly the surface of Venus is better mapped than the Earth's. The water and ice-covered parts of Earth are not nearly as well mapped as the surface of Venus. The radar pictures have revealed a surface that surprisingly does not look like Earth at all. In spite of the almost identical size of the two planets it seems that they developed very differently.

## Days longer than a year

Venus does not only rotate extremely slowly, it also rotates the wrong way. Whereas all other planets except Uranus rotate clockwise, Venus rotates anticlockwise, and uses no less than 243 days for one complete rotation. This is actually longer than a year on Venus since it takes the planet 225 days to rotate around the Sun. The length of the day, i.e. the time that passes from when the Sun is highest in the sky one day until it is highest in the sky the next day is however shorter, i.e. 120 Earth days.

## Millions of volcanoes

Venus also differs from Earth by having a crust of largely uniform thickness. It is approximately 30 km thick and of basaltic composition. It looks as if the entire surface is of the same age, approximately 300 to 500 Ma, formed by thin lava flows that covered the surface of the planet within a relatively short period of time. By contrast, the Earth's crust has very different ages depending on where measurements are made: on oceanic or continental crust.

That there has been a lot of volcanic activity on Venus can be seen from the almost one million larger or smaller volcanoes found on the surface.

## Water on Venus?

Venus may have had an ocean of at least 4 metres and possibly up to 100 metres deep. This can be deduced from the ratio between deuterium and hydrogen on the planet. There are various theories on how the water disappeared, if it was actually there in the first place. Some think that a giant impact early in the planet's history was large enough to make the planet rotate the "wrong" way and at the same time, vaporized the oceans. Others think that the intense greenhouse climate caused the water to vaporize and disappear out of Venus' atmosphere.

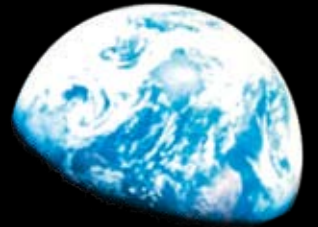
Whether there was an ocean or not, it was clearly not comparable in size to any of the Earth's oceans; this is one of the main differences between Venus and Earth. Water is essential for plate tectonic processes. Earth's entire surface has been modelled by plate tectonics whereas Venus' surface was formed by so-called hot-spot volcanism, where volcanic centres functioned as valves to expel internal heat from the planet.

Figure 3. Howe (in the middle), Danilova (upper left) and Aglaonice (upper right) are some of the impact craters found on Venus. The smallest is 37 km wide, whereas the largest is almost 63 km. Because of the dense atmosphere, Venus is only rarely hit by meteors below a certain size. Small meteors simply cannot penetrate the dense atmosphere. So the craters observed on Venus are all more than 30 km in diameter. © NASA/JPL-Caltech

Figure 4. The volcano in the middle of the picture is Sapas Mons – one of the numerous volcanoes on Venus, almost 1.5 km high and 400 km wide. In the background sits the volcano Maat Mons. The light areas are lava flows. © NASA/JPL-Caltech

# The Earth and the Moon

***Meteorites are a great gift to geology; they give us an insight into the processes that originally formed the Earth. The geological processes, which make the Earth a dynamic and habitable planet, are continually breaking down old surface rocks and replacing them with new ones. Therefore all traces of the rocks that covered the surface of the young Earth have disappeared. We can only speculate about the environment on the juvenile Earth's surface and which processes operated.***



By Minik Rosing

## What meteorites tell us about the Earth

(2.3) Practically all meteorites come from a remote and, more or less, uneventful warehouse between Mars and Jupiter. Here they have sat almost unchanged since the beginning of the Solar System. At regular intervals this asteroid belt delivers samples to us inquisitive Earth-dwellers. In this way we have access to some samples of the building blocks from which our world was originally constructed.

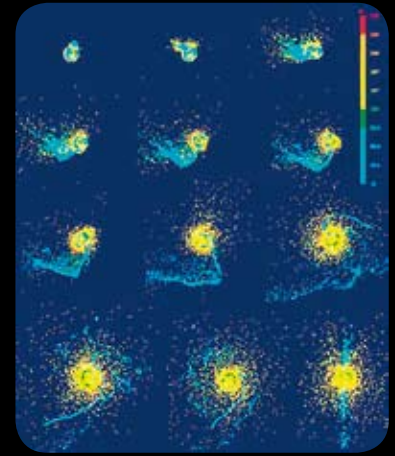
Most meteorites are fragments of smaller bodies that have all participated in various efforts to create real planets, but which have come to a stop at different stages in their development. Meteorites thus shed light on the very earliest processes in the Earth's history. Some meteorites, the chondrites, represent the primitive material from which our Earth was originally formed. By analysing their composition we can discover the average composition of the Earth. This knowledge is extremely important as all the materials we have on Earth today have been extracted from this modal material by chemical

processes that have sorted the various elements. When studying the continents, the sea water or the atmosphere, we know both the original material from which they were extracted and their composition today. So we can see which elements are concentrated and which are lacking compared with what was probably around at the beginning. Armed with this knowledge we can also understand the processes that formed the mountains, the oceans and the atmosphere, and we can often calculate when the element sorting took place. We are able to date the processes because radioactive elements and the elements, into which they eventually decay, are also extracted during the sorting processes. Each sorting process thus resets its own radioactive stop watch.

We can now say that the Earth was constructed as a planet shortly after the beginning of the Solar System 4,569 million years ago. Small particles in the Sun's nebula gathered as still larger lumps. The lumps collided and built up so-called planetesimals which again fused together and formed regular planets. The early dust

contained large amounts of radioactive matter, which produced heat. Small particles could easily expel the heat, but as they accreted to still larger bodies, the radioactive heat accumulated and the bodies began to melt. Iron and nickel melted and flowed inwards where they formed a core of liquid metal. The lighter elements evaporated and built up the proto-atmosphere, while large parts of the stony material melted and covered the Earth with a magma ocean several hundred kilometres deep. From radioactive isotopes we know that the Earth had achieved its present size and had separated its iron core already approximately 20 million years after the formation of the Solar System.

Figure 1. Here we see a simulation of the moon-forming impact where a meteor of the size of Mars fused together with Earth. Some of the material from this impact formed the Moon. © Southwest Research Institute.



## The Moon Is formed

At this early stage Earth had a sister planet orbiting at approximately the same distance from the Sun. The sister planet was very similar to Earth in construction, but was considerably smaller, approximately the size of Mars. The coexistence of two planets at almost the same distance from the Sun was a dangerous construction which only lasted a very short time. Within the first 20 million years the two planets collided with incredible force. Enormous amounts of stony material from the outer layers of the two planets were flung outwards from the collision while the two iron cores fused together into the core of the Earth today.

A large part of the material that was hurled away by the explosion returned to Earth, while the lumps farthest away gathered and formed a new celestial body, the Moon. The Moon consists almost exclusively of stony material like that forming the outer part of the Earth, the mantle, and it has none or only a very small iron core. Immediately after the collision, a large part of the Moon was molten, forming a deep magma ocean. The magma was cooled by the cold space

and formed a crust of the rock anorthosite, which almost exclusively consists of the chalk-white mineral feldspar. This is the crust that gives the Moon its clear white shine. Through time meteor impacts on the Moon have made larger and smaller holes in the crust. As the Moon lacks any geological activity, these scars do not disappear with time. Those in connection with very large impacts craters, which are several hundred kilometres across, are clearly visible. Later basaltic magma pushed up from the depth and filled the large craters with black basaltic lava. These dark areas are actually solidified lava lakes, which we call the Moon's "oceans" (mare) because they were previously thought to be oceans similar to those here on Earth.

Our sister planet hit us obliquely in the collision that formed the Moon, and in this way the Earth began to rotate around its own axis and the Moon's orbit followed the same axis. Thus we have inherited our circadian and monthly rhythm from the last giant collision in a number of events, which led to the formation of our planet from an original dust cloud.



Figure 2. The Earth and the Moon seen from the Galileo probe in 1992, while on its way to Jupiter. © NASA/JPL.

Figure 3. The Moon seen from the Galileo probe. The old, bright proto-crust and the younger, dark mare-areas of the Moon are clearly visible. © NASA/JPL.



## The origin of life

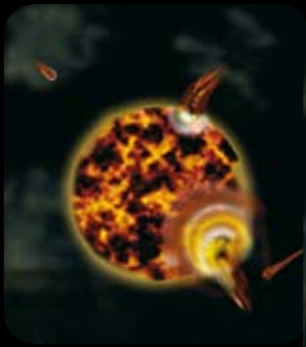
The first tens of millions of years were thus very hectic and there were no stable environments on the Earth's surface for long periods of time period. Surprisingly it appears, however, that already 150 million years after the beginning of the Solar System the Earth's crust had solidified and cooled enough for aqueous vapour in the atmosphere to condense and form the first oceans. We know this as 4.4 billion year-old grains of the mineral zircon have been found in Australia. The zircon grains have been formed by contact with sea water. The oldest proper coherent rocky areas we know on Earth are found in the area around Nuuk in Western Greenland. Here large areas of rocks are preserved that were originally formed on the Earth's surface and thus carry a geological memory of the conditions present when the rocks were deposited 3,800 million years ago. From these old sedimentary rocks we have evidence that life already was flourishing in the oceans. In other words, life has been on Earth for at least 3,800 million years.

The oldest rocks are preserved because they were an integral part of the construction of the continents. There are indications that Earth did not begin in earnest forming continents until 4 billion years ago. Continents are not just land areas that accidentally stick up out of the sea. The continents consist of specific light rocks, mainly granite, which is not found on the ocean floor. The oceans are large depressions where the rocks are dominated by the dark heavy rocks: basalt (similar to the Moon's so-called "oceans"). The reason why the ocean floor is low lying and the continents stick up is simply because the continents consist of lighter material and thus reside higher on the warm, soft and heavy mantle underneath.

All in all the Earth was roughly ready-constructed with all its most important components approximately 3,800 million years ago.

## The influence of the Moon on Earth

In relation to Earth, the Earth's Moon is very large compared with the other planets and their moons. The Moon orbits around the Earth at a distance of approximately 385,000 km and a trip round the Earth lasts a month, which is actually approximately 27 days and 8 hours. As we all know the Earth's rotation around its own axis lasts 24 hours. This means that the Earth rotates, in effect, under the Moon, so the gravitational pull of the Moon pulls on different parts of the Earth during the 24 hour cycle. The Earth is relatively stiff and robust, but none the less the Earth changes its shape on account of the influence of the Moon. The phenomenon is called Earth tide and means that points on the Earth's surface rise and sink approximately 20 cm during 24 hours. The oceans change their shape much more easily of course and this means that a tidal wave of around 1 m flows over the Earth during the 24 hour cycle or rather that the Earth rotates under a metre-high wave which

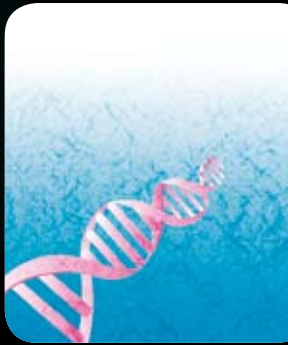


4,567 Myr ago Earth accreted from material similar to chondrite meteorites. The metal core segregated shortly after.



During the following 850 Myr (1½ phanerozoic time span) Earth did not produce any lasting geological constructions. Oceans most probably formed on Earth's surface 4,400 Myr ago.

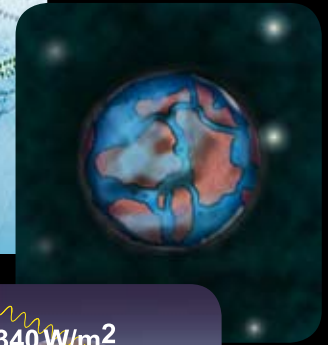
Which allows the possibility that life may have emerged 4,400 Myr ago.



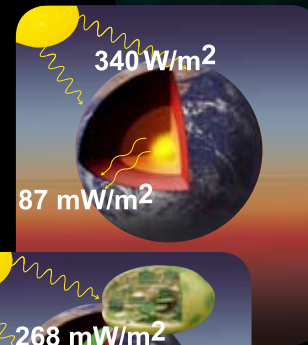
3,800 Myr ago life flourished in the oceans and photosynthesis was probably invented.



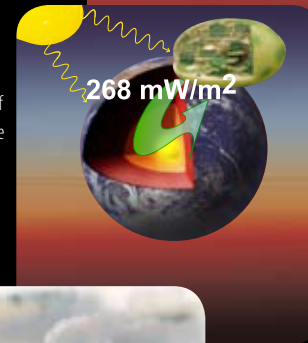
3,800 Myr ago continents became stable enough to preserve bits and pieces to our time. The stabilization of the continents marks the beginning of the geological record. Some familiar environments are recorded right from the beginning.



Earth's plate tectonic machinery is driven by the internal heat production which provides 87 mW for every m<sup>2</sup> of Earth's surface. In comparison sunlight contributes 340 W/m<sup>2</sup> to Earth's surface.



Chlorophylls capture 268 mW/m<sup>2</sup> of the Solar energy, which help fuel the Earth's geochemical cycles.



is maintained by the Moon's gravitational pull. These tidal phenomena mean that the Earth's rotation is slowly retarded at the same time as power is being transferred to the Moon, which then moves away from Earth.

So these tidal forces mean that a day and night and a month in the course of time will last just as long, and that the Moon will always be above the same point on Earth. Billions of years will pass before this happens, but in geological deposits we can see that days and nights were considerably shorter than now, and that the Moon was much closer to Earth than it is now. Both the Earth's rotation around its own axis and the Moon's rotation around the Earth began when the Earth was hit by the now-absorbed sister planet. The Moon's rotation around the Earth helps to secure the Earth's axis of rotation so it always points, by and large, in the same direction in relation to the Sun. Without the stabilizing effect of the Moon, the Earth's own axis could point in any direction. This would

The forcing of the geochemical cycles by photosynthetic life could have accelerated granite production and led to the stabilization of the continents.



mean that for some time it could point directly towards the Sun preventing any circadian rhythm. One side of the Earth would be very hot and dry and the other would be ice-cold and covered by thick glaciers. The Moon has thus been important in stabilizing the Earth's climate, so that stable conditions were permitted for higher life to adapt and evolve. There would be no humans, animals or plants on Earth if we did not have the good old Moon.

# Mars

***In spite of its small size Mars is one of the most interesting planets in the Solar System. It is not a coincidence that Mars is the planet in the Solar System to which the most probes have been sent. In many ways the landscape on Mars is superior to that on Earth; it has ice caps, an atmosphere and a variable climate. But the most important reason for this exploration, is that there was lots of water on Mars, and where there is water there might be life.***

By Christine Marwil

## The structure of Mars

Mars is the fourth planet from the Sun and thus Earth's neighbour. With an average diameter of 5,794 km, it is much smaller than Earth and it even has two moons, Phobos and Deimos. Mars' entire surface is covered by a thin layer of red dust, which is red because the iron contained in the dust has rusted. The red dust layer is the reason why Mars is called the red planet. The red colour makes it also easy to recognize Mars in the night sky; even when seen from Earth it is clearly something special.

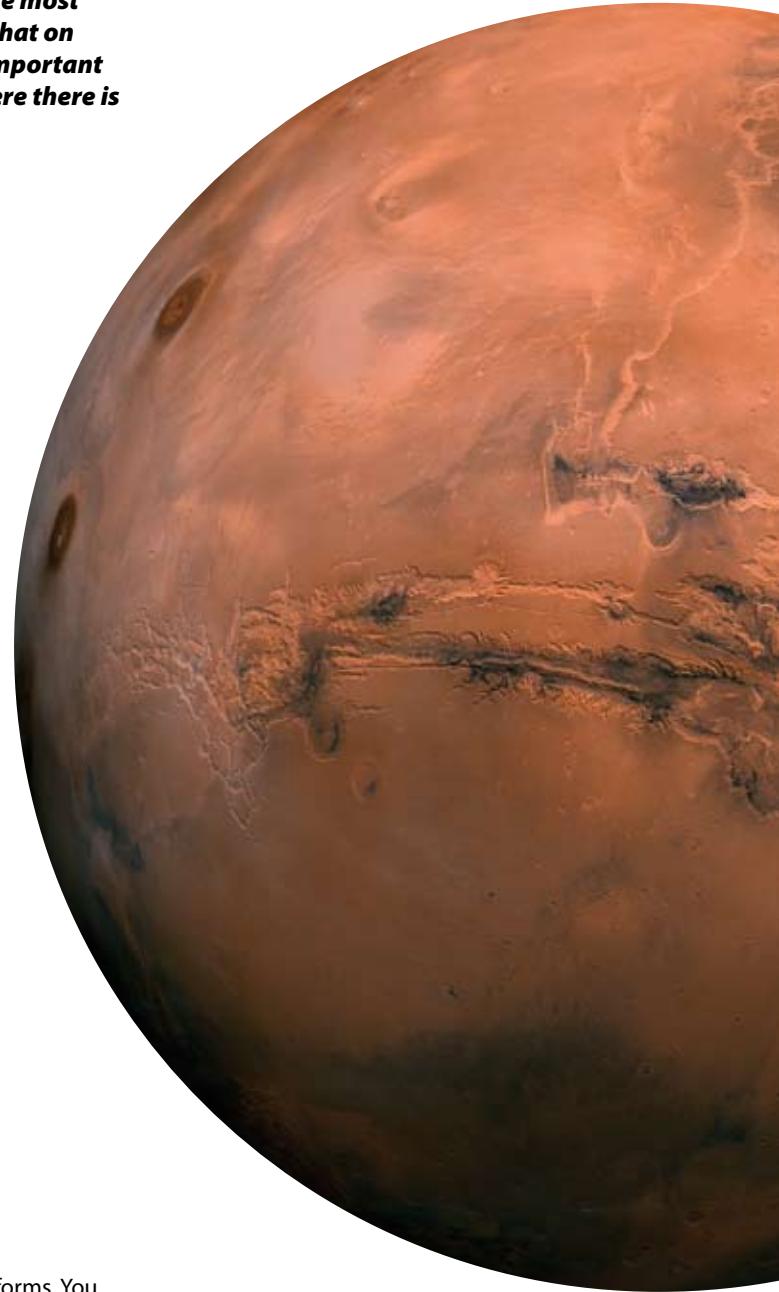
Mars' climate is more similar to Earth's than any other planet. Although the average annual temperature is  $-55^{\circ}\text{C}$ , the temperature at the equator may reach  $20^{\circ}\text{C}$  in the summer. The length of the day on Mars is on average 24.6 hours and in this way too it resembles Earth. However, it takes Mars 687 days to orbit the Sun in stark contrast to Earth's 365 days.

The upper part of Mars (the lithosphere) has an average density that is similar to terrestrial basalt. The crust, which is the uppermost part of the lithosphere, is on average at least 40-50 km thick and forms approximately 4% of the Mars' total volume.

The core has a radius of 1,300-1,500 km and makes up approximately 20% of Mars.

## Mars' surface

Mars has some amazing landscape forms. You can see both the largest and the tallest volcano in our Solar System on Mars. The tallest volcano, Olympus Mons, reaches 23 km above the surrounding ground. In comparison the tallest mountain on Earth, Mount Everest, is "only" some 9 km high. Terrestrial mountains cannot be much taller than Mount Everest because gravitation is consistently working to level the surface of the planet. On Mars gravitation is smaller than on Earth and Mars' crust is also thicker than Earth's. These are the main reasons that such a large mountains can exist on Mars.



