German Aerospace Center
Institute of Planetary Research

OUR SOLAR SYSTEM

A Short Introduction to the Bodies of our Solar System and their Exploration

Prepared by
Susanne Pieth and Ulrich Köhler

Regional Planetary Image Facility
Director: Prof. Dr. Ralf Jaumann
Data Manager: Susanne Pieth

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Addendum

These texts were written with the help of Dr. Manfred Gaida, Prof. Dr. Alan Harris, Ernst Hauber, Dr. Jörn Helbert, Prof. Dr. Harald Hiesinger, Dr. Hauke Hußmann, Prof. Dr. Ralf Jaumann, Dr. Ekkehard Kührt, Dr. René Laufer, Dr. Stefano Mottola, Prof. Dr. Jürgen Oberst, Dr. Frank Sohl, Prof. Dr. Tilman Spohn, Dr. Katrin Stephan, Dr. Daniela Tirsch, and Dr. Roland Wagner.

PREFACE

A journey through the Solar System

The year 2009 was proclaimed the International Year of Astronomy to commemorate a defining moment in history. It was exactly 400 years before that Galileo Galilei had turned his telescope to the sky for the first time – and what he discovered was truly revolutionary. His observations, which he duly noted in the Sidereus Nuncius, bore out the concept of the world proposed by Nicolaus Copernicus. Suddenly, the Universe no longer revolved around the Earth as it had done according to classical theory; instead, the Sun stood firmly in the center of our planetary system. It was also in 1609 that Johannes Kepler, in his Astronomia Nova, formulated the first two of three laws describing the orbits of the planets, providing the foundation from which we are now sending space probes to all the bodies in the Solar System with a degree of precision reminiscent of the proverbial endeavor to maneuver a golf ball struck in Berlin into a pinhole in New York.

In 1959, mankind succeeded for the first time in sending a space probe beyond the Earth's immediate gravitational field. The first one to reach the Moon, the Soviet probe Luna 1, paved the way for a veritable armada of spacecraft which subsequently set out to explore the planets, their moons, the asteroids and comets and, not least, the Sun itself. Finally, it was 10 years later that Neil Armstrong took the famous step that appeared small to him but was in fact one giant leap for mankind: in the night of July 20/21, the first human stepped on another celestial body, the Moon. While it was politically motivated initially, the cognitive gain reaped by science from the Apollo Moon project was enormous and boundless in the best sense of the word.

The race to the Moon led to unprecedented progress in all fields of astronautics, a young discipline at the time, and also brought blessings for research. Not only the Moon but also the planets of our Solar System could now be reached with robotic space probes, despite their incomparably greater distance. Venus and Mars were the first, followed in short order by Mercury, Jupiter, Saturn and other bodies even farther out. The innumerable observations that were made were both fascinating and enlightening, for by looking at other planets and their moons we learned an incredibly great deal not only about the Solar System but also about the early history and development of our Earth, peerless among all the planets, which, after all, is still the only place in the Universe that we know harbors life. And, not least, we came to appreciate that this 'Blue Planet' is fragile and needs to be protected, and that it is the best of all imaginable spaceships.

In fact, however, every riddle that is solved raises fresh questions. How did life originate on Earth? Did it come from another celestial body, and would life on Earth be possible at all without the Moon's stabilizing influence on the Earth's axis? And finally, there is the question that goes beyond the scope of science pure and simple: will we find life on another celestial body within or beyond of the boundaries of our Solar System?

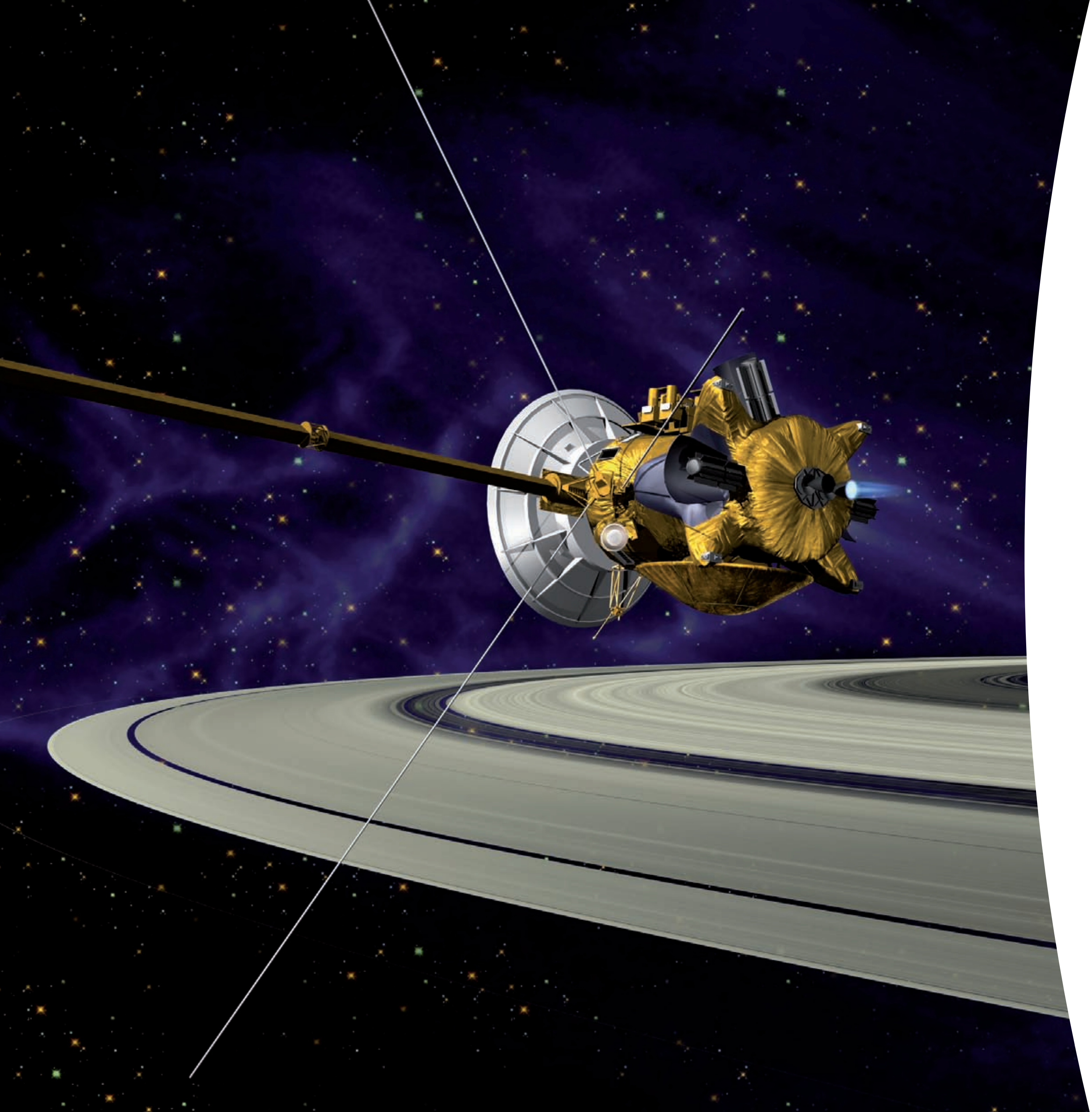
There is no other science in which pictures are as indispensable for comprehension as they are in astronomy and planetary research. The photographs which space probes have been transmitting to Earth for over 50 years have been showing us new worlds, new perspectives and new insights. Planetology, a comparatively young academic discipline, consists mostly of basic research. However, any cognitive gain entails an obligation – that of communicating scientific findings to the general public.

The German Aerospace Center (DLR) is happy to fulfill this obligation, and does so in many ways. To visualize the fascination and suspense of the results of planetary research, the Regional Planetary Image Facility (RPIF) has been created in cooperation with NASA at the DLR Institute of Planetary Research in Berlin-Adlershof. This library of planetary photographs keeps on file all the image data transmitted by space probes of NASA, ESA and other space agencies and makes them accessible to the public. Entitled 'Our Solar System', this small publication, which is now available in its third edition, is intended to provide a brief overview of the current status of our efforts to explore our immediate cosmic neighborhood. Share our fascination, and let us take you along on a journey away from Earth into the depths of the Solar System.

I wish you a thrilling read!

Ralf Jaumann

A teacher of planetary geology at the Free University of Berlin, Prof. Dr. Ralf Jaumann directs the Planetary Geology Department as well as the NASA/DLR Regional Planetary Image Facility at the DLR Institute of Planetary Research.



EXPLORING THE SOLAR SYSTEM WITH SPACE PROBES

The launch of Sputnik 1 by the Soviet Union on 4 October 1957 marked the beginning of the space age. Shortly afterwards, the former USSR and the USA succeeded in sending space probes to the Moon, to Mars and Venus, Earth's two neighbor planets. The more distant planets followed in the 1970s. Other nations began to participate in missions to explore the planets, moons, asteroids and comets of the Solar System, the Sun itself, the interplanetary space and our cosmic surroundings. Although hit by a number of setbacks, a large number of missions to the astronomical objects of our Solar System were successful, producing a wealth of knowledge about our neighborhood in space. Images that capture the surfaces of these diverse bodies or, in the case of the large gas planets, the outermost layers of their atmosphere play a key role in the exploration of our Solar System. For this purpose, space probes employ photography (conventional at first, later followed by digital technologies) as well as imaging spectroscopy across a range of shorter and longer wavelengths. Wherever a dense atmosphere obscures our view, as is the case on Venus or the Saturnian moon Titan, surfaces may be characterized by radar.

The remote sensing equipment employed in planetary exploration today operates in almost all wavelength ranges of the electromagnetic spectrum. Optial cameras with their state-of-the-art sensors allows a visual characterization of almost all bodies visited. But even though enourmous advancements have been made in the resolution of all kind of experiments, many questions still remain open and will have to be answered by future space missions.

Exploration methodology

The classical process by which alien astronomical objects are explored comprises the stages listed below. Each of these steps represents a mission scenario more complex than the last in terms of technology, navigation and propulsion technology:

- Launch; brief 'parking' in orbit (optional); injection into an interplanetary trajectory
- Flyby past the target body
- Hard landing on the surface and/or atmospheric probe
- Orbit around the celestial body
- Soft landing on the surface and activation of an experimental station
- Robotic vehicles (rovers), balloon and aircraft probes/drones
- Return of samples
- Crewed expedition

This sequence of events is not always followed strictly. Steps are often merged or skipped, as a glance at almost five decades of planetary exploration shows. The motivation may either be technical and scientific or financial and/or political.

Image: Rosetta on board an Ariane-5 launched from Kourou on 2 March 2004. *(© ESA/CNES/ARIANESPACE-Service Optique CSG, 2004)*

Image on the left: Artist's impression of space probe Cassini over the Saturnian Rings. *(© NASA/JPL)*

The first four decades

On 2 January 1959, the Soviet space probe Luna 1 reached Earth's escape velocity and flew past the Moon for the first time, ringing in the age of planetary exploration. After many failed attempts it was the first spacecraft to succeed in leaving the gravity field of our home planet. The subsequent exploration of the Solar System may be historically divided into four phases.

The first phase from 1959 to 1967 is characterized by robotic space probes exploring first the Moon and only a little later the Earth's two neighboring planets, Venus and Mars. Mainly designed to prepare crewed missions, the exploration of the Moon was marked by the race for technological leadership between two competing political and/or societal systems. At the same time, the gains in scientific knowledge made in this era were immense. Missions that deserve mention include the Soviet Luna 1 (Moon flyby), Luna 2 (hard Moon landing) and Luna 3, which provided the first pictures of the far side of the Moon, which is not visible from Earth, although these were not yet of high quality. All three probes were launched in 1959, followed by a number of US missions. The Moon exploration programs Ranger, Surveyor and Lunar Orbiter were all designed to look for potential landing sites for crewed missions. From 1966 onwards, Luna 9, Surveyor 1 and Lunar Orbiter 1/2 supplied the first images of the Moon taken on the surface and from orbit. Venus and Mars were mainly explored in flybys, few of which were as successful as those of Mariner 2 (Venus, 1964), Mariner 4 (Mars, 1964/65) and the first atmospheric probe Venera 4 (Venus, 1967). Even in this phase, launcher systems changed to more powerful rockets whose upper stages were fitted with high-energy cryogenic drives, like Atlas-Centaur (USA) and Proton (USSR).