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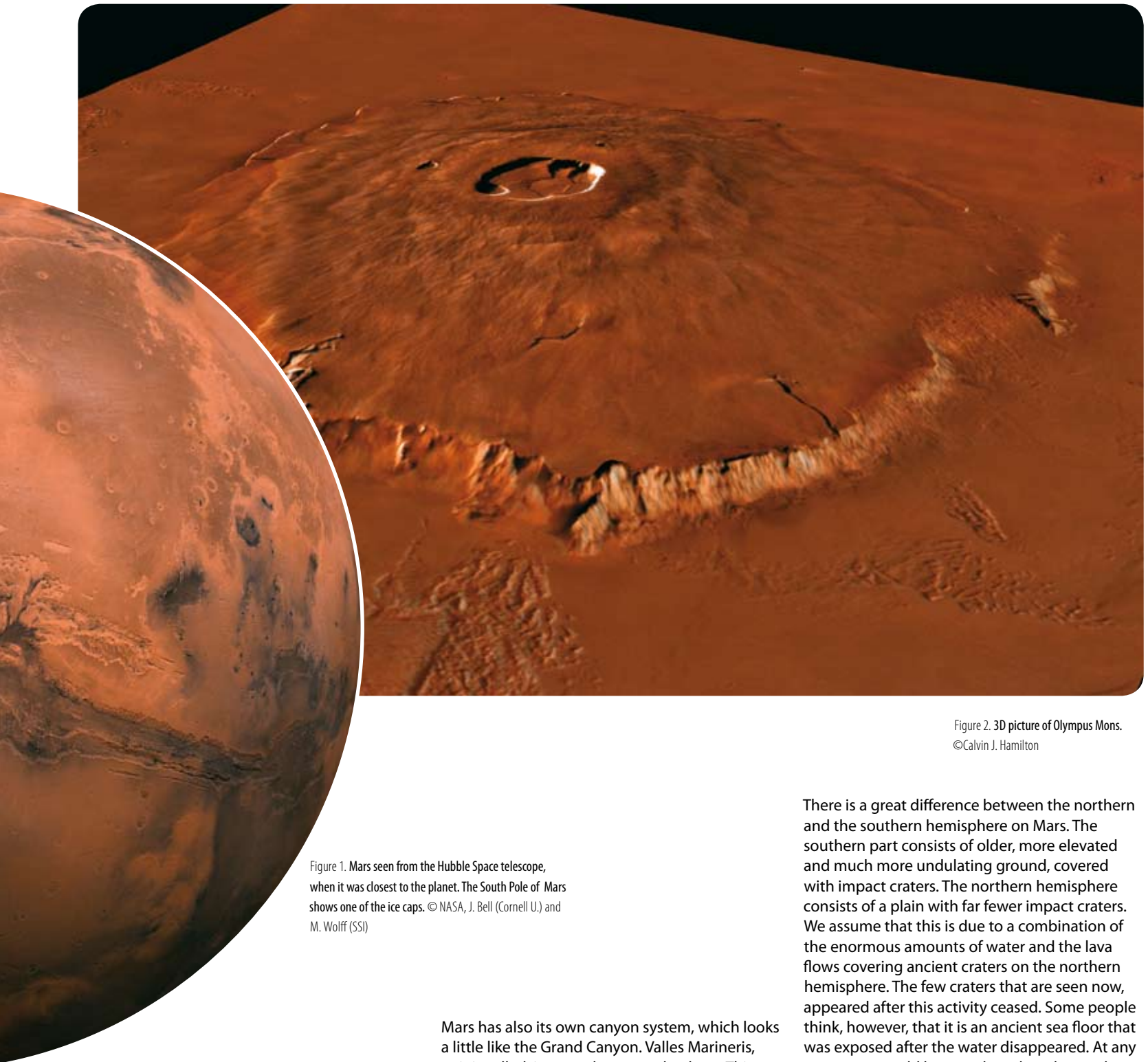


Figure 1. Mars seen from the Hubble Space telescope, when it was closest to the planet. The South Pole of Mars shows one of the ice caps. © NASA, J. Bell (Cornell U.) and M. Wolff (SSI)

Figure 2. 3D picture of Olympus Mons. © Calvin J. Hamilton

Mars has also its own canyon system, which looks a little like the Grand Canyon. Valles Marineris, as it is called, is more than 3,000 km long. This corresponds to the distance from the west coast to the east coast of the United States. The canyon cuts through Mars' surface with a maximum depth of 8 km. Although the canyon has not been "excavated" by water there are clear signs of water erosion and it is estimated that periodically no less than 5 km<sup>3</sup> water has coursed through the canyon per second. This is more than 15,000 times the water flow through the Amazon River at the height of the rainy season. Mars is the only other planet besides Earth in the Solar System that shows signs of having a hydrological cycle.

There is a great difference between the northern and the southern hemisphere on Mars. The southern part consists of older, more elevated and much more undulating ground, covered with impact craters. The northern hemisphere consists of a plain with far fewer impact craters. We assume that this is due to a combination of the enormous amounts of water and the lava flows covering ancient craters on the northern hemisphere. The few craters that are seen now, appeared after this activity ceased. Some people think, however, that it is an ancient sea floor that was exposed after the water disappeared. At any rate water would have gathered on the northern plain as it is approximately 7 km lower than the highlands on the southern hemisphere.

## Mars' atmosphere

Mars' atmosphere is very different from the nitrogen-rich atmosphere of Earth. Besides being much thinner than the Earth's atmosphere, Mars' atmosphere consists primarily of CO<sub>2</sub>. The opposite is true for the ice caps on Mars that are dominated by water-ice.

There is a perfect similarity between Mars' atmosphere and the gas content of the meteorites that are thought to come from Mars. This is the main reason that we can confidently state that these meteorites were derived from Mars, as the atmospheres of the various planets are just as distinctive as the fingerprints of human beings.

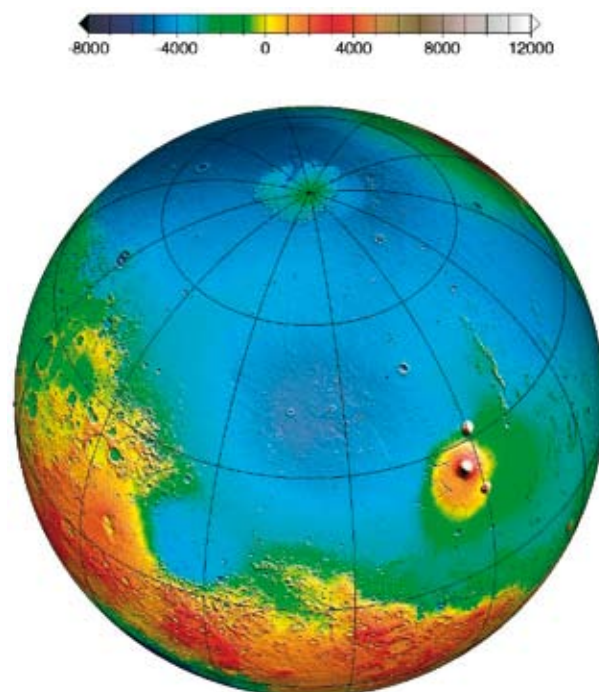


Figure 3. Topographic map of Mars' southern hemisphere based on MOLA (Mars Orbiting Laser Altimeter) data.  
© MOLA Science Team

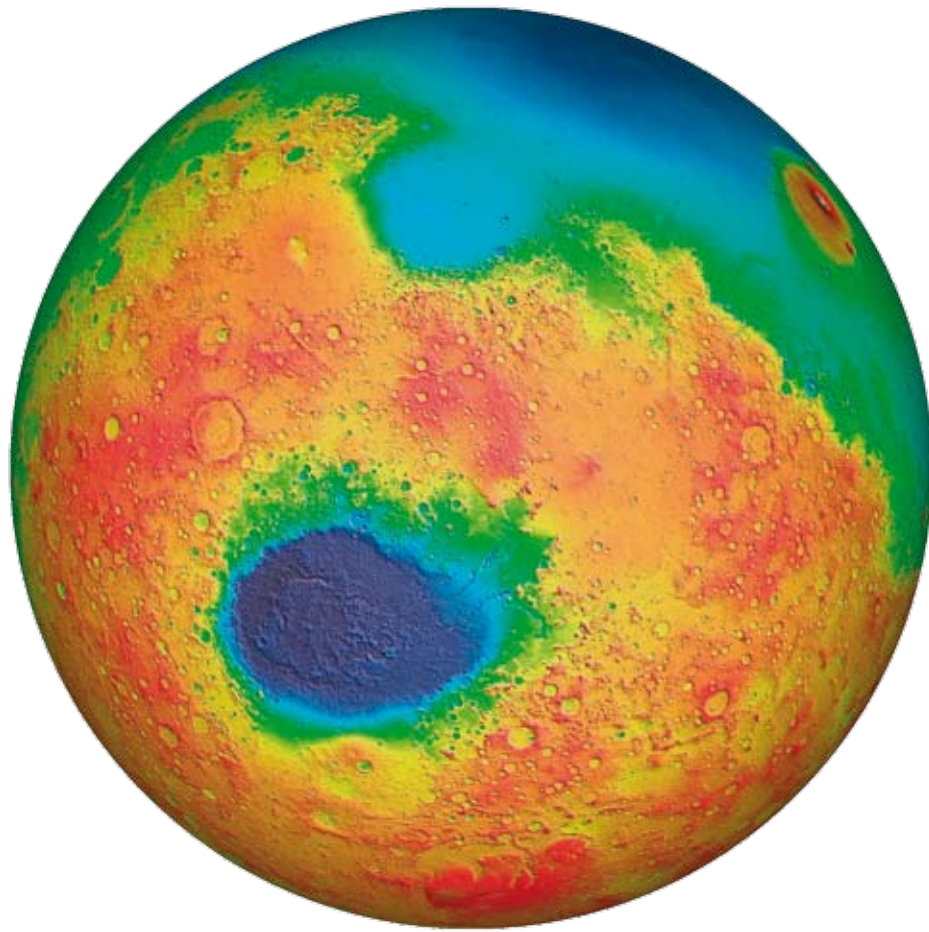


Figure 4. Topographic map of Mars' northern hemisphere based on MOLA (Mars Orbiting Laser Altimeter) data.  
© MOLA Science Team

# The poles and ice caps of Mars

By Christine Hvidberg

## Polar ice caps on Mars

Mars is the only other planet besides Earth where ice caps of frozen water have been found. The ice caps form a gigantic spiral pattern which is not seen in those on Earth. The ice caps have a fine layered structure which documents past climate changes on Mars just like the growth rings in a tree.

## Ice on Mars

There are two kinds of ice on Mars: common ice and dry ice. Common ice is just frozen water, i.e.  $H_2O$  as we know it on Earth, where it is found in ice caps and glaciers. Dry ice is frozen  $CO_2$ . Frozen  $CO_2$  is called dry ice as it evaporates instead of melting.

The winter snow on Mars consists mainly of dry ice. In winter it becomes so cold in the polar regions, that it snows with dry ice. The dry ice evaporates again in Spring. The snow cover can be seen from Earth through binoculars and has been known for centuries; we even know that the ice cover comes and goes with the seasons.

Most of the water ( $H_2O$ ) found on Mars occurs as frozen ice in the polar ice caps. The ice caps have been built up over millions of years and are of the size of the Greenland Ice sheet.

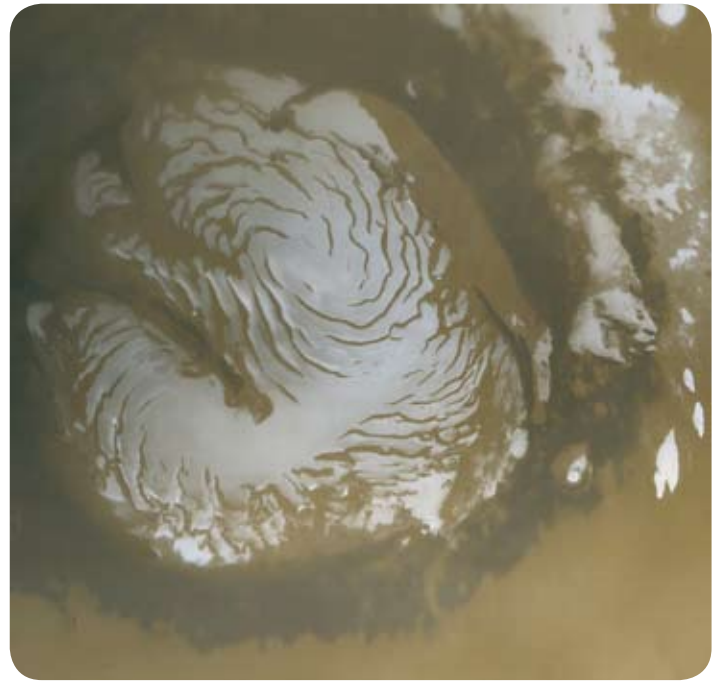


Figure 1. The ice cap in the north (top) and in the south (bottom). ©NASA/JPL/MSSS.

## The stratification and the spiral structure of the ice caps

On the ice caps, extensive white terraces and dark slopes form a gigantic spiral pattern around the pole. Layers, with varying dust content, are seen in the dark slopes. These layers can be tracked across large distances and indicate that the climate has varied throughout Mars' history.



Figure 2. Spring storm over the northern ice cap of Mars. ©NASA

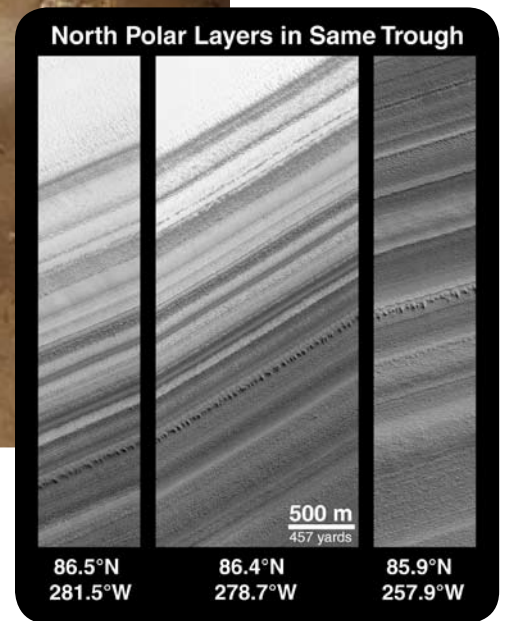
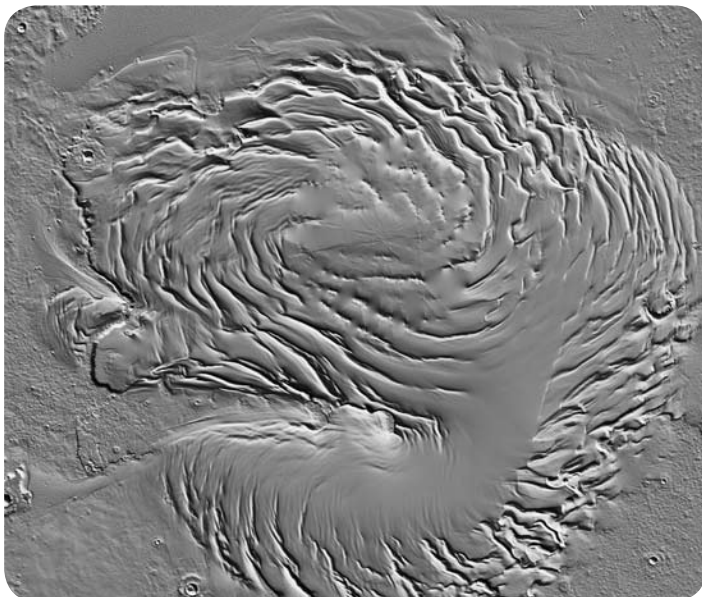


Figure 3. There are more than 100 km between these pictures taken of a slope on the northern ice cap. The layers are thought to contain ice from the last 1-2 million years. ©NASA/JPL/MSSS.

Figure 4. Chasma Boreale, a valley in the northern ice cap which possibly shows signs of the outwash of bottom melt waters. ©MOLA Science Team.



## Water below the ice caps

The ice caps of Mars have deep valleys which are thought to have formed by the outwash of bottom melt waters. In the Chasma Boreale which almost cuts through the ice cap in the north, there are signs of substantial outwash, together with vertical faces which indicate collapse. If this is indeed traces left by glacier torrent, that are known from Iceland, it must have been gigantic.

# Asteroids

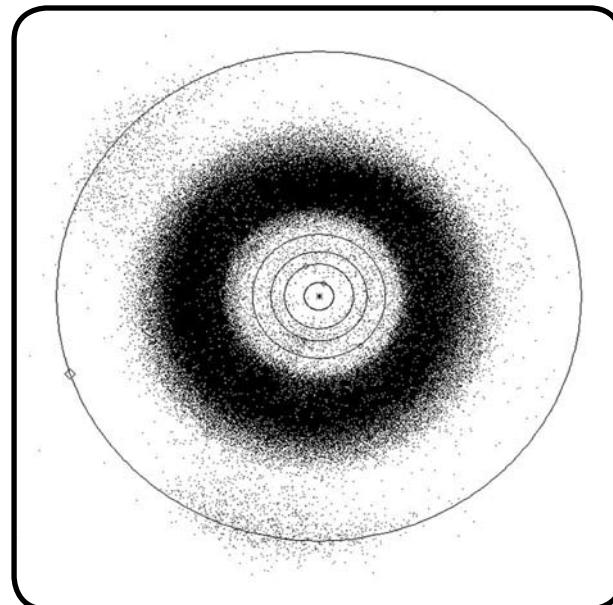
**Asteroids are metre to kilometre-sized objects of rock and metal orbiting the Sun. In spite of their overwhelming number they are often overlooked when discussing the Solar System. Today we know more than 200,000 asteroids, i.e. far more than the planets, moons and comets put together, and this number increases by approximately 30,000 new discoveries every year. With the exception of the asteroid Vesta, these celestial bodies cannot be seen with the naked eye and have therefore avoided the sort of attention they clearly deserve. Since asteroids were created approximately 4.5 billion years ago from the same material as the planets, they can tell us much about how the early Solar System evolved. Moreover, asteroids may have played an important part in the origin of life – a role which can still be determined from the studies of asteroids. Most of the evidence for the origin and early evolution of life here on Earth has long been lost because of the geological evolution.**

By Philip Rahhan Bidstrup

## The Asteroid Belt

The asteroids are derived from a very special place in the Solar System, that is from the transition zone between the inner Solar System with the Earth-like planets Mercury, Venus, Earth and Mars and the outer Solar System with the gas and ice planets Jupiter, Saturn, Uranus and Neptune. As illustrated on Figure 1 (showing the Solar System from above) the asteroids are distributed in a large ring around the Sun; this accumulation of asteroids is called the Asteroid Belt. Each dot is a known asteroid and the circles are the orbits of the planets. The Asteroid Belt shows – as do the inner and outer planets – signs of diversity in complexity; the inner part of the belt contains asteroids which have undergone melting and thus are very Earth-like with metal cores and lighter outer layers such as mantle and crust, whereas the asteroids of the outer asteroid belt are composed of primitive carbonaceous chondrite-like material resembling that from which the Solar System was originally created.

Figure 1. Outline of the inner Solar System. The circles are the orbits of the planets and each dot is a known asteroid. The cloud between the orbits of Mars and Jupiter is called the Asteroid Belt and it is thought that the asteroids were originally created here. ©GM



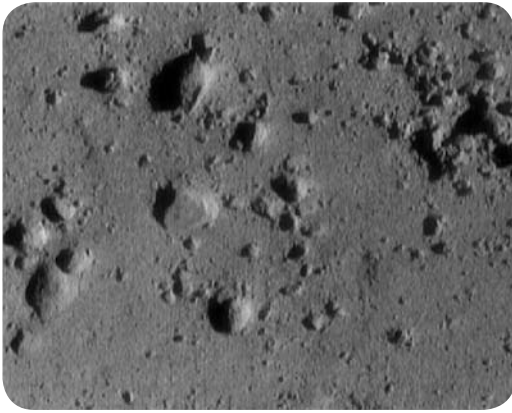


Figure 2. Close-up of Eros from a height of 250 m showing a 12 m wide section of the surface. ©NASA/JHU.

Only four of the many asteroids have been visited by space missions. On its way through the Asteroid Belt towards Jupiter, the Galileo space probe photographed in 1991 and 1993 the asteroids Gaspra and Ida; these were the first asteroids to be photographed at close range. Surprisingly Ida has a small moon in orbit, called Dactyl, which is no more than approximately 1.5 km in diameter. The mission Near Earth Asteroid Rendezvous (NEAR) also photographed the asteroid Mathilde in 1997 and landed on the asteroid Eros in 2001. During the Eros landing, pictures of such a high resolution were taken that it is possible to see the structure of the asteroid's landscape (see figures 2 and 3). Mathilde and Eros are both near-Earth asteroids, i.e. asteroids with an orbit that could bring them close to Earth, which means that there is a slight possibility that they could collide with the Earth in a distant future.

By examining the pictures of the four asteroids visited, the inner planets or those of our own moon, it is obvious that their surfaces are marked by numerous craters. These craters were created by collisions with asteroids or fragments of asteroids.

## The missing planet

The origin of the Asteroid Belt has been discussed for almost 300 years; as it was thought that there should have been a planet at this place. In 1766 Titius and Bode discovered a regular pattern in the mean distance of each planet from the Sun, clearly suggesting a planet was missing between Mars and Jupiter. During the hunt for this planet, the largest of the asteroids, Ceres, was found in 1801. As Ceres is only approximately one quarter of the Moon in size and thus too small to be accepted as a planet, the hunt continued and several more asteroids were found; but the missing planet was never found. The Asteroid Belt is not – as one might think – a planet that has been crushed into fragments;

it is, however in contact, a planet that never succeeded in accreting. The largest planet in the Solar System, Jupiter, which was formed very early, prevented, by means of its enormous mass and its gravitational attraction, the accretion of the asteroid belt and thus the possible creation of a new planet. Jupiter's gravitational field is currently responsible for the gradual depletion of asteroids from the Asteroid Belt. The total mass of the Asteroid Belt is less than one thousandth of the Earth's mass, indicating that quite a lot of material has disappeared from the belt. In contrast to the planets' orbits, which are stable within a time frame of billions of years, the orbits of the asteroids in the Asteroid Belt are chaotic; moreover the large gravitational field of Jupiter causes asteroids in specific orbits to be pushed out of the Asteroid Belt. Asteroids that depart the Asteroid Belt may eventually be absorbed by the Sun, be expelled from our Solar System or end up in temporary orbits within the inner Solar System, where they may one day risk a collision with Earth or another planet. The unstable orbits, also called resonant orbits, will quickly be depleted of asteroids and unless new asteroids end up in

these resonances, "loose" asteroids in the inner Solar System are unlikely, as they would have been removed by collisions with planets or the Sun, long ago. Asteroids do actually move near the Earth, because collisions between asteroids in the Asteroid Belt can cause asteroid fragments to join the resonances; in this way they leave the Asteroid Belt through interactions with Jupiter's gravitational field. This depletion of the Asteroid Belt is happening all the time at a rate, which over billions of years, will slowly decrease as the Asteroid Belt empties of asteroids.

## Impact(s)

Fragments of asteroids can find their way onto our planet, and if they reach Earth they typically are still moving at speeds of around 70,000 km/h. Most of the small asteroid fragments that reach Earth are burnt up by friction with the air in our atmosphere. The passage of such asteroid fragments through our atmosphere is well-known and is somewhat erroneously called a shooting star. A few asteroid fragments will survive the trip and when they hit the surface they may cause havoc on a large scale depending on how large and quick the fragments are. One of the most devastating impacts happened 65 million years ago and is thought to have wiped out 60% of all species on Earth, including the dinosaurs. Luckily such large impacts are very rare, but considering their destructive power, it is worrying that we have so little knowledge of the near-Earth asteroids that could prevent such disastrous impacts.