The first crewed missions to the Moon form the salient events of the second phase from 1968 to 1972. In addition to the six successful American landings on the Moon, robotic missions were sent to the Moon, Mars and Venus, mainly by the Soviet Union. The Apollo program gave spaceflight technology an enormous boost but proved equally significant for planetary research. During the same period, lunar rock samples were taken back to Earth by fully automated missions (Luna 16, 20 and 24), and the first robotic vehicle was placed on the Moon (Luna 17/Lunokhod 1). Several more spacecraft successfully flew by Venus and Mars; in 1970, the first probe landed on Venus (Venera 7), and Mariner 9, having entered into an orbit around Mars, became the first artificial satellite to circle another planet (1971/72).

Extending from 1973 to 1983, the third phase saw Mars and Venus being explored more intensely and probes being sent to investigate the outer planets. Between 1973 and 1975, Mariner 10 was the first probe to use the swing-by method in its flybys past Mercury, the only ones for a long time to come. In parallel, the USSR carried out further missions to Venus and Mars. There were two programs of great significance in these years: Viking and Voyager. In 1975, two landers and two orbiters were sent to Mars as part of the American Viking program. They went to work one year later and kept on sending data to Earth well into the eighties. The results produced by these missions, mainly photographic maps of the surface, furnish important basic information about the planet to this day; besides, they serve to prepare future missions.

Image: Ranger 7, launched on 28 July 1964, was the first successful lunar mission of the Ranger series. Until its impact in the Mare Nubium, it transmitted over 4000 images to Earth. *(© NASA)*

The Voyager program achieved similar eminence. Launched in 1977, the two identical Voyager probes went on an exploratory mission to the outer Solar System. Between 1977 and 1989, Voyager 2 set out on its 'Grand Tour' which took it past the gas planets Jupiter, Saturn, Uranus and Neptune and their respective moons. The two Voyager probes are now some 20 billion kilometers away at the brink of interstellar space, still transmitting signals to Earth. The images and measurement data they sent home represent a fund of basic knowledge about the outer Solar System that is indispensable to this day. During this phase, the USSR continued its extensive Venus program involving landings, surface images, balloon probes and radar maps. The American Pioneer program explored not only Venus but also comet Halley, which was visited by not one but several space probes from Europe, the USSR and Japan when it appeared in the inner Solar System in 1986. In those years, new or modified probe types were developed that were capable of carrying greater payloads; the first of these were Mars 2 and Venera 9 in the USSR, while in the USA, the spacecraft of the Mariner program were modernized after Mariner 10.

Having begun in 1989, the fourth phase focuses on launching and operating large space probes like Magellan, Galileo and Cassini-Huygens on the one hand and implementing highly specialized small-scale missions on the other. In this case, the scale of a mission relates not only to the mass of the spacecraft involved but also to its cost, development lead time and service life. Missions that stand out include Galileo, a sophisticated long-term trip to explore the Jovian system (start: 1989; mission end: 2003), and the Pathfinder/Sojourner mission to Mars that was designed to demonstrate the feasibility of a soft touchdown achieved by airbags instead of braking rockets and landed on Mars in the summer of 1997. The pictures taken by both these missions met with great interest among the public and did much to enhance the popularity of interplanetary spaceflight.

Current and future missions

The current phase of international planetary exploration began when, at the turn of the millennium, it became apparent that future research would essentially concentrate on two items: intensified long-term exploration of Mars and the exploration of the minor bodies of the Solar System. A continued exploration of the Moon, its future exploitation and a possible return of humans to the Earth's satellite are especially being pursued by the emerging Asian

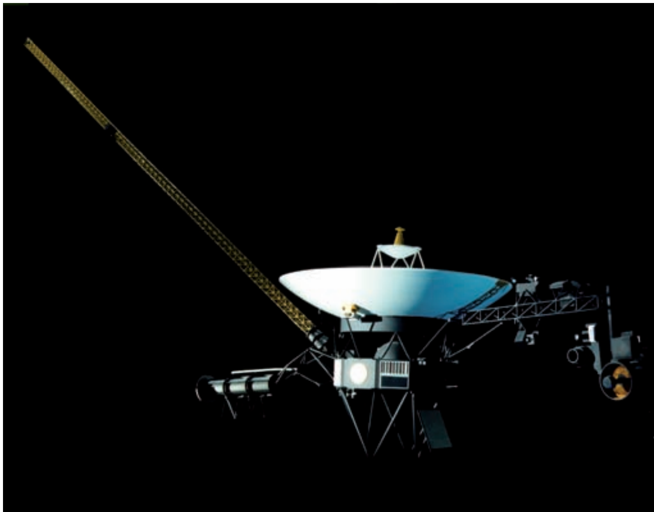


Image above: Apollo 17 astronaut Eugene Cernan standing next to the rover in the Taurus Littrow Valley. Mounted on the front of the rover is the TV camera and its antenna. *(© NASA, Scan: JSC)*

Image on the right: The Voyager space probe. *(© NASA)* spacefaring nations. Other destinations that have begun to move into the focus of attention are the ones that have not been visited for some time or are completely unexplored. These include Mercury, the dwarf planet Ceres and the large asteroid Vesta and, most importantly, Pluto, which lost its planetary status some time ago and represents one of the last 'white spots' among the larger bodies of the Solar System.

All in all, the number of planetary missions has been increasing again in the new millennium. As many of the probes that will be deployed in the years to come are being planned, developed and/or integrated and some of them are on the way to their destination even now, the trends and focal points of mission design can be seen clearly: small, specialized probes, an increasing proportion of which is not being developed by any of the major space agencies, and a trend towards minimizing planning and construction lead times in order to cut costs. Moreover, enormous progress has been made thanks to the miniaturization of cameras and measuring instruments and increased on-board data processing capabilities.

In the next few decades, spacecraft will probably be sent to our outer neighboring planet, Mars, at intervals of about two years. After the failure of the Mars Surveyor-98 program which would have involved a landing at the Martian south pole and the release of an orbiter to study the Martian atmosphere, NASA scored a great success with three other orbiter missions. The landing of two Mars exploration rovers, Spirit and Opportunity, in the year 2004, marked the highlights of the program. NASA's current exploration strategy can be summarized under the motto 'Follow the Water'. Looking for traces of water on the Martian surface will answer the question whether life-enhancing conditions may once have prevailed on Mars. The long-range objective, possibly to be pursued in collaboration with Europe, is to gather samples and return them to Earth. A human crew landing on the Red Planet at some later date is not being ruled out. Europe's current contribution is its highly successful Mars Express mission, which has been transmitting a wealth of data and images from Mars since the end of 2003.

The arrival of Mars Rover Curiosity as part of the Mars Science Laboratory Mission on 5 August 2012 lifted Mars exploration to a new quality level. Weighing 900 kilograms, the vehicle has greater mobility than its predecessor and carries a 95 kilogram payload of ten instruments. The mission's objective is to search for potential habitats on Mars, traces of hydrocarbons and other chemical elements necessary for the development of living organisms. From 2014 on, NASA's next Mars probe, MAVEN, will analyze the upper Martian atmosphere. Two years later, another mission, InSight, will undertake another landing on Mars, aiming this time to measure physical parameters, for which it will be equipped with a German-built drill. Towards the end of this decade, the European Space Agency ESA is planning to send first an orbiter and then a lander to Mars.

The European technology demonstrator SMART-1, having orbited the Moon between November 2004 and mid-2006, ended its mission with a scheduled impact on the lunar surface. It was only the 'curtain-raiser' of an intensive campaign to explore our satellite. What followed was a series of lunar missions run by Japan, India, and China. The lunar mapping database was given a significant boost by the USA's Lunar Reconnaissance Orbiter. The Moon will continue to be of great interest, since it is an easy-to-reach celestial body and continues to be interesting from a scientific point of view. Planetary scientists are particularly keen to know more about its far side as well as to obtain rock samples from its unexplored areas, a task that could be tackled by new robots, conducting automated sampling on unmanned missions. The return of humans to the Moon is also conceivable at some point within the next few decades.

In the inner Solar System, Europe's space probe Venus Express has been orbiting our neighbor planet since April 2006. In 2011, MESSENGER, a mission under NASA's Discovery program launched in 2004, entered the orbit of Mercury, making it possible for the first time to conduct a global characterization as well as taking images of the innermost planet. In August 2015 it will be followed by BepiColombo, the European-Japanese mission that is expected to explore Mercury for at least one year.

Another cornerstone is exploring the minor bodies in our Solar System. Early in 2006, the Stardust mission succeeded in bringing dust from the comet Wild/2 back to Earth. Japan's probe Hayabusa, too, although beset by numerous technical problems, succeeded in taking samples on the asteroid Itokawa and returned them to Earth in 2010. In late 2014, the Japanese will launch a follow-up mission, Hayabusa-2, aimed at the asteroid $1999JU_3$ to take samples in 2019 and return them to Earth in 2020. An increasingly strong focus will be put on the exploration of asteroids that cross the Earth's orbit, to look into possible ways of diverting their path in case they are on a collision course. Major investigations, funded by the European Union and ESA, are underway and will possibly lead to a first test mission, heading an asteroid off its original trajectory sometime within the next decade.

NASA's DAWN mission, launched in 2007, has been a great success so far. It arrived at Asteroid Vesta in 2011, exploring it from three different orbits before heading on to the dwarf planet Ceres in August of 2012. It will be the first mission ever to have been orbiting two different bodies of the Solar System.

The European Rosetta mission launched early in 2004 is still on its way to comet Churyumov-Gerasimenko whose orbit it will enter in mid-2014 to deposit the Philae lander on its nucleus a few months later. Also within this decade, NASA's OSIRIS-REx mission is scheduled to reach Asteroid $1999RQ_{36}$ (Bennu). It will first characterize the asteroid from an orbital position and subsequently land on it, take a sample from its surface to return it to Earth.

In the outer reaches of the Solar System, the last large-scale mission to explore the Saturnian system, Cassini-Huygens, arrived at Saturn in the summer of 2004 to pursue another research focus in planetary science. With the large volumes of data about the Saturnian system which it has been faithfully supplying, it has changed our knowledge about the outer Solar System from the ground up. Although highly complex in terms of the mission scenario, it was a thrilling event of great scientific interest when the Huygens lander descended through Titan's atmosphere and landed on its surface in January 2005.

The exploration of Jupiter will be another European space research focus in the next decade once the JUICE mission – Jupiter Icy Moon Explorer – has got under way in 2022. The probe is to arrive at its destination in 2030 and study Jupiter and its icy moons. An event scientists are impatiently waiting for is the 2015 Pluto flyby of New Horizons, a mission launched in January 2006.

Image: Self-portrait of NASA's Mars rover Curiosity inside Gale crater. (© ***NASA/JPL-Caltech/MSSS)***

COMPARATIVE PLANETOLOGY IN THE SOLAR SYSTEM

The Solar System in which we live is only one of many in the universe. To date, we have become aware of nearly a thousand planets orbiting other stars. We may assume that further planetary systems will be discovered in the next few years. There is no certainty that life has developed on any of the planets orbiting our Sun, other than Earth. However, if we study microorganisms that live under extreme conditions on Earth we must assume that life might be possible on other planets and moons of our Solar System, too. Life on Earth in its tremendous diversity did not develop until the Cambrian Era, which began about 570 million years ago. A little over 50 years ago humans found the courage to venture into space, first using robotic space probes to take a look at other planets and their moons from a closer distance, and crewed spacecraft later, flying in a near-Earth orbit and to the Moon. The capability to see the Earth itself from an orbital perspective opened up entirely new research aspects, as well as giving people an opportunity to view their home planet from a certain distance.