Figure 3. The asteroid Eros photographed from a distance of 200 km. The arrow shows where the NEAR mission landed on the asteroid's surface. ©NASA/JHU.

# The Outer Planets of the Solar System

By Christine Marvill

(2.7)

## Four giants and one dwarf

The outer planets of the Solar System are those, that viewed from the Sun, lie beyond the Asteroid Belt. In order, outwards from the Sun we have: Jupiter, Saturn, Uranus, Neptune and Pluto. The first four are also called the gas giants since they are, among other things characterized by a total lack of terra firma; in addition they all have ring systems.

Farthest away from the Sun is Pluto, which is covered by ice, and is much smaller than the others, suggesting that it must have been formed by processes other than those for its giant neighbours.

## Traces of the original nebula

By and large, the gas parts of Jupiter and Saturn have the same composition as the Sun, primarily hydrogen and helium.

This indicates that the gas around the outer planets is, in fact, from the original nebula, the rotating disc of gas that formed the Solar System. Jupiter, Saturn, Uranus and Neptune all have inner zones consisting of rock material, the composition of which is probably like the Earth's. The rocky parts of the outer planets are of a similar size, whereas the gas zones vary considerably. The formation of the gas giants is thought to have taken place in two stages: the first stage, the formation of the rocky part, dust, small particles, and ice are cemented together to the interior parts of the planets, whereas the second stage does not take place until the rock and ice parts have reached a size of approximately 10 Earth masses and thus has enough gravitational pull to attract gas from the nebula.

The difference in the amount of gas around the four planets is due to the fact that Uranus and Neptune were formed farther away from the Sun than Jupiter and Saturn. The farther away from the Sun in the early Solar System, the less material was present. For the same reason it took the outer gas giants longer to become large enough that gas from the nebula collapsed around them. When finally they reached the critical size for gas to collapse, a large part of the gas from the original nebula had disappeared. That is why Uranus and Neptune are smaller than Jupiter and Saturn.

## Ice and planets

One can speculate why the inner planets are not the largest, if density was largest close to the Sun; but this is simply due to the fact that they consist of only the small amounts of the firmest material that was present in the original gas cloud. All the gaseous matter was blown out of the inner Solar System. Farther away from the Sun, large amounts of aqueous vapour from the inner Solar System froze to form ice and in this way provided a lot of extra material to construct the large outer planets. As there was considerably more ice than dust and small particles in the nebula, the position of stable areas of ice was essential for the growth of the planets in the Solar System.



Figur 2. Close-up of the violent storms on Jupiter. Around the hurricane we can see further turbulence in the atmosphere. ©NASA/JPL-Caltech.

## Jupiter – the giant of the Solar System

Next to the Sun, Jupiter is the largest object in our Solar System. If it had just been 13 times larger, it would have been a brown dwarf, which is the smallest star in our universe. Jupiter is more than 300 times heavier than Earth and is so large and massive that the pressure in the planet's centre is calculated at around 50 million atmospheres.

Jupiter is the planet that has grown the fastest. This is clear from the existence of the Asteroid Belt, which is between the orbits of Mars and Jupiter. Because of Jupiter's large gravitational pull the Asteroid Belt has been unable to form a planet.

The surface of Jupiter is forever changing because of enormous wind systems in the atmosphere. Most well-known is Jupiter's red spot, which is actually a hurricane several times the size of Earth. It was discovered in 1664 by Robert Hooke and has thus raged for more than 300 years.

Figure 1. The gas giant Jupiter. A little below the centre, the hurricane that has been known for at least 300 years, is clearly visible. © NASA/JPL/Space Science Institute.

## Saturn

Saturn, which is the next gas giant, is the sixth planet from the Sun. Its interior is constructed in much the same way as Jupiter's, but even though it is the second largest planet in the Solar System, its mass is less than 1/3 of Jupiter's.

The planet is mostly known for its fantastic ring system, which consists of ice fragments. They are probably the remains of one or more comets that travelled too close to Saturn and have been torn apart by its gravitational pull. The rings stretch hundreds of thousands of kilometres from the planet and are divided into two distinct systems which each consist of a lot of finer rings. The rings do not live very long and were probably formed quite recently.

Of all the planets in the Solar System, Saturn has the strongest wind system with wind speeds of approximately 500 m/s. In comparison, the wind speed in the Earth's jet currents reaches only 110 m/s.

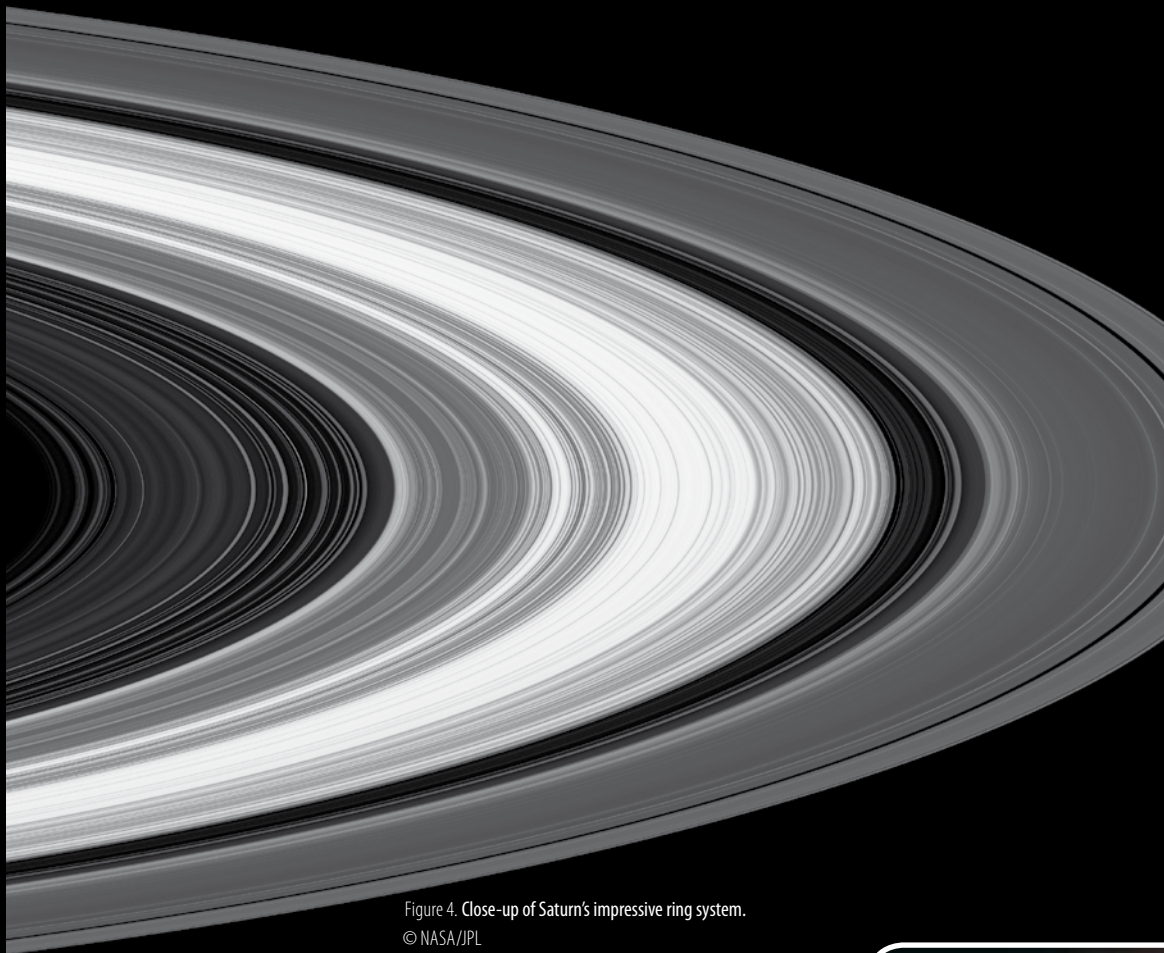


Figure 4. Close-up of Saturn's impressive ring system.  
© NASA/JPL



Figure 3. Saturn with its famous ring system. © NASA/JPL/  
Space Science Institute.



## Uranus

Uranus is the third largest planet in the Solar System. The major part of the planet consists of a frozen and liquid "gas" of water, ammonia, and methane. Besides hydrogen and helium, the outer layers also contain small amounts of water, ammonia, and methane. The methane gas gives the planet its blue-green colour. The planet has no less than 11 rings in its ring system.

Uranus is quite unique in the Solar System because it rotates round a horizontal axis in contrast to the other planets; this means that Uranus alternately has each of its poles towards the Sun whereas the other planets have their equator towards the Sun. It is believed that a large impact on the planet caused this; an impact that was large enough to knock Uranus off its original course. This would require oblique collision with an object the size of the Earth. The impact probably took place probably when Uranus was being formed by swallowing up other bodies in the proximity.

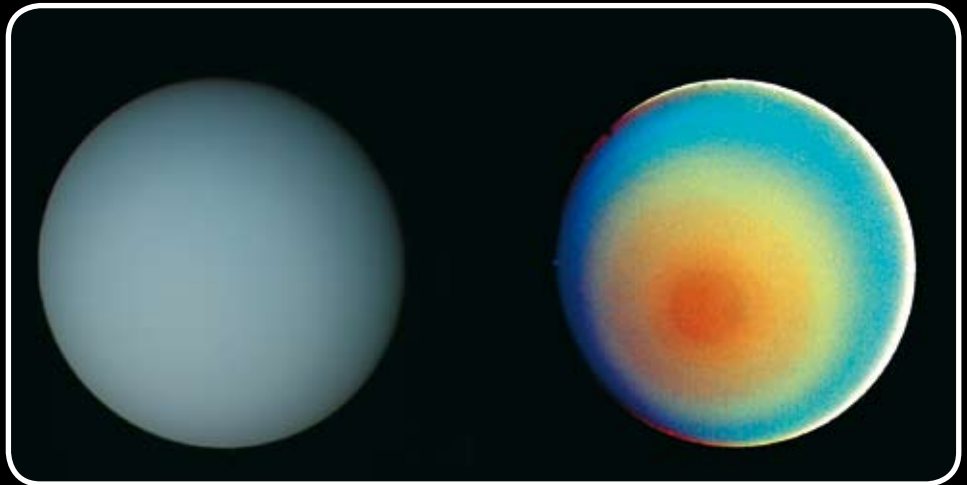


Figure 6. Uranus shown in true colours (left) and false colours (right). © NASA/JPL

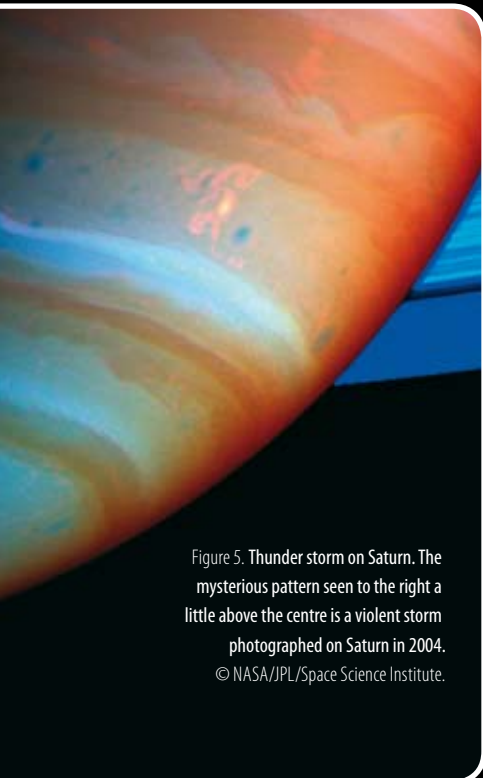


Figure 5. Thunder storm on Saturn. The mysterious pattern seen to the right a little above the centre is a violent storm photographed on Saturn in 2004.  
© NASA/JPL/Space Science Institute.



Figure 7. Uranus © NASA/JPL

## Neptun

Neptune is only slightly smaller than Uranus and is very similar to Uranus in structure. In contrast to Uranus, however, Neptune has a violent wind system with hurricanes and wind speeds reaching more than 330 m/s. In contrast to the wind systems on Jupiter it looks as if Neptune has much more rapidly changeable wind dynamics. The atmosphere on Neptune consists primarily of hydrogen, helium and methane. As with the other gas giants, Neptune has also a ring system, consisting of 10 rings.

Figure 8. The ice giant Neptune. The dark spot in the middle of the picture is a hurricane photographed by Voyager 2 in 1989. When the Hubble Space telescope took new pictures of Neptune in 1997, the dark spot had gone.  
© NASA/JPL

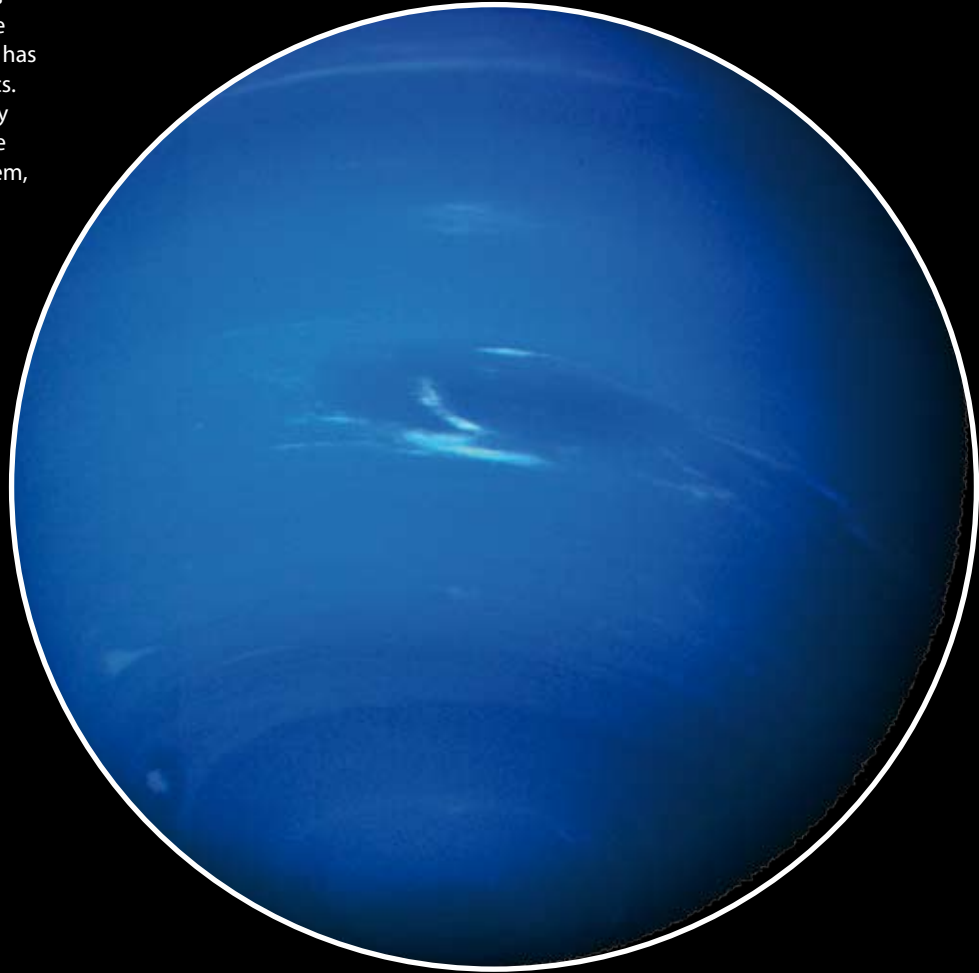


Figure 9. Cloud system on Neptune. © NASA/JPL

## Pluto

Pluto is the smallest planet in the Solar System with a diameter of only 2/3 of the Moon. It was discovered in 1930 and if we had discovered it today, with the knowledge we have now of the Solar System, it would probably not have been classified as a planet, but just an ice body belonging to the inner part of the Kuiper Belt, which also delivers some of the Solar System's comets. Pluto is often considered a twin planet system together with its largest moon, Charon, because Charon is approximately half the size of Pluto.



Figure 10. Pluto and its largest moon Charon.

© Dr. R. Albrecht, ESA/ESO Space Telescope European Coordinating Facility; NASA.

# The moons of the Solar System

By Christine Marwil

(2.8)

Since the beginning of time man has been fascinated by our own Moon. What really is that shining disc, that changes its form and position night after night? How big is it? How far away is it and how and when did it first appear? Most people have probably at some point in their lives stopped and looked at the full moon, wondering what it would be like to walk on its surface. We have come far in the understanding of our mysterious Moon, but even after the Apollo missions to the Moon, there are still many things we simply do not understand. Missions to the other planets in the Solar System have now shown us that the moons of the other planets are just as mysterious as our own Moon; we have only just begun to understand how these too were created.

The Earth is certainly not the only body in the Solar System that has a moon. Actually most planets in the Solar System have several moons and we have even observed several moons around the asteroids in the Asteroid Belt.

The moons of the Solar System are incredibly diverse; actually they are as different from each other as the planets in the Solar System. Some have almost circular orbits around their planets whereas others have more irregular or elongated orbits. Some are large, whereas others are small; and some have active volcanoes, whereas others have been inactive for billions of years. There are moons with different types of ice ( $\text{H}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{N}_2$  and  $\text{CO}_2$ ), and moons that are completely barren. Moons that have been captured by their planet and moons that were created together with their planets. There are moons that some time in the future will collide with their planet, whereas other moons will slowly increase their distance from their planet. Our own moon is drifting away from Earth by a couple of cm every year. In the following chapter we will mention some of the more interesting moons from the Solar System.

## The earth's Moon

In relation to other planets and their moons, our moon is very large compared to the Earth. It is very special in the inner Solar System as here, there are no other moons of that magnitude. It is also the only moon in the inner Solar System that was formed together with its planet. When looking at the Moon with the naked eye, the surface consisting of light and dark areas is visible. The light areas are the ancient crust of the Moon, consisting primarily of the mineral anorthite. The dark areas are volcanic deposits, called Mare basalt. They are similar to the basalts we find on Earth. The Mare basalts are from volcanoes on the Moon that were active until around 3 billion years ago.

Basaltic lava from the volcanoes filled up some of the enormous crater structures and formed what we today call Mare. Previously the dark areas were thought to be large oceans and hence the Latin name for sea, mare.





Figure 1. The Earth's Moon. In the picture the difference between the old light crust and the dark basaltic rock that has filled some of the large craters on the Moon, is clearly visible. © NASA/JPL

## Mars' moons Phobos and Deimos

These two small moons orbit the equator of Mars. Their composition is completely different from Mars' which is why we think they were not formed together with the planet. We also know that the orbits of Phobos and Deimos are unstable and that in the not too distant future they will collide with Mars. Phobos and Deimos were probably former asteroids that were captured by Mars' gravitational field. It is not unlikely that Mars may have captured asteroids, as it is on the edge of the Asteroid Belt.



Figure 2. Mars' two small moons, Phobos (bottom) and Deimos (top). The pictures show the irregular shapes of the moons and their impact craters. © NASA/JPL

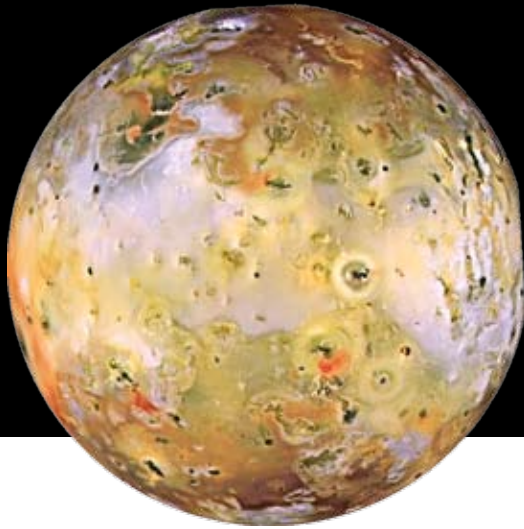


Figure 3. Jupiter's moon, Io. The picture is from NASA's Galileo mission. © NASA/JPL

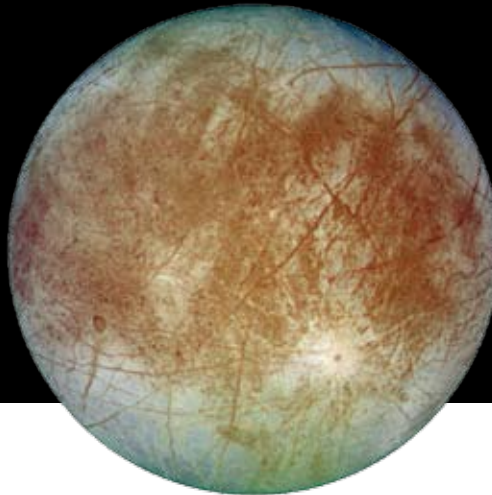


Figure 5. Jupiter's moon, Europa in true and enhanced colours. In the south-eastern part Europa's Pwyll crater is visible. © NASA/JPL

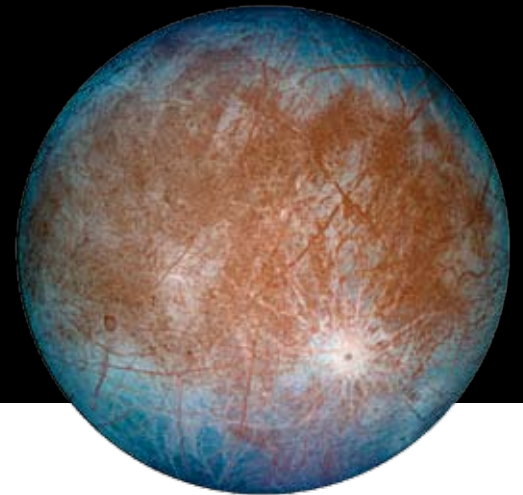


Figure 6. A close-up of the ice that covers the surface of Europa. It is evident that ice floes have been broken up and moved in relation to each other. © NASA/JPL

## Jupiter's moons

The four large moons of Jupiter were discovered on January 7, 1610 by Galileo Galilei. To his great surprise, next night, when Galilei looked at the newly discovered moons again he observed that they had moved compared with the night before. Galilei had thus for the first time observed something that, contrary to ecclesiastical wisdom, did not actually move around the Earth. If you look at Jupiter through ordinary binoculars, some of the four largest moons are easily spotted. Because of in particular Io's short period of revolution, you can, just as Galilei did, hour by hour, see that it is moving in relation to Jupiter.