Pinpoints of light that appeared to move against a ‘fixed‘, never-changing backdrop of the night sky were already observed by the early astronomers. They called these objects planets, which means ‘wanderers‘. Later on, they attributed names to those wanderers that were visible with the naked eye, names that we still use today, derived from the Roman pantheon: Jupiter – father of the gods; Mars – god of war; Mercury – messenger of the gods; Venus – goddess of love and beauty; Saturn – father of Jupiter and both god of agriculture and of time.

Our Solar System incorporates a multitude of different bodies ranging from agglomerations of dust and frozen water to Earth-like planets with a rocky surface to gigantic balls of gas, with diameters as large as eleven times that of Earth.

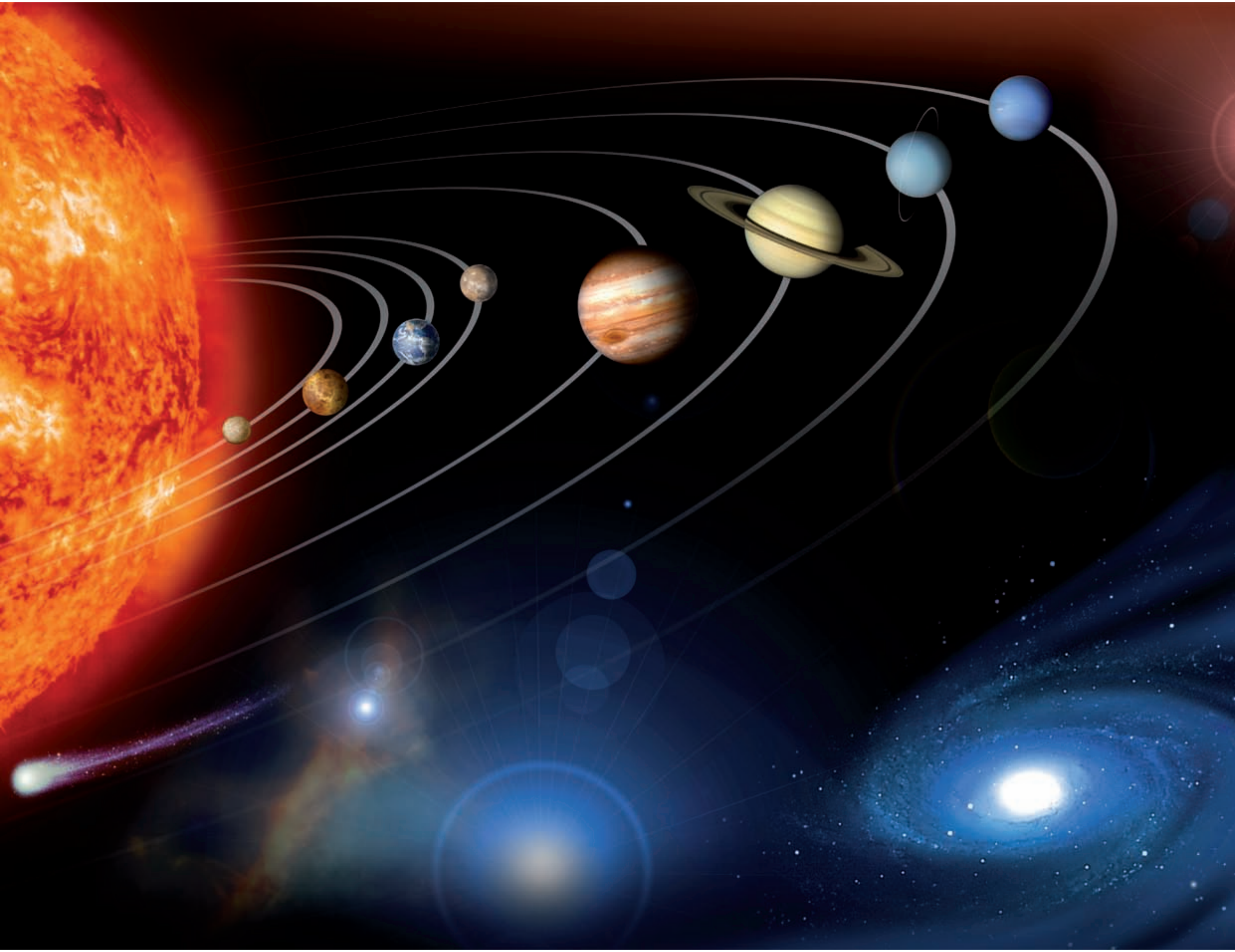
All planets circle the Sun in the same direction, and their near-circular orbits are all more or less on a plane called the ecliptic. The ecliptic is the plane on which the Earth revolves around the Sun, and which at the same time is aligned to the Sun’s equatorial plane. The rotational axes of most planets deviate only by a few degrees from the vertical to this plane, with Uranus and Pluto forming the only two exceptions. Pluto, a dwarf planet, is so far away from the Sun that it takes 248 years to complete a solar orbit. For comparison, the innermost planet, Mercury, takes only 88 days to do the same. Most of the minor, irregularly shaped bodies travel on elliptical orbits. Many comets follow elliptical trajectories that take them to the edge of the Solar System or even beyond. On its long, elliptical path, comet Halley, for example, enters the inner Solar System at intervals of about 76 years. Whenever Earth, on its annual journey round the Sun, travels through an area in which a comet’s tail has left behind tiny dust and rock particles, periodic showers of meteors can be seen in its atmosphere, which can look rather spectacular at times.