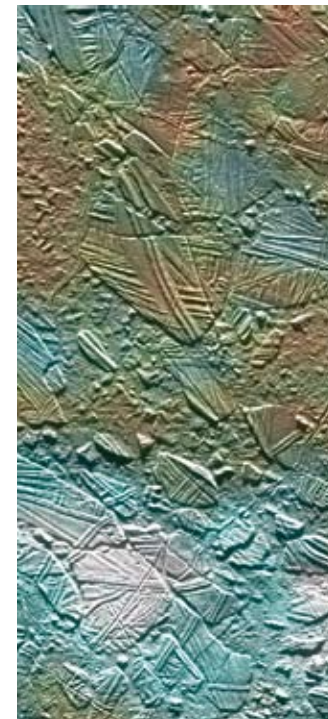
### Jupiter's moon Io

Io is the most volcanically active body in the entire Solar System. It is only a little larger than our own moon, but because of the strong tidal forces from Jupiter, enough heat is generated in its interior to keep Io molten. The heat production is in fact caused by the deformation of Io's interior when during its 19-hour orbit it alters its distance to Jupiter. The deformation produces enough heat to melt the interior of the moon. The melting generates vigorous volcanic activity, at times creating lava fountains several hundred kilometres high, that can be seen from space.

Io has a very dramatic landscape. For example, the mountains are up to 16 km high. In comparison the highest mountain on Earth, Mount Everest, is "only" some 9 km high. There are also depression craters of up to 2 km depth and up to 200 km across. So far 61 active volcanoes have been located on Io. Because of violent volcanism, the moon's surface is constantly being covered with new lava. Thus, no impact craters have been observed on Io.



Figure 4. Jupiter's moon Io. On the picture an approximately 100 km high lava fountain is visible, photographed by NASA's Galileo space probe. © NASA/JPL



### Jupiter's moon Europa

Europa is the smallest of the four large, classic moons of Jupiter, but is nevertheless very interesting. It appears that hidden under Europa's ice-covered surface, there is a 100 km deep ocean. The question is whether there could be life forms deep under the surface of Europa, associated with this water.



Figure 7. Jupiter's ice moon, Callisto © NASA/JPL



Figure 8. Jupiter's largest moon, Ganymede.  
© NASA/JPL

## Jupiter's moon Ganymede

Ganymede is the largest moon in the Solar System; it is even larger than the planet Mercury. Enormous rifts are seen on parts of the surface of this moon. These are due to extensive tectonic activity, i.e. parts of the moon's crust have moved in relation to each other. This phenomenon is similar to continental drift on Earth. Another part of the surface is filled with impact craters, thus we know that this part of the surface is much older and has been exposed to meteor impacts for a much longer time.

## Jupiter's moon Callisto

This moon is the third largest in the Solar System and almost as large as Mercury. It has an inner core of rock material, but most of this moon is ice. Of all the satellites in the Solar System, Callisto has the most heavily cratered surface. This tells us that Callisto has the oldest and most inactive surface we know in the Solar System. Apparently there have been no changes in this moon's surface during the last 4 billion years.

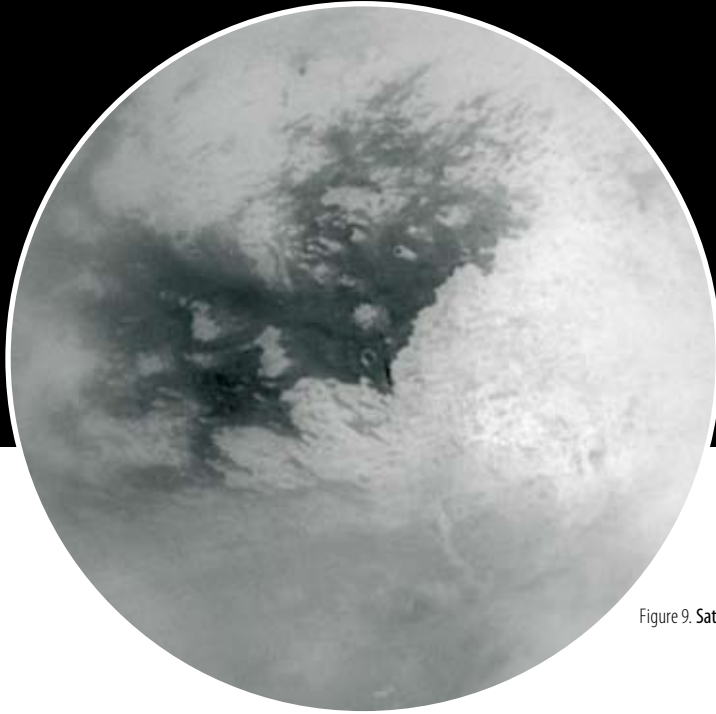


Figure 9. Saturn's moon, Titan. © NASA/JPL

## Saturn's moon Titan

Titan is the largest of Saturn's moons. It is the only large moon in orbit around Saturn, and is almost four times the size of the second largest moon, Iapetus. This moon has a nitrogen-rich atmosphere that is denser than Earth's, and has possibly liquid ethane, methane and nitrogen on the surface. These materials are found as gases on Earth, but because of the low temperature on Titan they are in fact liquid. The occurrence of methane is particularly mysterious. As methane is broken down in the atmosphere, this suggests that there are processes on Titan that produce or release liquid methane.

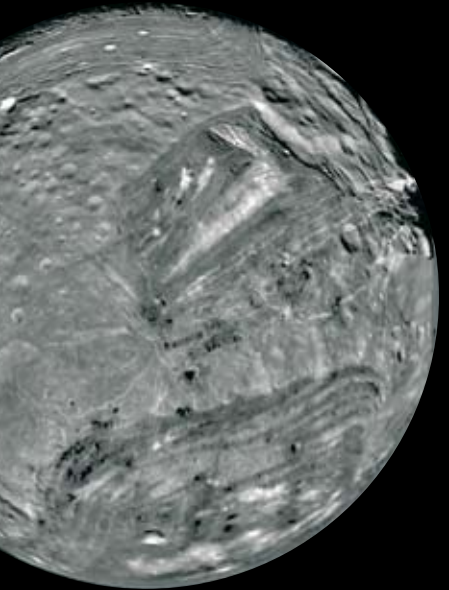


Figure 11. Uranus' moon Miranda. The shapes on the surface suggest that Miranda's surface has suffered a complex history during its formation. © NASA/JPL



Figure 10. The first picture of Titan's surface, taken by ESA's Huygens probe, which landed on Titan in 2005. © NASA/JPL

## Saturn's moons Janus and Epimetheus

These two moons have almost the same mass and an identical orbit around Saturn, very close to Saturn's ring system. The two moons have the lowest density of all the moons, actually their density is so low that it is less than that of H<sub>2</sub>O ice. A possible explanation is that the two moons were crushed and each are now only loosely cemented together.

## Uranus' moon Miranda

Miranda is a small moon, smaller than the asteroid Vesta. Yet its surface shows that the formation of the moon was both dramatic and complex. Since it is smaller than Uranus' other moons, but nevertheless is the one that is apparently the most molten, there must be other causes for these melts other than radioactive decay. It is thought that there are large amounts of ammonia in the interior of the moon, which may considerably depress the melting point of the moon's rocks.



Figure 12. Neptune's moon, Triton. To everyone's surprise this moon has a very varied surface. The black lines are thought to be the fallout from geysers on the surface of Triton. © JPL/USGS

## Neptune's moon Triton

Triton is the largest of all the captured moons in the Solar System. We can assume that it was captured as it orbits Neptune the "wrong" way, i.e. Neptune rotates in one direction while Triton orbits in the other direction. This body has the most circular orbit of all the bodies in the entire Solar System. Triton has a thin nitrogen-bearing atmosphere and has geysers blowing liquid nitrogen.

Figure 13. The asteroid Ida with its moon Dactyl. It was a great surprise to discover Ida's moon as asteroids were not thought to have enough gravitational pull to have an orbiting moon. © NASA/JPL

## The asteroid Ida's moon Dactyl

Dactyl was the first moon to be discovered actually orbiting an asteroid. It was spotted by the Galileo space probe in 1993 on its way to Jupiter. It is only 1.6 x 1.2 km and differences in the mineral compositions between Ida and Dactyl confirm with certainty that Dactyl is not just a piece of Ida.

Today, many moons are known to orbit asteroids.



Chapter (3)

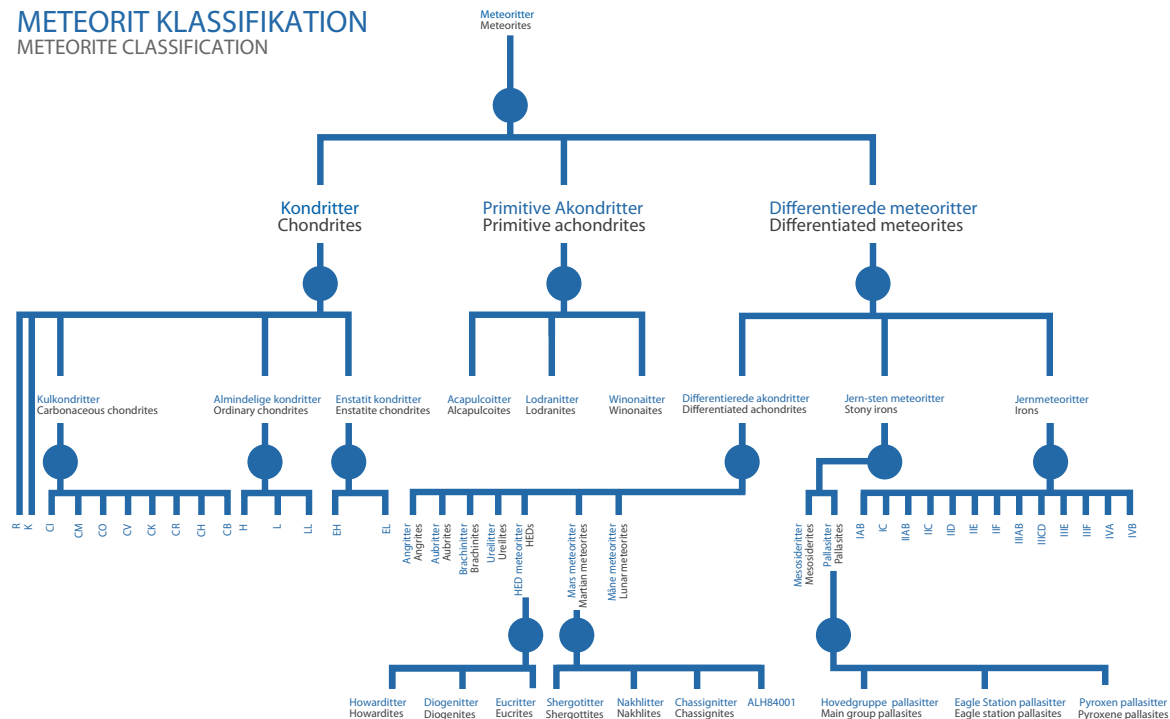
# Meteorites



# Meteorite tree

**Meteorites arrive on Earth in a completely random order and without any information about their place of origin. Therefore, the first thing we do with a new-found meteorite is to find out which type of meteorite it is – that is, if it looks like any other meteorite we already have on Earth.**

## METEORIT KLASSIFIKATION METEORITE CLASSIFICATION



By Christine Marwil

(3.1)

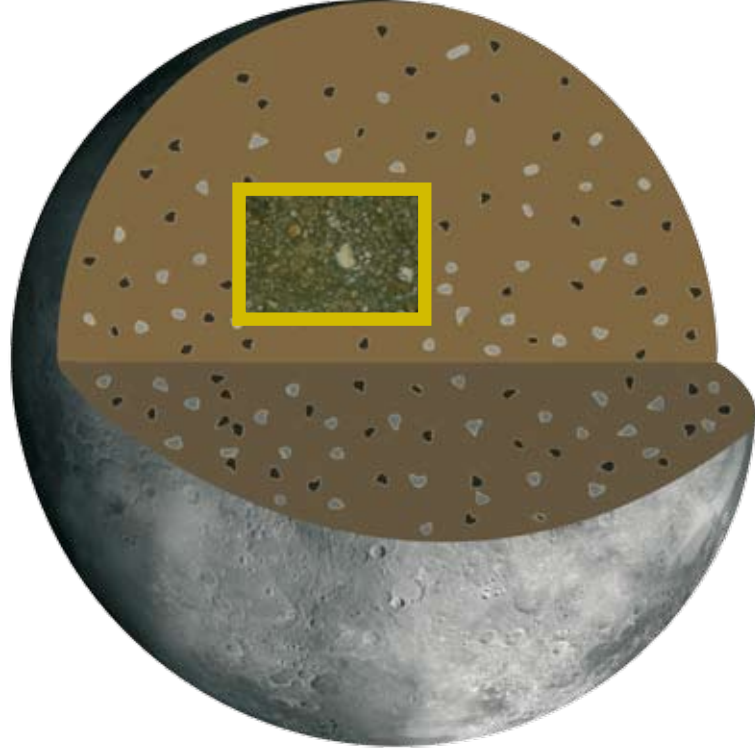
As seen from the diagram, meteorites are divided into different major and subgroups. The division is based upon the texture, chemistry, and mineralogy of the meteorites.

The three main groups are defined on whether the parent bodies of the meteorites have not undergone melting (chondrites), partial melting (primitive achondrites), or complete melting (differentiated achondrites).

Besides the groups displayed here, there are also several so-called ungrouped meteorites. Those are all the meteorites that don't fit into the already defined groups and those that have fewer than five members.

The differences in the chemical compositions of meteorites, their age and their mineralogical composition make it possible for us to determine if certain meteorites originated in the same parent body. Often we have to use several of these lines of evidence to distinguish the meteorite groups from each other. As more meteorites are found, our understanding of their relationships has changed. It is possible that with time more meteorites will be found that will help assign, to groups, the many extant meteorites that are currently difficult to classify. The diagram is therefore only an outline of currently understood relationships between meteorites.

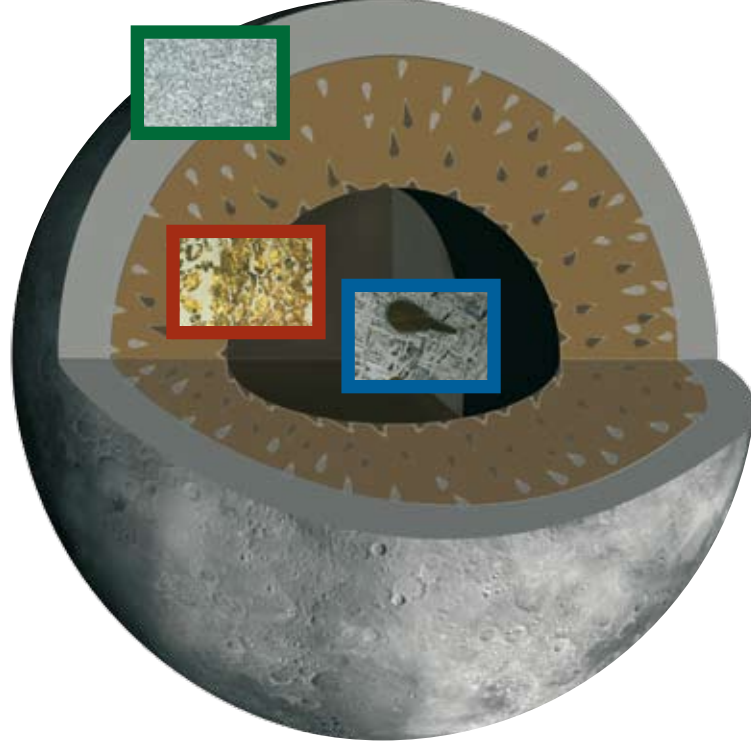
# Where do meteorites come from?



Cross section through a primitive asteroid, where dust particles, chondrules, and metallic grains have been preserved since the origin of the Solar System, 4.6 billion years ago. Chondrites are fragments from these asteroids.

 Chondrite from a primitive asteroid

 Achondrite from the crust



Cross section through a magmatic or differentiated asteroid. Within a few million years after the origin of the Solar System, these asteroids were internally melted and separated into a metallic core, a silicate mantle, and a crust.

 Pallasite from the core-mantle boundary

 Iron meteorite from the core

# Chondrites and the Oldest Preserved Matter in the Solar System

**Chondrites are sorts of time capsules that contain material dating all the way back to the origin of the Solar System, 30 million years before our own Earth was created. This is the material that the Earth and even ourselves was created from.**

Figure 1. An example of the interior of a chondrite when viewed under a microscope. In the centre a chondrule, approximately one mm in diameter, is visible. ©GM

## Our archive of the formation of our Solar System

Even though the rocks on Earth may be very old, they cannot tell us much about the actual origin of the Solar System. The oldest terrestrial rocks are “only” about 3,800 million years old, that is almost 800 million years younger than the Solar System itself. This is due to the fact that the Earth is a geologically active planet. If we want to find material dating from the origin of the Solar System, we must look for objects that are geologically unaltered since then. Chondrites are bits of primitive asteroids that have not undergone any significant geological changes since they were formed in the early Solar System; thus they contain some of the oldest and most primitive material from the Solar System.

By Christine Marwil

(3.3)

## From asteroid to meteorite

Primitive asteroids consist of primitive dust and small particles that were formed in the early Solar System, long before the planets were formed. This primitive material clotted together to form still larger objects; the largest clumps became the planets, while others ended up as asteroids which are today circling the Sun between the orbits of Mars and Jupiter. From the formation of the first dust, it took approximately 30 million years to construct the entire Earth. When primitive asteroids are hit by other bodies or are even involved in disastrous collisions with other asteroids, fragments are propelled into the Solar System and may fall on Earth in the form of meteorites. By examining chondrites we are able to say something about events that occurred in our Solar System since its creation approximately 4,570 million years ago.

## A complicated history

Chondrites are the types of meteorites that fall most often on Earth. They consist of a mixture of chondrules and calcium-aluminium-rich inclusions cemented in a fine-grained matrix.

Chondrules are mm-large spheres that were originally formed as molten droplets floating freely around the Sun. Two chondrules that today occur adjacent to each other in a chondrite, may have actually been formed a million years apart and several hundred million kilometres from each other before they accidentally were combined in the same piece of material. Calcium-aluminium-rich inclusions (CAI's) were the first formed material in the Solar System and are thus the oldest dateable material we have available. The matrix in the chondrites consists of dust particles, fragments of chondrules and CAI's, together with metallic iron. The chondrites can relate the earliest history of the Solar System much better than any other meteorites, since they are the only meteorites that have not been remelted since their initial formation.

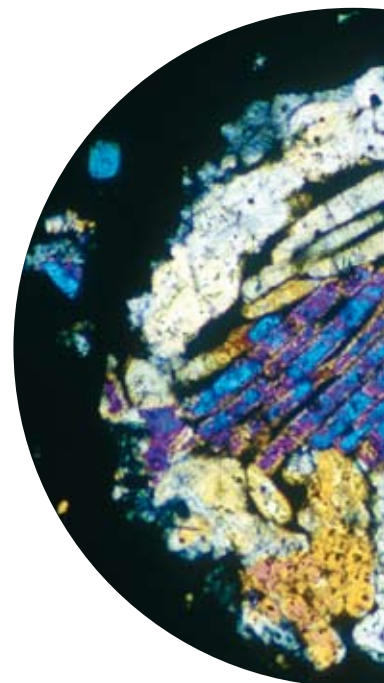
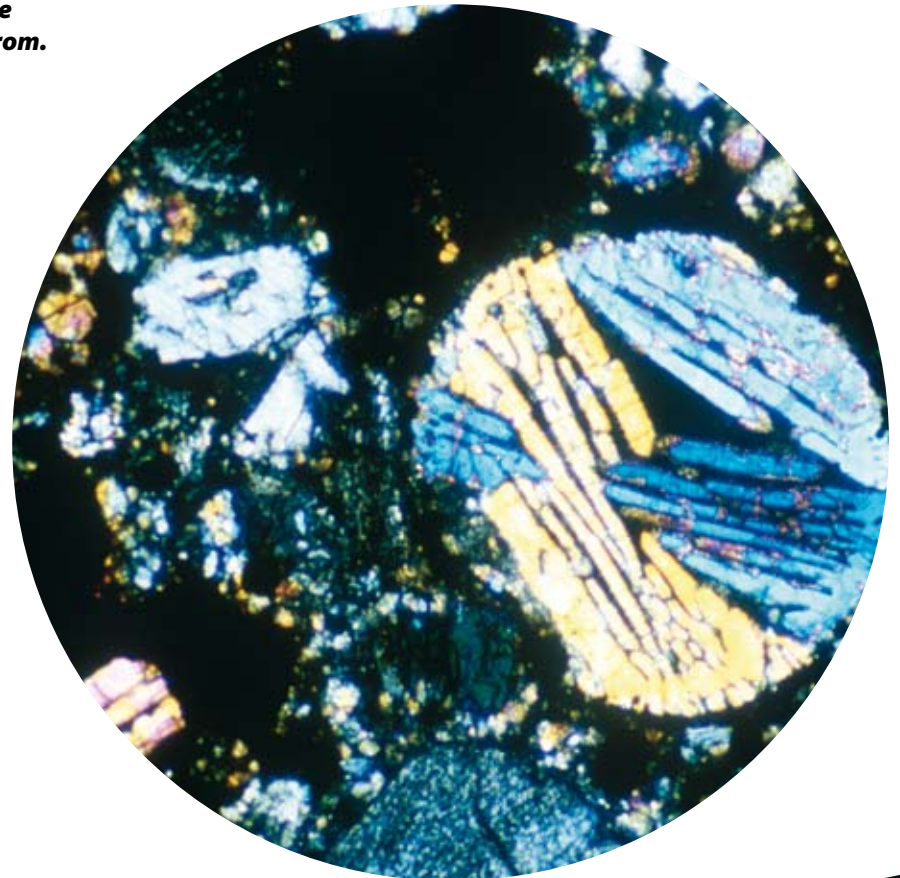




Figure 4. Close-up of the Allende meteorite. The round chondrules and the irregular CAI's are clearly visible in the fine-grained matrix. ©GM



Figure 3. The carbonaceous chondrite Allende, one of the most primitive chondrites known. This piece is one of several that can be found in the collections of the Geological Museum. ©GM/Ole Bang Bertelsen.

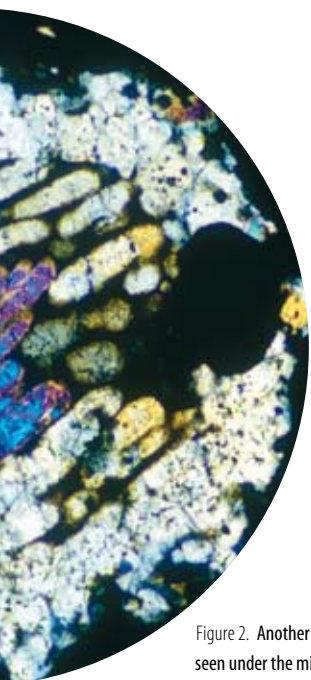


Figure 2. Another chondrule from the Allende meteorite seen under the microscope. ©GM

As the pictures demonstrate, the different types of chondrites are very diverse. Even the untrained eye can spot the difference between a metal-rich chondrite like Gujba (fig. 5), which contains up to cm-large chondrules and a metal-poor chondrite like Kainsaz (fig. 6), where the chondrules on average are no more than 0.5 mm in diameter. At the same time there are many other differences between the various types of chondrites. Some chondrites are very oxidized while others, by and large, lack oxygen entirely. Where oxygen is absent, the element iron will occur in metallic form and oxygen-poor chondrites are therefore easy to recognize by the presence of an array of shining metal grains. At the same time there is also a large differences in the oxygen isotope compositions of the various chondrites (see section on isotopes).

As all these different types of chondrites consist of dust and particles from the early Solar System, it clearly must have been very complex. We hope that in time we will be able to understand and explain these differences. There are many processes that have played a part. The young Solar System developed very quickly and it is clearly important to date the individual objects precisely to fit them into the chain of events. Simultaneously there has also been a substantial difference between conditions close to the Sun and those farther out in the Solar System, where the asteroids are today. Objects that originally were formed close to the Sun are probably different from those that formed far out. It is thought that, e.g. the CAI's were formed close to the Sun whereas the chondrules were formed at a more distant location. But since they now occur in the same meteorites, they must have been transported across the Solar System. Finally it was easier for the smallest objects to react with the gas that originally pervaded the whole Solar System. Chondrites consisting of very small objects, e.g. Kainsaz, are therefore different from those consisting of large objects, e.g. Gujba.

Chondrites with the same properties probably were derived from the same asteroid.



Figur 5. The metal-rich coarse-grained chondrite Gurbu. The slice measures 7 cm across. ©GM



Figur 6. The fine-grained and metal-poor chondrite Kainsaz. The cut surface is 10 cm wide. ©GM

## Different main types

Chondrites are divided into three main groups which are further divided into 14 subgroups and several types that are not part of these 14 groups. At least five meteorites of the same type are required to form a group. Otherwise we call them ungrouped meteorites. This applies to chondrites as well as to all the other types of meteorites. The main groups of chondrites are 1) ordinary chondrites, 2) enstatite-chondrites and 3) carbonaceous.

Chondrites are divided into these groups on the basis of their chemistry as well as the composition of their oxygen isotopes together with the relationships between the various components in the chondrites [e.g. matrix, chondrules and calcium-aluminium inclusions (CAIs)].

## Ordinary chondrites

These chondrites are, as the name implies, the most common chondrites and make up about 80% of all meteorites and 85% of all chondrites. Ordinary chondrites are subdivided into three subgroups based on their content of iron. Since ordinary chondrites are so common, one might guess that there were also many asteroids that were a source for this material. It has, however, proved difficult to find even one asteroid with the same mineral composition as the ordinary chondrites.

## Enstatite-chondrites

These chondrites make up approximately 10% of all chondrites. Between 60 and 80% of their volume consist of the mineral enstatite, which is a magnesium-rich silicate. They are divided into two groups together with one single ungrouped individual. This grouping has been based on their content of metallic iron. Enstatite-chondrites contain several minerals not known from Earth. This is because the minerals from the enstatite-chondrites were formed under extremely anoxic conditions in the early Solar System and such conditions are rare here on Earth.

## Carbonaceous chondrites

These chondrites make up the last 5% of the chondrites and are presently divided into 8 subgroups, based on their chemical composition, their mineralogy and their oxygen isotope composition.

The CI chondrites (Ivuna-type), one of the eight groups, have the same element composition as the Sun. Exceptions are the elements N, C, He and H (extremely reduced in the CI chondrites compared with the Sun) as well as the element Li which is broken down in the core of the Sun (enriched in the CI-chondrites compared with the Sun).

The Allende chondrite is a so-called CV carbon chondrite. The designation "V" comes from the first known V-type carbon chondrite, named Vigarano.

## Naming after texture

Although the chondrites are the best preserved samples of early Solar System material, they have unfortunately been slightly altered in the asteroid where they have resided for 4.5 billion years. Thus chondrites are also designated by a number, which refers to their degree of alteration. The number ranges from 1 to 6. Type 3 is the least altered of all the chondrites and they are therefore those with the best-preserved material dating back to the origin of the Solar System. A good example is the Allende meteorite, which is a CV3 type chondrite. The processes that have changed the texture of chondrites are recrystallization, because of heating in an asteroid (higher number), and alterations caused by water in the asteroid (lower number).

# Iron meteorites

**Iron meteorites look like nothing on Earth! If you are lucky enough to find an iron meteorite, you will notice at once that it is approximately twice as heavy as a normal rock of the same size. Iron meteorites are small chunks of the planetary cores of asteroids. Deep inside the Earth you will find similar material, but sadly we will never be able to see a sample. So iron meteorites are our only way to see what planetary cores look like.**

By Henning Haack

Iron meteorites are not only twice as heavy as ordinary rocks, often they are also beautifully formed after their violent journey through the Earth's atmosphere (Figure 1). If you cut through them you will see that inside they consist of one single branched crystal (Figure 2). Even the large Agpalilik slice in room 1 is a fragment of a large branched single crystal. By studying the crystal it is possible to say something about how slowly the asteroid core solidified, and thus how large the asteroid was.

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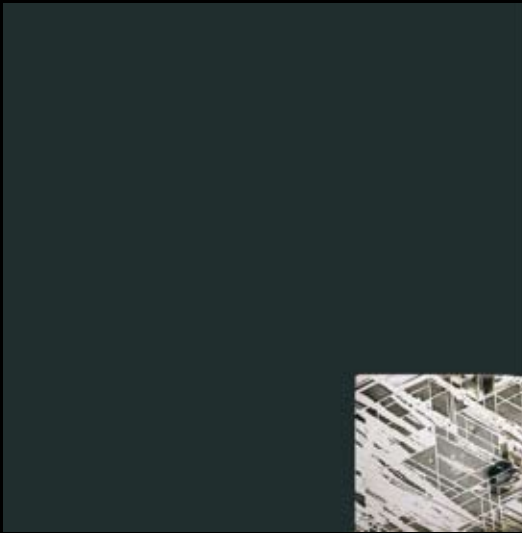


Figure 1. Fragment of the IIIAB iron meteorite Henbury. Henbury is from a very large prehistoric impact in Australia. The largest fragments were too heavy for the atmosphere to slow them down and they hit the Earth at supersonic speeds. These fragments, probably weighing several hundred tons, evaporated and formed a number of so-called explosion craters. The smaller fragments were slowed down in the atmosphere and fell as meteorites. © D. Ball Arizona State University.



Figure 2. Polished and etched slice of the iron meteorite Carbo, which can be seen in the exhibition. Carbo was found in Sonora, Mexico in 1923. The 15 cm wide slice has a very clear, coherent Widmanstätten structure, which shows that it originally solidified as a single crystal. Just as the large Agpalilik slice Carbo contains brownish inclusions of the mineral troilite (FeS). The troilite solidified from sulphur-bearing melt inclusions that remained after the surrounding metal had solidified.

© O. Johnsen, GM.



Carlton



Gibeon



Carbo

## How are the iron meteorites formed?

The presence of iron meteorites shows that molten asteroids must have existed in the early Solar System. It is only possible to create metal with the same properties as those of the iron meteorites within an asteroid's core. Take an asteroid consisting of the same material as chondrites and heat it to the melting point of metal; the metal will melt and flow to the centre of the asteroid and form a core. The same process took place within the planets, such as the Earth. The metal carries all the elements that are soluble in molten metal. These are, e.g. gold and platinum; this is the reason why both elements are so rare at the Earth's surface. It is not necessarily the heaviest elements that are concentrated in the core. Heavy elements such as uranium, lead and mercury are not soluble in metal, thus they remain in the mantle and crust of molten asteroids and planets.

For many years it has been a mystery: How were small asteroids heated to approximately 1500°C, melting and concentrating metal in the asteroid's core? The parent bodies of iron meteorites were not larger than approximately 100 km in diameter and they would have cooled quickly unless there was both a sudden and strong energy source present. It is now thought that short-lived radioactive elements caused this heating and melting. In the nebula, from which the Solar System was created, there were two short-lived radioactive isotopes of aluminium and iron present:  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  (aluminium 26 and iron 60). New analytical methods, – among others

developed at the University of Copenhagen, have shown that the two radioactive elements were present in the asteroids, from which the meteorites originated. As described in chapter 1.1  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  are formed in supernova explosions. If the material within an asteroid accreted before the radioactive elements were completely decayed, the asteroid would be exposed to internal heating and melting because of heat generated from radioactive decay. As the short-lived radioactive isotopes decay completely within a few million years, this implies that the Solar System was created shortly after one or more supernova explosions in our immediate vicinity.

## From which asteroids do the iron meteorites originate?

When you analyse the chemical composition of the iron meteorites, it is clear that many of them are similar. These iron meteorites have approximately the same chemical composition, the same type of crystal structure, and contain the same minerals. Iron meteorites that are chemically and structurally comparable are thus interpreted as originating in the same asteroid core. In this way iron meteorites may be divided into designated groups, each with a probable common origin in the same asteroid core.

The largest group of iron meteorites is called IIIAB and contains around 300 known meteorites, among these the Cape York meteorites. You can find the names of the other iron meteorite groups in the first section of this chapter. If you

look at the iron meteorites in the exhibition, you will clearly see that all IIIAB iron meteorites have the same structure, and are different from most other groups of iron meteorites.

Not all iron meteorites fall into these groups. Those that do not fit, we call unique or ungrouped. The unique iron meteorites are probably from asteroids that have not yet yielded other meteorites. By counting the number of iron meteorite groups and unique iron meteorites, we can establish that we have just under 1000 known iron meteorites derived from approximately 100 asteroids.

When we have a chunk of an asteroid's iron core in our hands, there is hardly anything left of the asteroid; it must have been destroyed some time ago. So it makes no sense to look for it in the sky. Nevertheless we can say something about from where the iron meteorites come. As described in the chapter on asteroids, we can determine the composition of their surfaces by analysing the light we receive from the asteroids. It appears that some of the asteroids have surfaces that consist mainly of metal. We have, however, no way of measuring the chemical composition of their surfaces, so we do not know if any of these metallic asteroids correspond to any of our iron meteorite groups.

## Where is the rest of the asteroid?

If we have iron meteorites from approximately 100 different asteroid cores, one might think that we should also have a lot of stony meteorites from the mantles and crusts of these asteroids.



Toluca



Old Woman

Figure 3. Comparison of the Widmanstätten pattern in five different iron meteorites: Carlton (finest octahedrite); Gibeon (fine octahedrite); Carbo (medium octahedrite); Toluca (coarse octahedrite), and Old Woman (coarsest octahedrite). All five meteorites are shown in natural size. © O. B. Berthelsen/GM.

Surprisingly it does not look as if any of the stony meteorite groups are from the same asteroid as the iron meteorite groups. Some of the pallasites, which are mentioned in the next chapter, probably are from the boundary between the core and the mantle in the IIIAB asteroid; but we do not have any pure stony meteorites from the mantle or the crust of the IIIAB asteroid. We do not know what happened to the stony material, but there is a possible explanation. We can see that the IIIAB iron meteorites have been exposed to cosmic radiation for approximately 650 million years. Thus it must have been 650 million years since the asteroid was destroyed, probably in a giant collision with another asteroid. We have never found any stony meteorites that have been exposed to cosmic radiation for so long, so clearly they cannot survive so long in space. Stony meteorites decay faster when they are bombarded with micro meteorites and there is evidence to suggest that they move more quickly into the Sun or out of the Solar System than the iron meteorites.

### How large were the asteroids?

By analysing the crystal structure of the iron meteorites we can calculate how quickly the asteroid core cooled after it had solidified approximately 4.5 billion years ago. In practice, the growth of the crystals are calculated by computer. It appears that if the core cools quickly, the crystals end up having a different structure than if it cools slowly. We then experiment with different cooling rates until the calculation gives a result that looks reasonable for that meteorite. For group IIIAB we have e.g. measured that the

core cooled by approximately 50 degrees per million years. In other words, it is not possible to make a copy of an iron meteorite in the laboratory unless one has plenty of time!

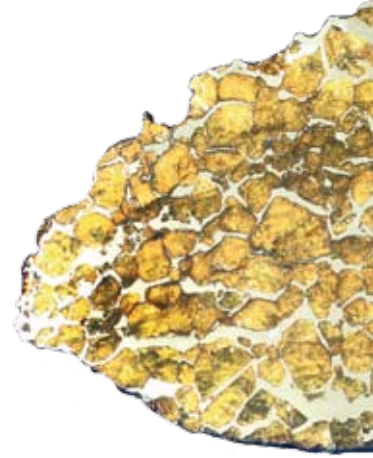
As large bodies cool slower than small bodies the cooling rate of the core can tell us how large the asteroid was originally. In the case of the IIIAB asteroid, the asteroid probably had a diameter of approximately 50 km. Even if the molten asteroids had an inner structure like the Earth's, they were certainly much smaller.

# Pallasites

**Pallasites are some of the most beautiful meteorites and those easiest to recognize. They consist of more or less equal parts of metal and silicate, the latter in the form of olivine. If you hold a thin slice of a pallasite against the light, the light will shine through the cm-large olivine crystals.**

The mixture of metal and olivine gives us a good idea about the origin of these pallasites. Olivine is a common silicate mineral, which probably dominated the lower mantle of asteroids just as metal dominated the core. So it is hard to imagine that the pallasites are from anywhere other than the border zone between core and mantle in a differentiated asteroid.

By Henning Haack



## From how many asteroids do we have pallasites?

Not all pallasites, however, are from the same asteroid. The large olivine crystals in pallasites contain oxygen. By measuring the relationship between the three stable oxygen isotopes  $^{16}\text{O}$ ,  $^{17}\text{O}$  and  $^{18}\text{O}$  we can check if two meteorites originated in the same asteroid. If an asteroid is molten, its interior will be thoroughly mixed and the oxygen isotope composition will no longer vary randomly

within the same asteroid, as is the case in some chondrites. Analyses of the relationships between the oxygen isotopes show that our pallasites are from at least three different asteroids. Besides olivine, some of the pallasites contain small amounts of another silica mineral, pyroxene. This is also typical of the pallasite on exhibit, Vermillion. These so-called pyroxene pallasites must have originated in an asteroid, where the mantle had a different chemical composition, i.e. there was not exclusively olivine at the base of the mantle.

(3.5)



Figure 1. Polished slice of the pallasite Esquel, found in Argentina in 1951. The meteorite consists of equal parts metal and amber-coloured pieces of the mineral olivine. ©GM.

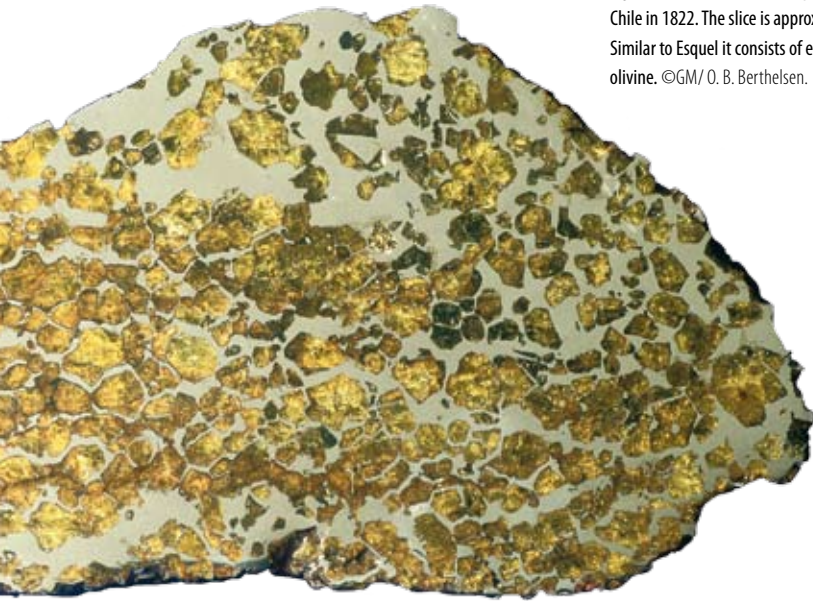


Figure 2. Polished slice of the pallasite Imilac found in Chile in 1822. The slice is approximately 30 cm wide. Similar to Esquel it consists of equal parts metal and olivine. ©GM/O. B. Berthelsen.

Even though pallasites are amongst the meteorites whose origin we understand the best, there are still things we cannot quite explain. For example, it is a little difficult to understand why they are not better divided separately into metal and silicate. The metal has a density twice that of silicate and one would think that silicate would ascend within the molten metal core forming a sharp boundary between itself and the metal. But this is obviously not the case; in most pallasites metal and silicate are found together. For example, the large pallasite slice, Imilac, is clearly layered. This suggests that silicate and metal must have been remixed while the metal solidified.

## The pallasite Krasnojarsk

Pallasites have also played a key role in the history of meteorite science. The first person to demonstrate that meteorites were visitors from outer space was Ernst Friedrich Chladni who, in 1794, published an article entitled:

*"Über den Ursprung der von Pallas Gefundenen und anderer ihr ähnlicher Eisenmassen, und Über Einige Damit in Verbindung stehende Naturscheinungen."*

(On the Origin of the Iron Masses Found By Pallas and Other Similar Bodies and Associated Natural Phenomena.)

What Pallas had found was a meteorite of the type that later would be named after him, the pallasite Krasnojarsk. One of the specimens he studied ended up in Copenhagen as the first registered meteorite in the museum's collection. It can be seen in the exhibition (Figure 3).

Before the pioneering work of Chladni,

meteorites were thought to be rocks that were either thrown out from volcanoes or whipped up in a thunder storm. Naturally scholars could simply not believe country-folk who claimed that showers of rocks could fall from a clear sky. Not until Chladni travelled through Europe studying accounts of meteorite falls and the rocks themselves, was it clear that meteorites were rocks from outer space. A new and exciting branch of science was born.



Figure 3. The pallasite Krasnojarsk found in Russia in 1749 and first studied by the German scientist Peter Pallas in 1772. As with other pallasites, the meteorite consists of metal and yellow olivine crystals. Krasnojarsk had been buried for a long time and the metal has therefore been strongly corroded. Krasnojarsk was acquired by "Universitetets Nye Natural Theater" ("The New Natural Theatre of the University") around 1800, as the first meteorite in the collection which today is part of the Geological Museum. The specimen measures 14 cm in width. © GM/G. Møller Brovad, SNM.

# Mesosiderites

By Henning Haack

## Remains of a giant collision in the early Solar System

Mesosiderites are some of the most remarkable and mysterious of all the meteorites. No matter how they are examined, the results you get are confusing. We all agree, however, on one thing: they are bits of a large asteroid that was involved in a giant collision with another asteroid shortly after the Solar System was formed. Our task is thus to reconstruct what really happened on the basis of a few erratic bits that fell on the Earth. Without having seen the collision, this is of course a difficult if not impossible task. There are various theories, but none can easily explain all the properties of the mesosiderites..