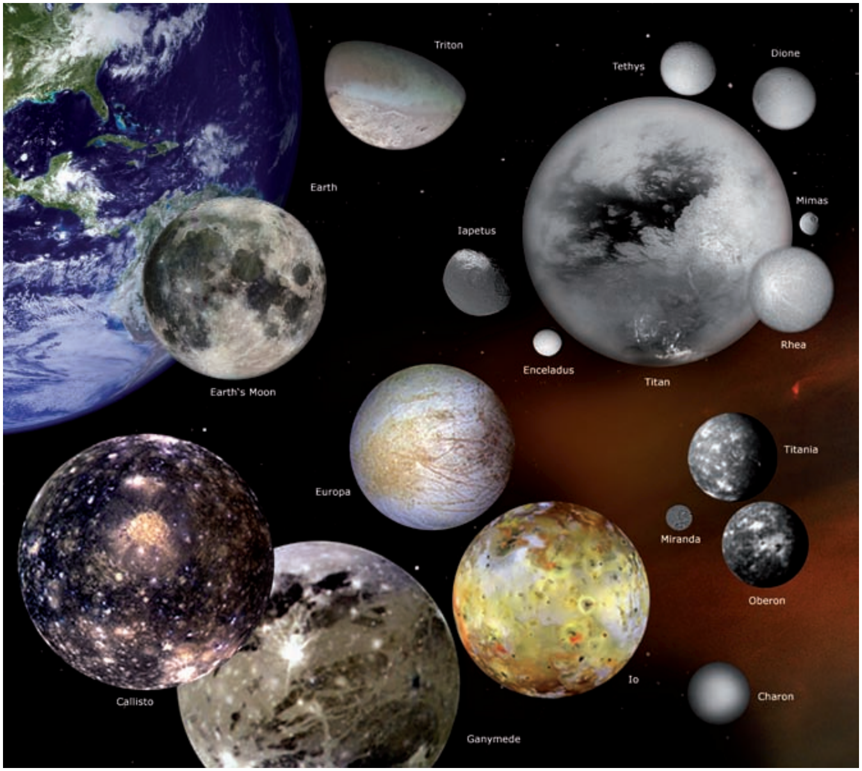
There is a marked trend for the mass and composition of planets to change with their distance from the Sun. Planets of comparatively low mass but high density, i.e. the Earth-like, or ‘terrestrial’ planets (Mercury, Venus, Earth, Moon* and Mars) in the inner Solar System consist mainly of silicate rock and iron. Conversely, the large planets of the outer Solar System – the gas giants Jupiter and Saturn, and the ice giants Uranus and Neptune – have a much greater mass but a lower density, and mainly consist of gases (mostly hydrogen and helium). They all have moons that largely consist of ice. Water, methane, ammonia and nitrogen condense at low temperatures, while hydrogen and helium will remain gaseous under almost all conditions that occur in nature. However, deep inside, even the gas planets have cores composed of a more dense material, presumably silicate rock and metal.

All in all, the planets of our Solar System have more than 170 moons. These moons vary greatly in size, ranging from small rock and ice fragments to bodies larger than Earth’s own satellite. Many moons were only discovered with the help of space probes. Only one of them, the Saturnian moon Titan, has a dense atmosphere, while the Jovian moons Ganymede, Europa and Callisto are the only ones with a magnetic field. Europa’s and Callisto’s magnetic fields are being induced by Jupiter’s own magnetic field, while that of Ganymed is being generated deep in its own interior, similar to that of Earth. The Jovian moon Io is the most geologically active body in the entire Solar System, as evidenced by its extreme, sulfur-rich volcanism. Scientists assume that the ice crust on the Jovian moons Europa, Ganymed and Callisto hides an ocean, and images of Ganymede and especially of Europa prove that their icy crust of these two moons is moving. These movements are possibly

*** Under the criteria of comparative planetology, the Moon, given its size and composition, is considered as one of the terrestrial planets.**

Image on the right: Artist’s impression of our Solar System; distances and sizes are not to scale. *(© NASA/JPL)*



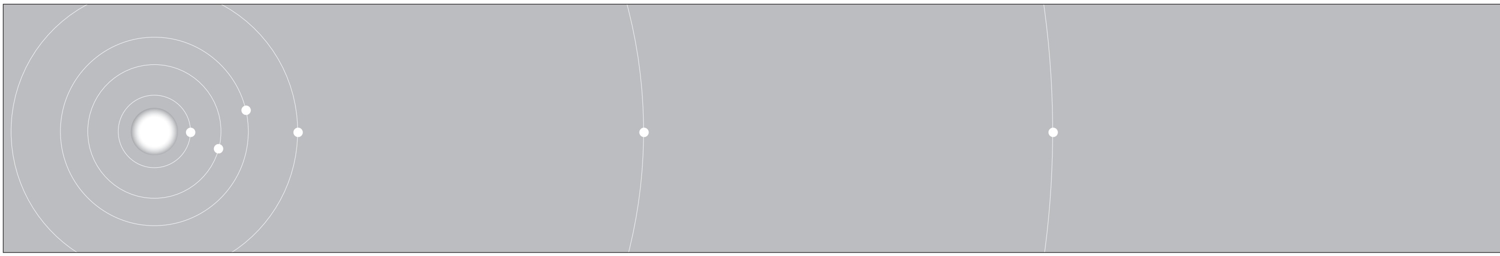


caused by the oceans believed to be hidden beneath. Yet other moons like the two Martian moons Phobos and Deimos could possibly be asteroids that were captured by the planet's gravitational pull, or, in the case of the Saturnian moon Phoebe, might be a body from the remote areas of the outer Solar System, steered into its present orbit by Saturn's gravity.

All current theories about the origin of our Solar System are derived from the generally accepted idea, first proposed in the 18th century by Immanuel Kant and Pierre Laplace, that the Sun and its planets developed within a few tens of million years from a protostellar nebula 4.6 billion years ago. The nebula itself was created when a cloud of interstellar dust collapsed. It is assumed that the first planets that came into being were Jupiter and Saturn, the giant planets. A more recent assumption is that these two spent some time traveling inwards, towards the Sun, and then outwards again. This planetary migration would have been a result of the interaction between the two giant planets and what was left of the nebula. The assumption of the outward movement implies that there must have been a fixed constellation between the two. This outward movement eventually 'cleared' the region of the inner Solar System, making room for the smaller terrestrial planets to form. In most other recently discovered planetary systems, giant planets have not (yet) migrated back to the outer regions. Further research is required to see what this means

Image above: The moons in our Solar System. (© *NASA)*

Image below: True-to-scale distances in our Solar System irrespective of planet sizes. (© *DLR)*



for the chance of discovering a 'second Earth' in such systems.

The accretion (or lumping together) of a planet occurs like a snowballing process. Once the first solid particles have formed, they consolidate into larger lumps, which impact into each other and join together. The remaining gas in the protoplanetary disc is then pulled towards the largest one of these cores. This is how the gas planets came into being. The accretion of the four innermost, terrestrial, planets took place in a region where no ice particles could persist for any length of time, given the higher temperature.

That said, current theories also maintain that the development of planetary systems per se is neither unique nor particularly striking. Stars that are currently in their formation phase are showing similar conditions. Yet, the structures of planetary systems can be very diverse, depending on the position of their respective parent star in its galaxy.

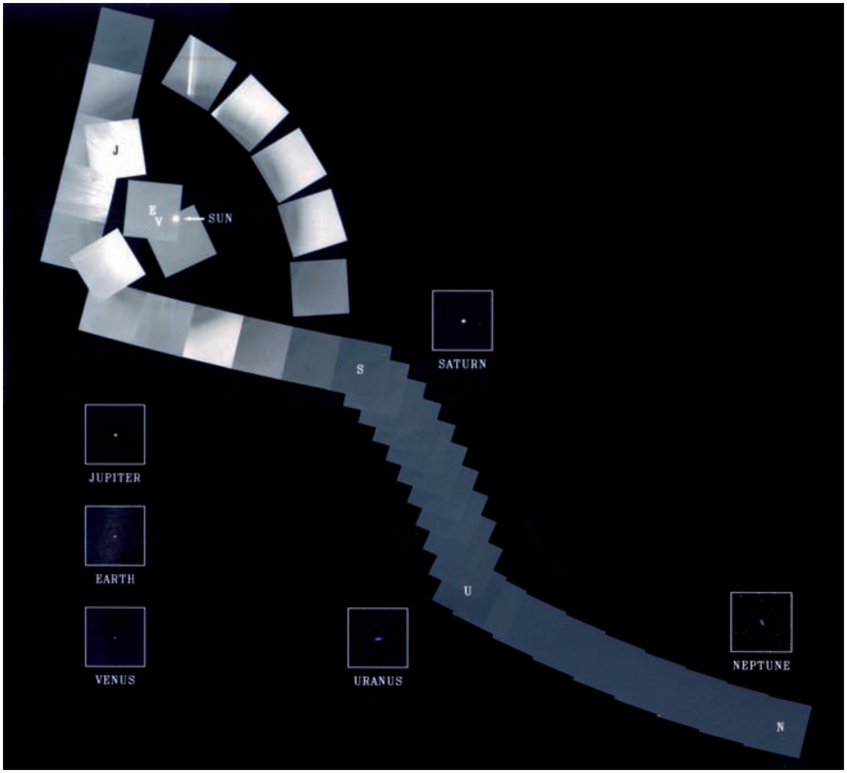
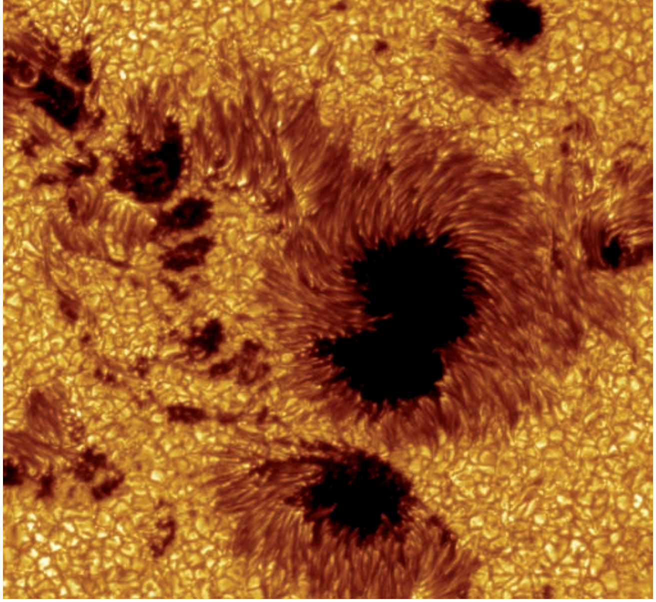


Image: A look back at our Solar System from Voyager 1 probe. *(© NASA/JPL)*

THE SUN – OUR SOURCE OF ENERGY



Since time immemorial, humans have worshipped the Sun as a deity, a source of life, light and strength. A wealth of myths, paintings, poems and songs from all civilizations attribute a special role to the Sun. In more rational terms, the Sun is our nearest fixed star about 150 million kilometers away from us, and the only star the surface of which we can study in some depth and detail. The impact of the Sun, as opposed to that of the more remote stars, on us and the nature around us is directly perceivable. Ultimately, the Sun was and still is the source of energy that powers most physical, chemical and nearly all biological processes in the Solar System.

That said, the Sun, in astronomical terms, is an average star of the G2 V spectral type that came to 'life' and began to shine not quite five billion years ago somewhere within a dense interstellar cloud of gas and dust. At a diameter of almost 1.4 million kilometers and a mass of nearly 2 x 10^{33} grams, the Sun's mean density amounts to 1.41g/cm^3. More than 330,000 Earths would be needed to make up its weight. The gravity field that emanates from this gigantic central mass governs the orbits of each individual planet, asteroid and comet in the Solar System as well as the inclination of each of those orbits relative to the Sun's equator. When we watch the positions of other stars during a total solar eclipse, we can even observe that the Sun does indeed bend the surrounding space in the way predicted by Albert Einstein (1879-1955) as part of his Theory of General Relativity as early as 1916.