(3.6)

## The most mysterious meteorites

Mesosiderites consist of basalt from the crust of an earlier molten body, thoroughly mixed with molten metal from the core of an asteroid. We are not quite sure if the metal is from the same asteroid as the basalt. At any rate it seems strange that the mesosiderites are mixtures of materials from both the surface and the core. By and large we do not see anything of the mantle which otherwise fills most of an asteroid. The metal is extraordinary as presumably it cools the slowest of any material we know today. Parts of the metal have, similar to iron meteorites, a Widmanstätten structure (see chapter 3.4). By analysing it we can calculate that the metal cooled slower than 1 degree per million years. Not even on Earth have we rocks that have cooled so slowly. The slow cooling suggests that

the asteroid must have been large, with a radius over 100 km. The silicates on the other hand cooled rapidly, round one degree per year. This is not as strange as it seems because the silicates record the cooling rate at high temperatures while the metal records the cooling rates at very low temperatures, probably just a few hundred degrees. This indicates that when the meteorites were part of the original asteroid, it first cooled rapidly at high temperatures and then extremely slowly at low temperatures. The rapid cooling was probably related to the giant collision that involved the asteroid.

## A large asteroid

Another strange thing about the mesosiderites is that they are much younger than all other meteorites, except those from Mars and the Moon. In meteorites there is a radioactive isotope called Potassium-40. It decays slowly into Argon-40. Argon is a gas and if the asteroid is hot, the gas will quickly escape and find its way into space. By measuring the amount of Potassium-40 and Argon-40 in the mesosiderites, one can discover how long ago the mesosiderites were hot enough for Argon to escape. It appears to have been 3.9 billion years. That may seem a long time ago, but it is unusually short for a meteorite from an asteroid. Meteorites from asteroids are normally approximately 4.5 billion years old. Asteroids are much smaller than planets and have thus lost their heat quickly. Consequently





Figure 1. The mesosiderite Mincy found in Missouri, USA in 1857. It is clear that this is a crushed rock. It consists of large pieces of both basalt and metal in a matrix, mainly consisting of mm-large basalt pieces which have been mixed with metal while the metal was still molten. The specimen measures 14 cm lengthwise.

©GM/O. B. Berthelsen.

they have been geologically active only for a short time after their creation. The mesosiderites are the only ones that presumably come from an asteroid which was active much longer, thus indicating that it was unusually large.

## Two asteroids collide

There are reasons to believe that the collision that led to the formation of the mesosiderites was exceptionally violent. We assume that an asteroid with a radius of around 150 km was hit by another asteroid with a radius of at least 50 km. They probably collided with each other at speeds of around 5 km/s, the typical velocity difference between individual asteroids in the Asteroid Belt. The largest asteroid was still partially molten, at

any rate the metal in its core was completely molten. It is hard to image what would happen in such a collision. It was undoubtedly a violent collision, far greater than anything man has ever seen. It is, however, possible to calculate the course of events by means of computer models. We find that both the asteroids would have been totally crushed and that fragments probably flew out in all directions. The speed was, however, not so large, since most of the pieces were reunited within about a week. Furthermore they were reunited in a completely random order. So there is nothing strange in having the metal from the core mixed with basalt from the surface, but perhaps a little strange that we do not see any material from the mantle. On the other hand we do not know if the material we have is typical of the entire asteroid after it had been turned

inside out. It is more likely that the samples we have are not particularly typical; no-one carefully picked these pieces for us. As like everything else in meteorite science, we have to work with the bones that have accidentally been thrown at us.



Figure 1. The Geological Museum's howardite, 'Old Homestead'. ©GM/O. B. Berthelsen.

By Christine Marvil

# HED meteorites

(3.7)

## What are HED meteorites?

The HED meteorites (howardites, eucrites and diogenites) belong to a group of differentiated or achondritic meteorites, which are derived from a differentiated parent asteroid – i.e. an asteroid with a core, mantle and crust. The HED meteorites comprise the largest suite of magmatic rocks that we have from the Solar System apart from the Earth and the Moon.

Some of the eucrites are basalts and thus volcanic rocks. More than 4 billion years ago they formed as lava erupting onto the surface of an asteroid. The lava flows were at least 10 km thick and formed the crust of the parent asteroid. The remaining eucrites are more coarse-grained rocks with the same composition as basaltic eucrites. They are called cumulate eucrites.

Diogenites are coarse-grained rocks that were formed in the upper mantle of the parent asteroid. There is some uncertainty as to where exactly they formed, but a depth of at least 20-50 km is realistic. However, some of the minerals in the diogenites were formed at much greater depths.

Howardites consist of a crushed mixture of diogenites and eucrites, which presumably were

generated during repeated meteor impacts on the asteroid.

## Vesta and the HED meteorites

Howardites, eucrites and diogenites were originally divided into three different groups; but when eucrite and diogenite fragments were found within all known howardites, clearly all three groups are closely related, derived from the same parent body. The parent body is most likely the asteroid Vesta.

There are several reasons that suggest that Vesta is the source of the HED meteorites.

- The mineral composition of Vesta and the HED meteorites are identical. Moreover there is no large asteroid with the same unique composition as Vesta and the HED meteorites.
- Vesta has an average diameter of 516 km and is thus the third largest asteroid in the Asteroid Belt. A size like that of Vesta is necessary to explain the formation of the HED meteorites because some of their minerals, originating in the upper mantle of the asteroid, were formed at depths of more than 120 km.
- A related group of smaller asteroids, the Vestoids, have been found relatively close to

Vesta and have the same mineral composition. It is assumed that they were the result of a large meteor impact on Vesta and this explains how material was transported to Earth.

Figure 2. 'Hammada al Hamra 262', one of the Geological Museum's eucrites. ©GM/O. B. Berthelsen.



Figure 3. The diogenite 'Johnstown', Geological Museum. ©GM/O. B. Berthelsen.

## Age of the HED meteorites

The HED meteorites are among the oldest material in the Solar System. The eucrites are the oldest of all the HED meteorites, and the oldest eucrites are only a couple of million years younger than the calcium-aluminium rich-inclusions found in the chondrites; these are regarded as the oldest material in the Solar System with an age of 4.569 billion years.

The content of the daughter isotopes, following decay of the short-lived radioactive isotopes  $^{26}\text{Al}$ ,  $^{60}\text{Fe}$  and  $^{53}\text{Mn}$  in the HED meteorites, also shows that the parent body of the HED meteorites was formed not later than a few million years after the formation of the Solar System. The last-mentioned of the short-lived isotopes,  $^{53}\text{Mn}$ , also shows that the parent body was divided into a core, a mantle and a crust soon after its formation – between 4.564 and 4.557 billion years ago.

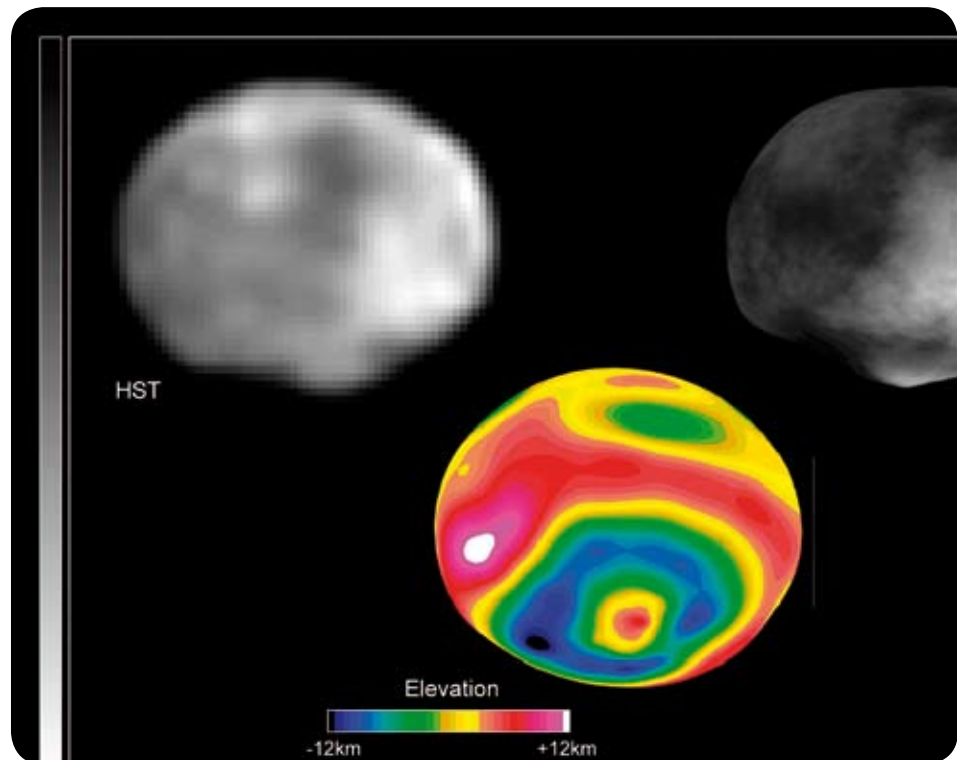


Figure 4. Hubble Space Telescope picture of Vesta. The lowest model shows a topographic map of Vesta. Here a large meteorite crater on the surface of the asteroid (blue area) is clearly displayed. ©NASA/Bent Zellner (Georgia Southern University)/Peter Thomas (Cornell University).

# Lunar meteorites

## A known parent body

Besides the meteorites from Mars and Vesta, lunar material is the only material we have from the Solar System outside our own Earth, where we know its exact place of origin. The material from the Moon consists of lunar meteorites as well as samples brought back from the Moon by American and Russian space vessels in the 1960s and 1970s. A total of almost 400 kg of material was recovered from the near side of the Moon. The lunar meteorites presumably are from both the far and near side of the Moon.

By Christine Marvill

Figure 2. An example of a brecciated meteorite from the Moon with angular clasts of varying sizes. This is one of the lunar specimens in the Geological Museum, the meteorite NWA 773. ©GM/O. Bang Berthelsen.

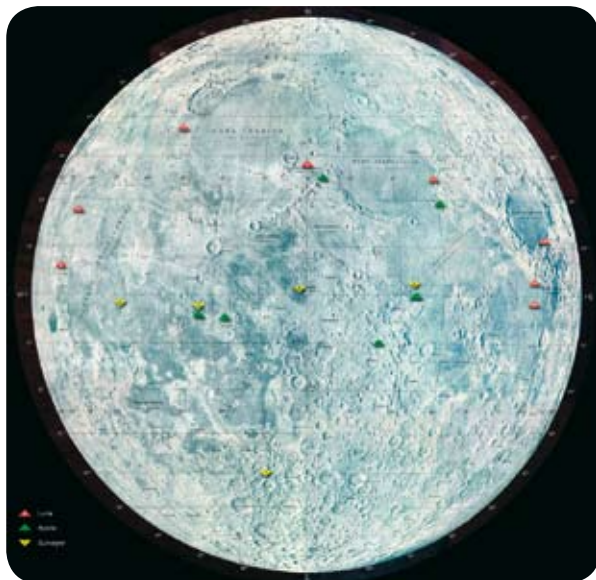
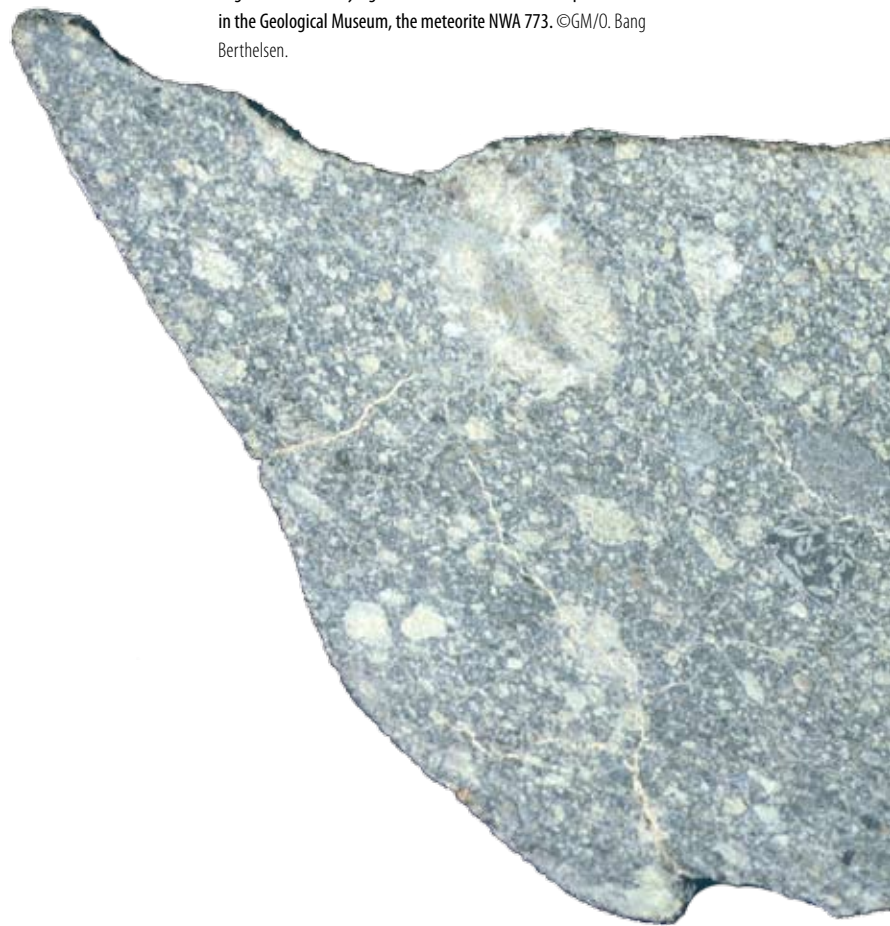


Figure 1. Map of the Moon showing the landing sites of the Luna, Apollo and Surveyor missions. ©NASA



## Rocks of the Moon

Since the Moon over time has been subjected to numerous meteor impacts and does not have a protective atmosphere like the Earth, its upper surface is completely crushed and covered by a several-metres thick layer of very fine-grained and porous material, the so-called lunar regolith. All the material brought back from the Moon is from this uppermost part of the crust. If we want to know more about the formation of the Moon and its primitive rocks, we have to examine meteorites from the Moon. These meteorites are some of the rarest meteorites of all, and only approximately 40 specimens have been found. Meteorites from the Moon generally consist of a crushed mixture (or breccia) of two main rock types:

1) The Moon's Highlands are the remains of the ancient lunar crust. They consist primarily of the pale mineral anorthite, which is a light silicate. This crust is thought to have been formed from a global ocean of magma on the Moon, where anorthite floated to the surface as it was lighter than the magma in the magma ocean.

2) Mare basalt from the large impact structures. The mare basalt received its name because it was previously assumed that there were large oceans on the Moon (Latin: mare = sea).

The two rock types can be seen with the naked eye as pale and dark areas, respectively, on the lunar surface at full moon.

As there is no water and no atmosphere on the Moon, material cannot be transported on the surface, so there are no rock types other than the igneous ones.

## Ages of the meteorites

As a starting point, there are three different ages of interest when examining meteorites: 1) their age of crystallization, 2) the time it took the meteorites to travel from their parent body to the Earth, and 3) the length of their stay on Earth.

## Crystallization of the Moon

In order to determine the time of crystallization, we use long-lived radioactive isotopes and their daughter isotopes, which have accumulated in the interior of the meteorite over time.

There is a large difference in the formation ages of the various lunar meteorites, but all were formed between 4.4 billion years and 2.7 billion years ago and are thus older than most of the rocks we know from Earth. The Highlands crystallized shortly after the formation of the moon and are 4.4 billion years old. The mare basalts are the youngest of the Moon's rocks with ages between 4.23 and 2.70 billion years. By far

the majority of these rocks were formed more than 3.9 billion years ago at a time in the history of the Solar System when there were far more meteor impacts than today.

## The meteorites journey to Earth

To determine how long the meteorites were en route, from when they were knocked off the Moon until they landed on the surface of the Earth, cosmic radiation is used. All meteorites, surfaces on asteroids and moons without atmosphere are exposed to cosmic radiation from space. By measuring the influence of cosmic radiation on the meteorites we can determine how long it has been since they were knocked off their parent body until they landed on Earth. By using this method it appears that the lunar meteorites typically have been less than 100,000 years in transit before they landed on Earth and that most of them have been travelling between 1,000 and 10,000 years. It is, in other words, still a slow process to have a lunar meteorite delivered to Earth.

## When did the meteorites fall on Earth?

Due to exposure to cosmic radiation, radioactive isotopes are formed in the meteorites on their way to Earth. After the meteorite has fallen on Earth, these isotopes slowly decay and the amount remaining can thus be used to determine when the meteorite landed on Earth. In the case of the lunar meteorites the average time on Earth has been approximately 100,000 years, but there are ages of around 140,000 years. Meteorites that have been here even longer are not known and this suggests that older meteorites may have disintegrated and disappeared, or that there is not enough ice in Antarctica, older than 100,000 years, capable of preserving them.

# Martian meteorites

**Mars is currently the object of intense research. A small armada of space probes has been sent to our neighbouring planet investigating it both from orbits high above the surface and by means of ingenious landing crafts that drive around on the planet's surface. There is, however, one thing all these missions have been unable to give us, a piece of Mars to study in a terrestrial laboratory. Although the space probes contain all kinds of advanced measuring instruments, they can in no way give results that compare to those obtained in a laboratory here on Earth. So it is hard to overrate the importance of Nature's samples from our neighbouring planet, delivered free in the form of meteorites.**



Figure 1. The shergottite Sayh al Uhaymir 005 which is one of the Martian meteorite in the collection of the Geological Museum. ©GM/O.B. Berthelsen.



Figure 2. The shergottite Zagami, which is another one of the Geological Museum's Martian meteorites. ©GM/O.B. Berthelsen.

By Christine Marvill

(3.9)

## How do we know that they are from mars?

Besides the meteorites from the Moon and the asteroid Vesta, the meteorites from Mars are the only meteorites from where we know the place of origin. The Martian meteorites are in many ways similar to the rocks we know from Earth. As material has never been brought back from Mars, they are our only source for the study of Mars' development. There are two good reasons why we are convinced that these meteorites are actually from Mars. One is that their age can be determined. As they are volcanic rocks, the age of volcanic activity can be determined. The youngest of the Martian meteorites have ages of only 170 million years. This is very young for a meteorite as they were normally formed 4,400-4,567 million years ago. This suggests that these meteorites must come from a large body that was still volcanically active 170 million years ago, i.e. they must have come from a planet. The only planets that have been volcanically active recently are Earth, Venus and Mars. As Venus and Earth can be excluded for various other reasons, we can be reasonably certain from the age data alone that they are from Mars.

Moreover, gas bubbles with the same composition as Mars' atmosphere have been found in some of the Martian meteorites of volcanic origin. As Mars' atmosphere is unique in the Solar System, it is not possible to find any place other than Mars for the origin of these meteorites.

## The SNC meteorites

The meteorites from Mars are divided into three groups: Shergottites, nakhlites and chassignites, which are jointly called the SNC meteorites. In addition one meteorite has been found, viz. ALH84001, that falls outside the above groups and which will be treated separately. All the meteorites from Mars are silica-poor and rich in iron and magnesium. In other words they are not from evolved rocks such as these here on Earth.

Shergottites are the most common of the Martian meteorites and this is also the group that has the largest variation as to both chemistry and rock type. They all have a chemical composition like basalt, but the group is made up of both volcanic rocks (basalts) and cumulates from deeper layers in the Martian subsoil (Iherzolites).

The basaltic shergottites consist primarily of the minerals clinopyroxene and plagioclase, while the shergottite cumulates primarily consist of olivine, clinopyroxene and chromite.



Figure 3. The photograph shows the Martian meteorite ALH84001, which was part of Mars' proto-crust. ©NASA

Chassigny after which this group was named.

## ALH84001

ALH84001 is the only Martian meteorite that was a part of the ancient crust of Mars (approximately 4.5 billion years old). All other meteorites from Mars are chunks of rocks that are younger than 1,300 million years. It was found in Antarctica and it has since been the centre of a heated debate as some scientist at one time thought that they had found traces of life in it. This theory has been abandoned by most people since. But it is still very interesting if we want to understand the processes in the early history of Mars. Why are there not more specimens of the very old crust? How was the part of the crust preserved, from where ALH84001 originated?

ALH84001 consists of 96% of the mineral orthopyroxene as well as very little chromite and plagioclase; it is hence called an orthopyroxenite.



Figure 4. Geological Museum's nahklite, Nahkla, which is the meteorite that has given this group its name. ©GM/O.B. Berthelsen.

Nahklites are cumulates, but they have different mineralogical composition and consist of approximately 80% augite (pyroxene) and 5-10% olivine.

Chassignites consist of up to 90% iron-rich olivine and are very similar to terrestrial mantle rocks. Melt inclusions in olivine contain the water-bearing mineral amphibole and this tells us that the rock was formed under conditions where relatively high amounts of oxygen were present in Mars' mantle. This meteorite type is the rarest of all the Martian meteorites and until a few years ago only one specimen had been found on Earth,

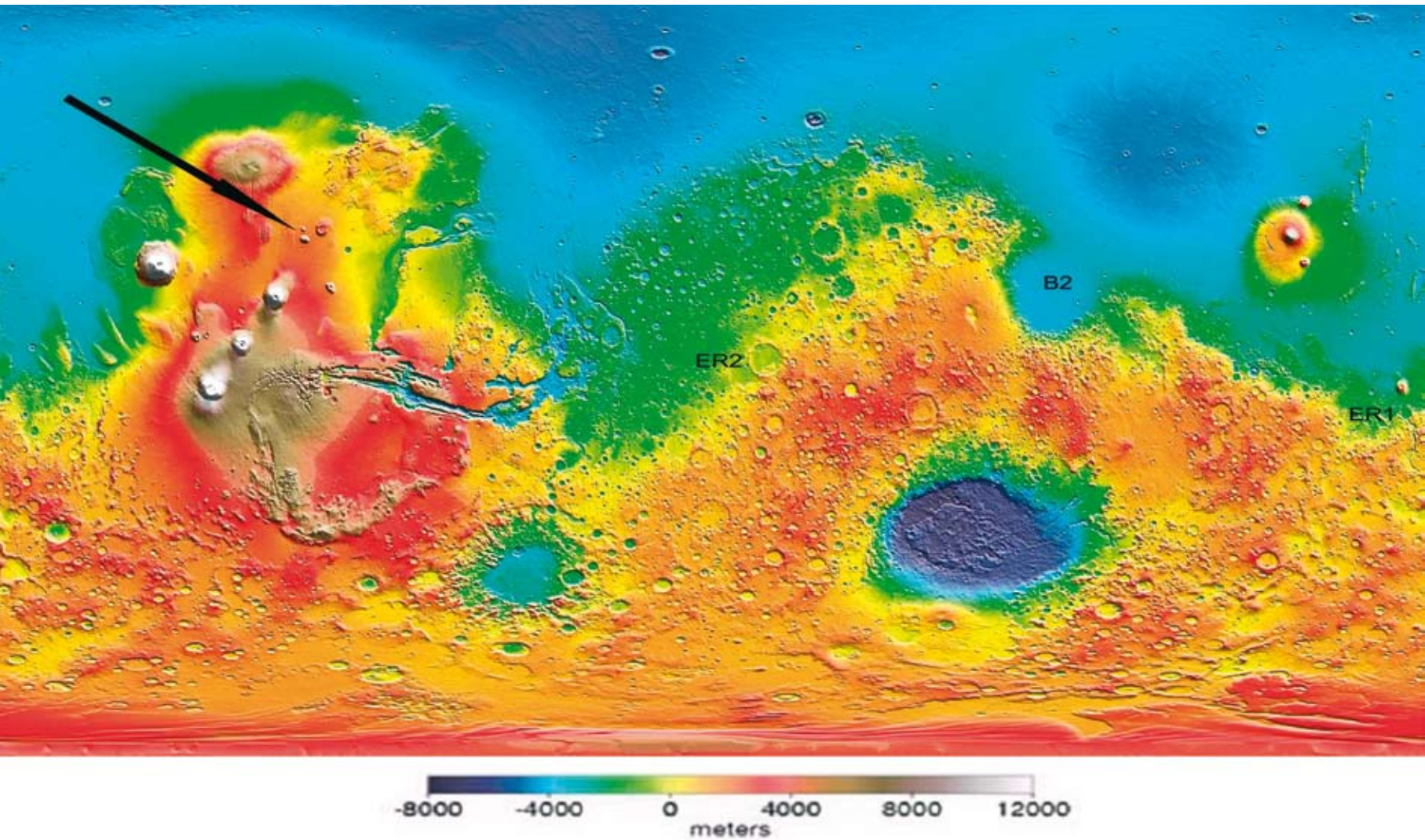


Figure 5. Contour map of Mars based on the so-called MOLA data (Mars Orbiter Laser Altimeter). The three landing sites of the European Beagle 2 (B2) which probably landed on Boxing Day 2003 and NASA's two Exploration Rovers: Spirit (ER1) and Opportunity (ER2), which landed on January 3 and 24, 2004, respectively, are marked. The black arrow marks the two volcanoes that are seen in the picture below. ©MOLA Science Team.

## Ages of the Martian meteorites

As mentioned in the dating chapter, there are different ways to date meteorites. When we want to look at the age of the solidification of the minerals, we use the decay of radioactive elements in the mineral to determine the age. The shergottites, which are the youngest rocks we have from Mars, have crystallization ages of approximately 170-180 million years. In this way we can say that Mars was hot enough internally to have volcanic activity at this time. Nakhrites and chassignites have ages of approximately 1.3 billion years. They were formed deeper in Mars' crust and together with the other Martian meteorites they indicate that Mars, just like Earth, experienced magmatic activity at several different times in its history. As previously mentioned, ALH84001 is approximately 4.5 billion years old.

Except for ALH84001 all the Martian meteorites are too young to have come from an asteroid; the asteroids are not large enough to have retained the inner heat necessary to melt magma so late in the history of the Solar System.

## How did they end up here?

While in space, meteorites are exposed to cosmic radiation and by measuring the amount of this radiation, it is possible to determine how long they have been travelling since they were knocked off their parent body. These ages show us that there were at least three impact events on Mars, which supplied Earth with Martian meteorites.

The reason that pieces of Mars fall on Earth is because Mars, like Earth, occasionally is hit by an asteroid. This happens more often to Mars than to the Earth as Mars sits on the edge of the Asteroid Belt between Mars and Jupiter. When such an asteroid hits Mars, a large crater is formed and small pieces of the surface may be thrown up through the thin atmosphere and free of the gravitational field.

These pieces will then move around the Solar System for millions of years. It has been calculated that approximately one fourth of these ejected meteorites will eventually find their way to Earth, where we may be lucky enough to find them.

If we know that the meteorite is actually from a crater on Mars and we have photographs of



Mars' entire surface with all its craters, is it then possible to locate the crater it comes from? Actually it is possible to nominate a specific crater on Mars' northern hemisphere, where several of the Martian meteorites may have originated. This particular crater is in an area of recent volcanic activity, which is confirmed by the very few meteor craters in the area. This may be due to the fact that the craters from previous meteor impacts have been covered by lava, thus only the most recent ones are now visible. The picture shows an unusual crater on Mars' northern hemisphere which meets all our requirements as to age and local geology. At the same time the crater is very unusual by being elongated. Elongated craters are formed when an asteroid hits the surface at a very low angle (i.e. it almost grazes the surface). Only such impacts are thought to be capable of knocking off pieces of Mars and releasing them free of Mars' gravitational field.

### Planet formation in the early Solar System

The Martian meteorites are important for several reasons. First of all it is the only material available from another planet other than Earth. This gives us a unique chance to test our theories for the geological development of Earth on another planet. One Martian meteorite is particularly interesting in this connection. It is ALH84001 (Allan Hills 84 001). ALH84001 has a crystallization age of 4,500 million years. That is, it is more than 500 million years older than the oldest known rocks from Earth, a little surprising when considering the care that has been taken in locating and investigating the oldest rocks here on Earth. It was quite unexpected that an erratic chunk of Mars could beat records for the oldest known rocks on Earth by more than 500 million years! ALH84001 thus gives us a unique opportunity to study Mars' early development. We can, sadly, only speculate about the corresponding phase of our own Earth's development.

Figure 6. The elongated meteor crater in the centre of the picture may have originated from the impact that sent Geological Museum's Martian meteorite Sayh al Uhaymir 051 on its trip to Earth. It lies between the volcanoes Ceraunius Tholus (southernmost) and Uranius Tholus. With a diameter of 60 km Ceranius Tholus is one of Mars' smaller volcanoes. The impact crater itself measures approximately 18 km lengthwise. ©NASA/JPL/MSSS.

# How to recognize a meteorite

By Henning Haack

(3•10)

If you have read the previous chapters about the various types of meteorites, then you have considerably increased your chances of recognizing a meteorite, if one day you should be lucky enough to stumble over one in the countryside. Approximately three meteorites a year fall in Denmark; but around 100 years pass between each time a freshly fallen meteorite is reported in Denmark. The main reason that so many meteorites are never found is that most people who happen to see them simply do not know what they are looking at; or maybe they just do not notice them at all. If more people knew what meteorites actually look like, many more will be reported and we would thus learn more about the Solar System.

As we have seen in the previous chapters, meteorites can look very different. So it is not possible to give any simple instructions about how to recognize them. Moreover there is a large difference between the appearances of freshly fallen meteorites and those that fell some time ago.

There are, however, some general features to watch out for. Most meteorites will have some of the following characteristics:

- Black fusion crust
- Rounded shapes
- Attracted to magnets
- High specific gravity
- No bubbles or gas vesicles

There are, however, also many meteorites that lack one or more or maybe all of the above characteristics. So one has to be careful not to exclude anything on the absence of one or more

of these criteria. If in doubt the specimen should be taken to the Geological Museum or one of the other natural history museums. A list of natural history museums in Denmark can be found on the Geological Museum's website.

Many specimens are brought in because a fireball was seen disappearing behind a nearby tree or a similar such object. If you then find an unusual stone behind the tree next day, you may naturally think that you have found the meteorite. Unfortunately this is never the case. If you have seen the fireball, you are undoubtedly nowhere near the site of impact. If you want to know more about fireballs, read the chapter on meteorite impacts.

Figur 1. The iron meteorite Sikhote Alin, which fell near Sikhote Alin, Siberia on February 12th, 1947. The meteorite measures approximately 10 cm across.  
©G. Brovad, SNM.



Figure 2. The picture shows an ordinary chondrite, Modoc, which fell on September 2nd, 1905 in Kansas, USA.  
©G. Brovad, SNM.



## Iron meteorites

Iron meteorites are the easiest to recognize because their specific gravity of 8-9 g/cm<sup>3</sup> makes them more than twice as heavy as ordinary stones. Freshly fallen iron meteorites have a characteristic granulated, surface structure with cm-sized soft depressions and knobs. Iron meteorites that survived some time on Earth will eventually be totally corroded by rust and can be difficult to recognize.



## Stony meteorites

A freshly fallen stony meteorite is relatively easy to recognize because of its normally black fusion crust. Mars and Moon meteorites have, however, often a brownish fusion crust. The fusion crust is formed when the main part of the meteorite burns up during its passage through Earth's atmosphere. The fusion crust is up to 1 mm thick, sharply separated from the inner part of the meteorite and completely lacking crystals. This lack of crystals can often be used to immediately distinguish a meteorite from a typical terrestrial rock. Some terrestrial rocks can react with their surroundings and form a dark or black layer on the surface. It is, however, rarely sharply divided from the inner part of the stone and will often contain various fragments. If you have found a rock with something that looks like a fusion crust, it is a good idea to look further at the crust under a magnifying glass or a microscope.

The inner parts of the meteorite are not heated during short periods of de-acceleration in the atmosphere. If some of the crust is knocked off on impact the inner part of the meteorite will appear light grey to almost black. Commonly

small metal grains and mm-sized round chondrules are seen (as described in the chapter on chondrites). Because of their metal content, most meteorites will be attracted to a magnet. As terrestrial rocks very rarely are metallic, a magnet is useful to have available when testing if a rock might be a meteorite. However, you must be aware that there are also meteorites lacking metallic content, such as the very interesting meteorites from the Moon and Mars.

Ordinary chondrites are, as the name implies, the most common type of meteorites. They make up approximately 85% of all meteorite falls on Earth. They have visible metal grains in their interior and are thus also attracted to a magnet. Unless they are completely fresh, the metal grains will be more or less rusty. The fusion crust is a dull black and has often cracked during cooling.

## Rocks that are often mistaken for meteorites

Slags and cinders from refuse disposal plants and various industrial melting processes have often a black burnt surface and may contain metal. They are often mistaken for meteorites. Slags may, however, be distinguished from meteorites because of their content of gas bubbles and vesicles and sometimes also because of their content of effects of terrestrial origin. Gas bubbles are very rare in meteorites, thus rocks with many gas bubbles are almost certainly not meteorites. Chunks of lava are also often mistaken for meteorites. They may, however, also be distinguished from meteorites because they usually contain gas bubbles. Among the rocks and minerals that are mistaken for meteorites, pyrite concretions are commonly confused with meteoritic material. Pyrite concretions normally occur in chalk and may weigh several kilos. Its specific gravity is around 6 g/cm<sup>3</sup>, which make many people think that they may

have discovered an iron meteorite. However, pyrite is completely non-magnetic and one can easily test whether it could be a metal-bearing meteorite or a pyrite concretion with a magnet. Pyrite concretions also have a very characteristic botriodal surface, which looks a little like a cauliflower.

## **WHAT TO DO IF YOU THINK YOU HAVE FOUND A METEORITE IN DENMARK**

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First of all it is important that you have an expert examine the specimen if you think it could be a meteorite.

Although meteorites are few and far between, the discoveries that are brought to the Geological Museum are always assessed and, of course, we are always pleased when people make contact if there is the least chance that a new meteorite has been found. You may send the specimen to the [Geological Museum in Copenhagen](#) or perhaps to one of the other natural history museums in Denmark.

Please enclose information about the place of discovery and the time as well as your name, address and telephone number. Write why you think it might be a meteorite. Are there any circumstances about the find that make you think that something has dropped from the sky or do you think that the rock just looks like a meteorite?

Please do not cut or otherwise deface the specimen or make any attempt to clean it.

We will then examine the material and as far as possible discover exactly what you have found, even if it is not a meteorite. If it turns out to be a meteorite, the specimen will automatically be declared Danekræ. This means that it must be handed over to the Danish State.

The finder will, however, get a reward, the size of which will be determined by the State's Danekræ Committee. If it is not Danekræ, the find will be returned with a short description and explanation.

# Where does one find meteorites?

**There are many meteorites in the Danish countryside that are just waiting to be found.**

**Unfortunately they are very difficult to find – even though I am always looking I have never found any here in Denmark – and the same is true for a lot of other people. The four meteorites that have been found in the southern part of Denmark have been found either because someone saw them fall (Mern and Aarhus) or because they turned up when the ground was dug (Jerslev and Feldsted). So even though we assume that approximately three meteorites fall in Denmark every year, there is not much chance of finding any of them. However, I hope you will continue to look when you walk around in the countryside – if we all did that, many more meteorites could be found.**

By Henning Haack

## Wherever do we find them?

Meteorites fall almost evenly all over the globe – but they are easier to find in some places than in others. We will hardly see the meteorites again that fall in the oceans, and there is not much chance either of finding the ones that fall in areas with dense vegetation. It happens that meteorites fall in densely populated areas and here we must assume that by and large all material will be found. An example of the latter is the Park Forest meteorite shower that hit a suburb in Chicago on March 27, 2003. In the days after the fall meteorites were found in parking lots, and in highways and byways. Several fragments had gone through roofs and windows. Luckily no animals or humans were hit. The very best place to find meteorites is, however, so far from civilization as one can get – Antarctica. Here there is no vegetation to hide the meteorites and Nature herself helps us gather the meteorites.

## Hunting meteorites in Antarctica

Antarctica has proved to be the best place on Earth to find meteorites. In 1974 a group of Japanese glaciologists found by chance a fistful of meteorites on the ice of Antarctica. Great was the surprise after analysis when it turned out that they came from five different meteorite falls. They had not stumbled upon a single shower of meteorite fragments. There was no other explanation but that the ice in some way or other had gathered the meteorites. Since the first discovery around 30,000

meteorites have been found in Antarctica. Every season an American expedition with voluntary meteorite researchers is sent off to find meteorites in Antarctica. Typically they bring back around 500-1,000 meteorites after 5-6 weeks of field work on the ice.

There are several reasons for so many meteorites being found in Antarctica. First of all Antarctica is a very large continent. So many meteorites fall every year in Antarctica. When the meteorites have fallen, they are covered with snow and flow slowly with the ice towards the coasts. On its way towards the coast much of the ice is going through The Transantarctic Mountains. Most of the ice glides through the mountain range in some of the largest glaciers on Earth, but some of the ice is stranded on the front of the mountains. A cold and bone dry, so-called katabatic wind

from the central part of Antarctica then sweeps the stranded ice clear of snow, so the ice is laid bare.

The ice has a wonderful blue colour and the areas are therefore called blue ice areas. Because the air is so dry and the wind is blowing incessantly, the ice also evaporates. Although it never thaws, approximately 20 cm of ice disappears every year. As the meteorites do not evaporate, they are left on the surface as it evaporates.

Another great advantage of looking for meteorites in Antarctica is that it is very easy to spot a black meteorite on a glittering ice cover. Small meteorites are easily seen from a distance of 50-100 m, so it is possible to search very large

Figure 1. Cross-section of The Transantarctic Mountains. The ice is flowing from left and is blocked by the mountains. The stranded ice on the front of the mountains is swept clear of snow by the wind and will slowly evaporate laying its contents of meteorites bare. ©GM

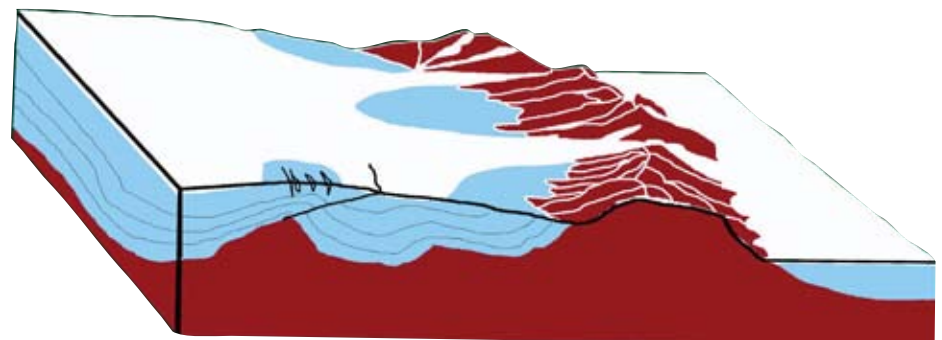




Figure 2. A newly discovered meteorite on the ice. ©GM

areas from a snow mobile. Finally Antarctica is also a good place to store meteorites – the ones we find today have typically been lying in the ice for 100,000 years – and still look like newly fallen meteorites.

There have been several voluntary Danes in Antarctica over the years. I myself was there during the 1999-2000 season. If you want to be a meteorite researcher, you may also get the opportunity to go to the most inaccessible continent on Earth.

## Meteorites on the Greenland ice sheet?

As so many meteorites have been found in Antarctica, could one imagine that there would also be meteorite concentrations on the second largest ice cap in the world – the Greenland Ice Sheet? As in Antarctica we have found blue ice areas at great heights in North Eastern Greenland. In August 2003 we searched the most promising blue ice areas, but unfortunately we did not find any meteorites at all.

The explanation might be that although it is also very cold and windy on the ice sheet in North East Greenland there are also quiet summer days with sun when the temperature sneaks above the freezing point. When the sun is shining on dark rocks such as meteorites they will sink into the ice and thus be hidden from our searching eyes. At the same time meteorites also break down quicker when the weather changes between thaw and frost.

Figure 3. Here the wind has blown nearly 100 different meteorites into an area with ordinary terrestrial rocks. Each flag marks a meteorite. ©GM



## Meteorite hunting in desert areas

It is not only in the cold desert areas such as the blue ice in Antarctica that one finds meteorites. Hot deserts have also proved to be good places to look for meteorites. As in Antarctica, there is no vegetation to hide the meteorites and simultaneously they may survive relatively long in the dry climate. The ever moving sand in desert areas may also play a role. Apparently the meteorites may be covered by drift sand after they have fallen. They may then lie for millennia well protected under a layer of sand. If at some point the erosion pattern changes and the sand starts to drift away, the meteorites and other large rocks will be left behind. It is such areas that are searched by meteorite hunters with a knack of finding rocks that differ from the surroundings.

Figure 4. Meteorite hunting in blue ice in North East Greenland. ©GM



# Shooting stars, fireballs and meteorite impacts

By Henning Haack

(3.12)



Figure 1. Photograph of the Peekskill fireball just after the meteor broke to pieces in the atmosphere. You can see a video of the fall and a piece of the meteorite in the exhibition. ©S. Eichmiller.

Most of us have seen shooting stars many times in the night skies. Although the phenomenon is not particularly rare it does make us stop, look up at the sky and enjoy the sight. Normally a shooting star is seen as a shining track across the heavens, but if one is lucky there may also be a glowing head at the front, sometimes a slightly glittering tail and in rare cases, one can also see the head break into several pieces, which then continue on their separate ways.

Shooting stars are generated when particles enter the upper atmosphere at very high speeds. Typical speeds in the atmosphere are around 15-20 km/s, but speeds of up to approximately 70 km/s may occur. By comparison, a normal aeroplane flies at 0.3 km/s. Because of these extremely high speeds, one might be led to believe that the fireball is passing at very low heights. It is not unusual for eye witnesses to experience a fireball apparently passing above them at a few hundred metres. Actually the burning takes place at a height of around 100 km. The burning is due to the fact that the particles move through the atmosphere at supersonic

speeds. Just like space capsules returning to Earth, the supersonic speed causes the front of the object to be heated to several thousand degrees. The space capsules are protected by a heat shield, which is designed to withstand excessive heating, whereas meteors mostly melt or evaporate. If it is a larger body, a shockwave is transmitted which, with a bit of luck, can be heard as a sonic boom.

## Meteors, meteoroids and meteorites

For historical reasons there are different types of names for meteorites depending on whether they are floating about as isolated chunks in our Solar System, if they have entered our atmosphere, or if they actually land on Earth. A meteoroid is a chunk of metal or rock that has been knocked off an asteroid or a planet. A meteoroid is typically about a metre in size before it enters the atmosphere. When the meteoroid enters the atmosphere and begins to glow, it is called a meteor, a fireball or simply

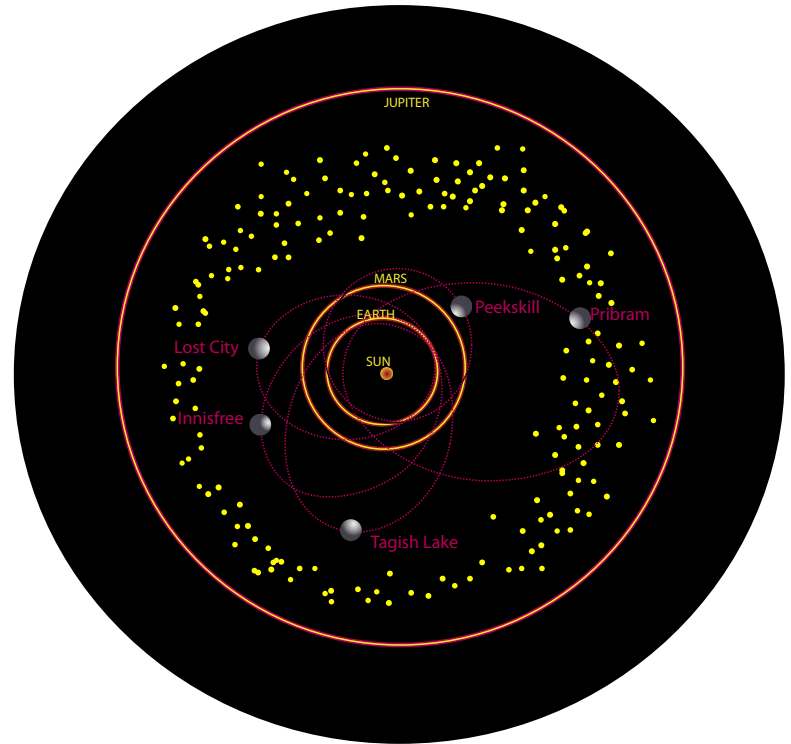
a shooting star. Shooting stars are normally not quite so bright shining lines that are created when small particles enter the atmosphere, whereas fireballs and meteors are powerful shining phenomena. In rare cases they may be observed in full daylight.

If the speed is not too fast, some fraction of the body may fall to Earth and it changes name once more, it is now a meteorite. The iron meteorite Sikhote Alin fell in Siberia on February 12, 1947 at 10:38 and eyewitness accounts state that the fireball shone stronger than the Sun. This was also a large meteorite fall, where up to three tons of iron meteorite fragments were collected after the impact. You can see fragments from the fall in the exhibition. The surfaces of the fragments are characterized by strong heating.

Figure 2. Photograph of a fireball observed over Oklahoma on January 3, 1970. The photo was taken with an automatic camera which had been placed there for the purpose of registering fireballs. The diaphragm of the camera was open all night and the stars are therefore seen as long shining circles around the north pole of the sky. The holes in the track of the fireball are due to the fact that the shutter of the camera was activated at regular intervals. This makes it not only possible to determine the trajectory of the fireball, but also its velocity. Together with pictures taken with a couple of other cameras it led to the discovery of the Lost City meteorite. ©Prairie Network, Oklahoma.



Figure 3. In all the cases where we have managed to determine a meteorite's trajectory around the Sun before it hit Earth, we can see that the trajectory follows the same path around the Sun as the Earth, and that it passes through the Asteroid Belt. This agrees with our assumption that most meteorites are from asteroids and all meteorites are from our own Solar System. The figure shows the trajectories of Peekskill and Lost City, mentioned in this chapter. ©GM



## Having seen the fireball, how do we find the meteorite?

Unfortunately it is very rare that fireball observations lead to the find of a meteorite. In principle it is possible to determine the trajectory of the fireball and calculate the point of impact from eye witness accounts. In practice, however, eye witness accounts are unfortunately not very accurate. It is almost impossible to assess, for example, the velocity of the fireball. Secondly the fireball usually is extinguished at 20-40 km height after which the meteor continues without being seen. The Peekskill meteorite whose fall can be seen in the exhibition continued for about 150 km after it was extinguished. A slight error in the determination of the shining part of the trajectory may lead to a large uncertainty as to the point of impact. If you see a fireball it is very important that you fix precisely in your mind the trajectory it followed across the sky. If you know where you were standing when seeing it and can remember behind which tree it disappeared, or maybe even through which stellar constellation it passed, it

may be possible to determine the trajectory with much greater precision. Such observations are very valuable to us when we try to ascertain what happened. If you have seen a fireball, please type in the observation on our website:

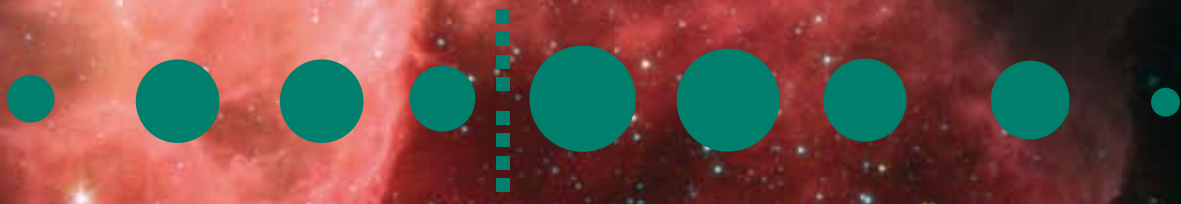
[www.ildkugle.dk](http://www.ildkugle.dk)

It is possible to set up cameras that constantly monitor the night sky. Camera surveillance has in four cases led to not only the discovery of a meteorite, but has also made it possible to calculate the meteorite's trajectory around the Sun before it hit Earth. The latter is particularly interesting since we would, of course like to locate the asteroids from where our meteorites originated.





# Appendix



# Dating rocks

By Christine Marvil

When working with meteorites, planets, rocks from Earth, as well as archaeological and fossil objects, it is often necessary to date such material in order to understand its history. This technique is called dating.

Dating can be divided into relative and absolute dating.

## Relative dating

Relative dating is when you date one object compared to another. For example, we can say that Jupiter is older than the Asteroid Belt, as Jupiter grew so quickly that it, using its gravitational pull, destroyed all attempts of the Asteroid Belt to form a planet. We cannot, however, say precisely how long Jupiter was formed before the Asteroid Belt.

## Absolute dating

Absolute dating relies on the fact that there are several radioactive elements that exist naturally on Earth as well as in the rest of the Solar System. Since radioactive elements decay and most have a well-defined half-life (and we know their rate of decay), we can use the relative amounts of the parent and daughter isotopes to determine the age of the material where they are found.

Radioactive isotopes are both long-lived and short-lived. The long-lived radioactive isotopes are those that have not yet completely decayed since their formation some time before the origin of the Solar System.

The remaining radioactive isotopes, which are no longer present and which can only be seen by the presence of their daughter isotopes, are called the short-lived radioactive elements. Today we find, however, a few of the short-lived isotopes mainly because they have been artificially created in nuclear power stations and atom bombs, or are generated by continuous production during the decay of the long-lived radioactive elements uranium and thorium.

## Dating of meteorites

When dating meteorites we are interested in a number of ages:

- 1) We wish to date the individual constituents of the meteorites (e.g. the calcium-aluminium-rich inclusions).
- 2) We wish to know when, during the life of the Solar System, the parent body of the meteorite was formed.

3) We wish to know when, during the history of the parent body, the specific rock, from where the meteorite fragment comes, was formed.

4) We also wish to know how long the meteorite has been travelling since it was broken off the parent body and landed on Earth.

5) And finally we would also like to know how long the meteorite has been on Earth.

We can try and answer the first two questions using long-lived radioactive elements and by determining the content of the short-lived radioactive elements that were formed at the beginning of the Solar System.

By measuring the influence of cosmic radiation on the meteorites, we can determine how much time has passed since they were broken off the parent body before landing on Earth.

Finally by means of e.g., carbon dating as well as the decay of unstable isotopes that were formed by cosmic radiation in space, we can determine how long the meteorite has been on Earth.

## Short-lived radioactive isotopes

There were numerous short-lived radioactive elements present at the creation of the Solar System and during the first millions of years of its history, elements that are no longer present today. We only see the traces of them in the form of their daughter elements. However, we do have a good knowledge of their half-lives and can thus use them to investigate the processes that occurred early in the history of the Solar System.

Short-lived radioactive isotopes that are used for dating of the origin of the meteorites are:

Radioactive element	Daughter element	Half-life (T <sub>1/2</sub> )
<sup>244</sup> Pu	X	82 mill. years.
<sup>129</sup> I	<sup>129</sup> Xe	16 mill. years
<sup>247</sup> Cm	<sup>235</sup> U	15.6 mill. years
<sup>107</sup> Pd	<sup>107</sup> Ag	6.5 mill. years
<sup>53</sup> Mn	<sup>53</sup> Cr	3.7 mill. years
<sup>60</sup> Fe	<sup>60</sup> Ni	1.5 mill. years
<sup>26</sup> Al	<sup>26</sup> Mg	0.7 mill. years
<sup>41</sup> Ca	<sup>41</sup> K	0.15 mill. years

where T<sub>1/2</sub> is the half-life and X is material that is formed by the decay of <sup>244</sup>Pu.

Of the short-lived systems, the system <sup>26</sup>Al » <sup>26</sup>Mg is of great interest as aluminium is one of the most common elements in rocks from the Solar System. With a half-life of only 0.72 million years, it has released an enormous amount of energy during its decay and this energy, in the form of heat, is presumed to be the main reason that some of the early asteroids melted internally. This melting formed an inner stratification in the asteroids in the form of a core, mantle and crust as we also know from Earth.

## Long-lived radioactive isotopes

When working with material from the earliest Solar System we need radioactive elements with a very long half-life. Below are a number of long-lived isotopes that are used in the dating of meteorites:

Radioactive element	Daughter element	Half-life (T <sub>1/2</sub> )
<sup>147</sup> Sm	<sup>143</sup> Nd	106 bill. years
<sup>87</sup> Rb	<sup>87</sup> Sr	48.8 bill. years
<sup>176</sup> Lu	<sup>176</sup> Hf	37 bill. years
<sup>40</sup> K	<sup>40</sup> Ar	11.93 bill. years
<sup>132</sup> Th	<sup>208</sup> Pb	14.01 bill. years
<sup>238</sup> U	<sup>206</sup> Pb	4.5 bill. years
<sup>235</sup> U	<sup>207</sup> Pb	0.7 bill. years

In the case of the long-lived radioactive isotopes, it is possible to measure directly the amount of both the radioactive element and its daughter element. This gives the precise age when the radioactive element was "locked" in place in the meteorite; this is precisely when the material, in which it is situated, cooled from a molten phase to form rock. Here we make use of the fact that meteorites consist of minerals with very different amounts of radioactive elements. Such minerals will, in time, accumulate a surplus of the daughter element, related to the initial concentration of the radioactive elements in the mineral. This surplus can be used to determine the age of the meteorite with very great precision.

# Isotopes

The differences between the isotopes of the individual elements are very small. Commonly isotopes of the same element will behave, more or less, in the same way and form part of the same types of compounds. Thus the relationship between the various isotopes of the same element reflects a relationship that was present between each when the compound was originally formed.

An example of the different isotopes of the same element is oxygen. Oxygen occurs as  $^{16}\text{O}$ ,  $^{17}\text{O}$  and  $^{18}\text{O}$ ; all are stable isotopes.

The same is the case with carbon, which occurs as the stable isotopes  $^{12}\text{C}$  and  $^{13}\text{C}$ , and as the radioactive  $^{14}\text{C}$ .

Knowledge of isotopes of the various elements is a very effective tool for the investigation of material from Earth as well as from the rest of the Solar System. They are used both for dating, in the case of a radioactive isotopes, and for understanding something about the processes taking place, and that have taken place, during the history of the Solar System.

A good example of the use of isotopes in the investigation of material from the Solar System is the element oxygen. It appears that the distribution of each of the three oxygen isotopes was different in the early Solar System. We do not know precisely what has

caused these differences, but it may be due to the fact that oxygen is found in gasses, water molecules and in solid substances and that all three components have moved through the Solar System at different rates, through various mechanisms.

The different compositions of oxygen's isotopes may thus be used to assign meteorites to different groups. For example, the Mars meteorites have a quite distinctive oxygen composition, which is different from that of terrestrial rocks and the meteorites from Vesta.

In the same way it can be demonstrated that the Earth and the Moon were formed in the same geographical area in relation to the Sun as their content of oxygen isotopes are similar. Our Moon is therefore not a captured moon as is the case of the moons of some other planets, but it was formed together with the Earth.

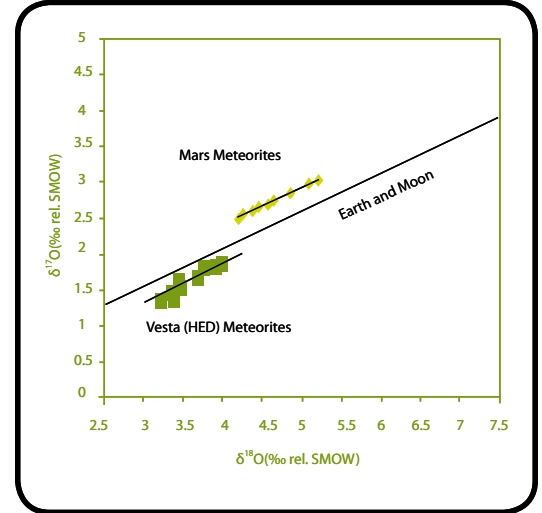


Figure 2. Oxygen isotopes from different materials within the Solar System. It is clear that there is a substantial difference in the composition between the various materials. ©GM

By Christine Marwil

(A.2)

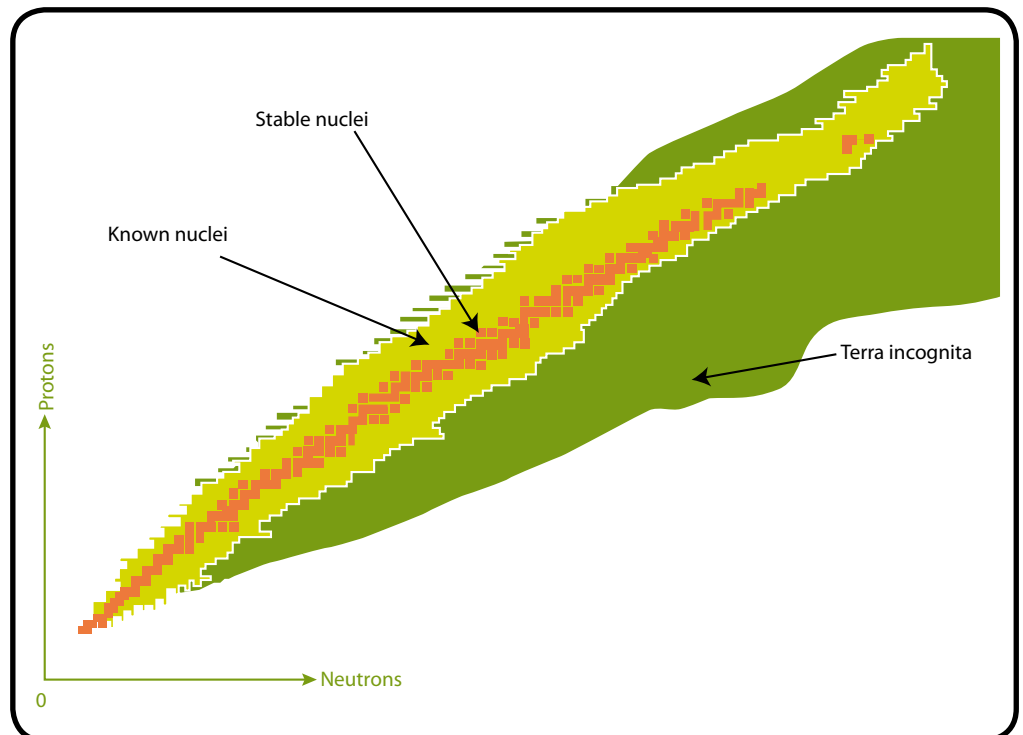


Figure 1. Map of the nuclei of the elements. The orange fields indicate the stable isotopes, whereas the light green areas are the known unstable isotopes. ©GM

# Glossary

Achondrites	Non-chondritic meteorites, i.e. meteorites where the parent body has undergone internal melting since the creation of the Solar System.	Howardites	Meteorites from the asteroid Vesta, consisting of crushed material.
Amino Acids	Building blocks of, among other organic substances, proteins.	Interstellar	Refers to the areas within the galaxies between the stars.
Angrite	Rare type of achondritic meteorite.	Isotope	Form of an element. Most elements are found in several different forms, i.e. isotopes.
Anorthosite	Rather pale rock primarily consisting of the mineral feldspar.	Jökullaup	Glacial torrent formed by the melting of glaciers.
Asteroid	Small planetary body residing in the Asteroid Belt in the Solar System.	The Kuiper belt	Cometary belt of frozen ice and stone bodies orbiting the Sun, farther out than Neptune.
Asteroid Belt	Area between the orbits of Mars and Jupiter, where several million asteroids orbit the Sun.	Lithosphere	Upper rigid part of rocky planets comprising the crust and the upper part of the mantle.
Basalt	Volcanic rock found on Earth as well as on other planets and asteroids.	Long-lived isotope	Radioactive isotopes still around in the Solar System today.
Bipolar jet currents	Young stars emit jet currents from their poles. In the jet currents gas is emitted at velocities of up to several hundred km/s.	Magmatic	Bodies and features, including meteorites, showing evidence of having crystallized from a melt.
CAI	Calcium-aluminium-rich inclusion.	Matrix	The fine-grained "cement" surrounding and binding together the larger parts of, among others, the chondrites.
Chassignite	Olivine-rich type of Martian meteorites.	Meteorites	Pieces of asteroids or planets that have been knocked off their parent body and have ended up on Earth.
Chondrites	Primitive meteorites that have not been molten since the beginning of the Solar System.	Nakhlite	Type of Martian meteorite.
Chondrules	Small round melt droplets that have crystallized. They comprise a large part of most chondrites.	Nebula	Star forming a molecular cloud.
Chromite	Iron- and chrome-rich oxide.	Nucleobases	Nucleotides are the building blocks of DNA and RNA. The DNA chain is built up of four different nucleobases (Adenine, Guanine, Cytosine and Thymine). The genetic code of life is determined from the order of these nucleobases in the DNA chain.
Cosmic radiation	Very, energy-rich particles travelling through the Solar System. Cosmic radiation consists mainly of positive nuclear particles (protons – 85%), Helium nuclei (14%) and electrons (1%); in addition to this, small amounts of heavier nuclei are present.	Oktahedrites	Iron meteorite with a hexagonal crystal structure.
Daughter isotope	The element that is created when a radioactive element decays to a more stable element.	Olivine	Iron- and magnesium-rich silicate mineral.
Differentiated asteroid	Asteroid that melted and was divided into a core, mantle and crust.	Pallasite	Type of meteorite from a differentiated asteroid. The Pallasite contains both iron from the asteroid's core and olivine from the mantle and is thought to have originated at the core-mantle boundary.
Differentiated meteorite	Meteorite from a differentiated asteroid.	Parent bodies	Asteroid or planetary bodies which are the source of the meteorites we have on Earth.
Diogenites	Coarse-grained meteorites from the upper mantle of the asteroid Vesta.	Plagioclase	Calcium- and sodium-rich silicate mineral.
Enstatite	Magnesium-rich silicate mineral.	Planetesimals	Small planetary bodies.
Eucrites	Basaltic meteorites from Vesta.	Protoplanetary disc	The disc-formed structure that was formed around the early Sun and from which the planets grew.
Feldspar	Aluminium-rich group of silicate minerals with a varying content of calcium, sodium and potassium.	Pyroxene	Mineral group of primarily iron- and magnesium-rich silicates.
Fusion	Process where lighter elements fuse together into heavier elements and emit energy during the process.	Radioactive isotope	Unstable isotope of an element decaying into a stable element by emitting radiation.
Half-life (period)	The time it takes for a well-defined amount of radioactive material to decay so that only half of the original amount is left.	Red giant	A large star with a mass of less than 8 times the mass of the Sun at the end of its life.
HED meteorites	Suite of meteorites from the asteroid Vesta comprising Howardites, Eucrites and Diogenites.	Resonance areas	Orbits in the Asteroid Belt, which are unstable because of Jupiter's gravitational pull.
Hot-spot volcanism	Volcanism known both from Earth and from other planets and moons, where hot material moves upwards in the interior of the planetary body and becomes the source of enormous lava eruptions.		

Runaway growth	In the early Solar System still larger bodies were formed by attracting dust and smaller bodies in their proximity. The larger they became, the more material could be drawn from their surroundings. This process is called "runaway growth".
Shergottite	The most common type of Martian meteorite.
Short-lived isotope	Radioactive isotopes are split up into short-lived and long-lived radioactive isotopes according to the length of their half-life period. The short-lived isotopes are the ones that have completely decayed today.
Solar System	System of one or more stars with planets orbiting around it/them. In our solar system the Sun is the star while the planets orbit the Sun.
Supernova	When very heavy stars die, they end in a gigantic explosion, a so-called supernova.
T-Tauri stage	T-Tauri stars are very young stars with masses similar to the Sun's that are still undergoing gravitational collapse. This stage lasts approximately 10 million years and represents the intermediate phase between a proto star and a small star like the Sun in its main phase.
Undifferentiated asteroid	Asteroid that has never been molten.
Undifferentiated meteorite	Meteorite from undifferentiated asteroid.
Vesta	The third largest asteroid in the Asteroid Belt.
The Vestoids	Small group of asteroids relatively close to and presumably related to Vesta. They are probably km-large fragments of Vesta's crust that have been knocked off by impacts.
White dwarf	A very small, extremely dense star.
Widmanstätten structure	Crystal structure seen in iron meteorites with lamellae of different chemical composition that can tell us something about their cooling rates.
Zircon	Zirconium silicate mineral.

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