However, the Sun's chemical composition is just as important as its mass. As can be demonstrated spectroscopically, it is composed of 73 % hydrogen, 25 % helium and 2 % heavier elements. Like that of any other star, the course of the Sun's life crucially depends on its total mass and its chemical composition.

The surface of the Sun, the photosphere, has been under close investigation ever since the telescope was invented. As early as 1610, the Jesuit monk and mathematician Christoph Scheiner (1579–1650) and the East Frisian scholar Johannes Fabricius (1587–1616) independently from each other discovered a number of dark spots which migrate from one edge of the Sun to the other within two weeks. This soon led observers to conclude that the Sun must have a rotational period of around one month. Today, we know that the gaseous surface of our central luminary rotates at different velocities, increasing with heliographic latitude. A revolution takes nearly 27 days at the equator and 36 days at the poles of the Sun. At about 2 kilometers per hour, the Sun rotates rather slowly compared to other stars.

The sunspots themselves appear dark because they are up to 1,500 degrees Celsius colder than the surrounding photosphere, which is as hot as 6,000 degrees Celsius. They appear black against their hotter background. In 1843, the apothecary and amateur astronomer Samuel Heinrich Schwabe (1789–1875) successfully demonstrated that sunspot numbers regularly vary over a period of eleven years. It is thought that this eleven-year sunspot cycle might be overlaid by even longer cycles

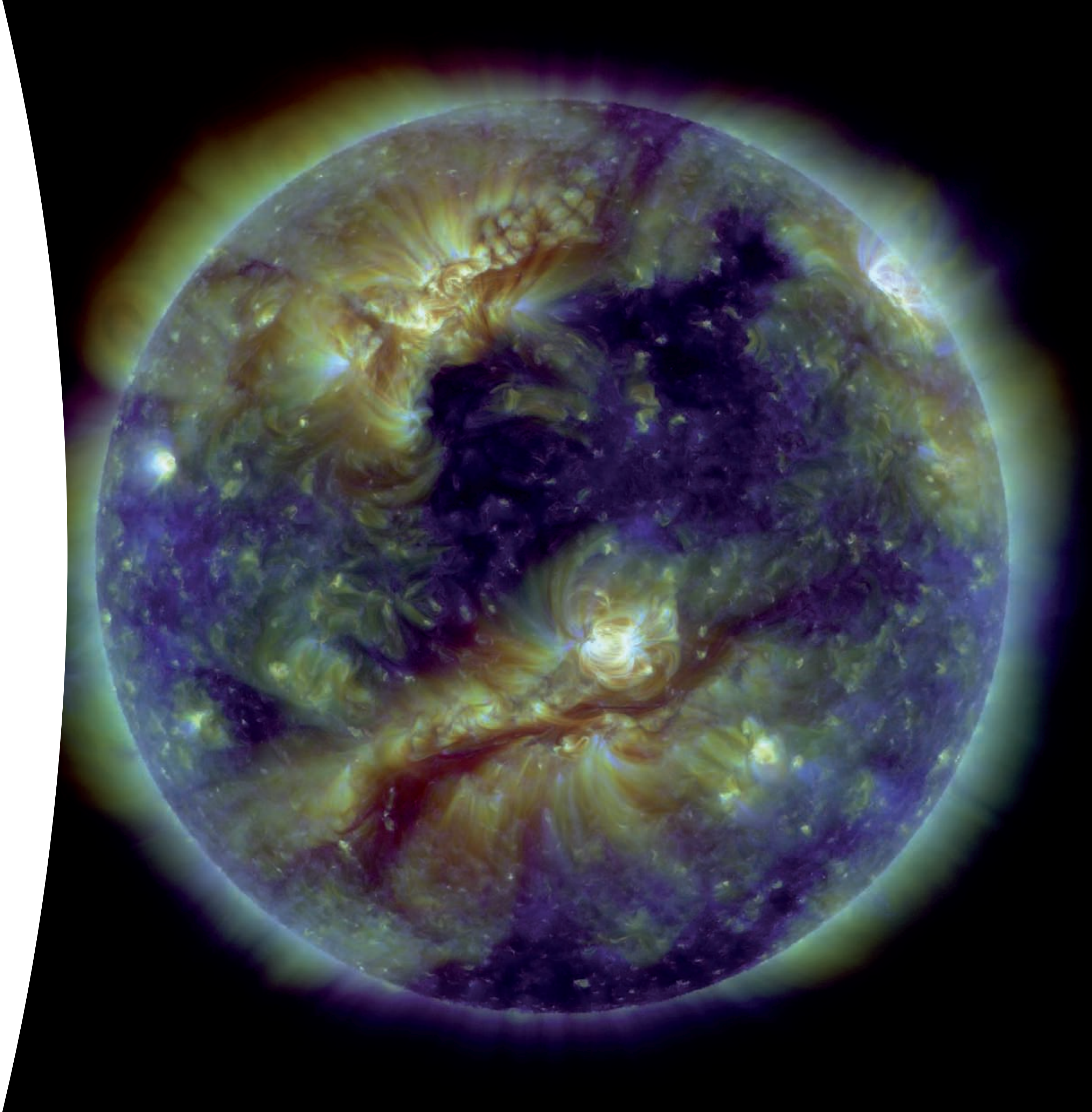
1. Astronomers refer to this distance as an Astronomical Unit, or, for short, AU.
2. In 1814, Joseph von Fraunhofer (1787–1826) was the first scientist to notice some black lines in the solar spectrum, which, as Gustav Robert Kirchhoff (1824–87) and Robert Wilhelm Bunsen (1811–1920) discovered a few decades later, turned out to be the fingerprints of chemical elements. It was in these birth years of modern astrophysics that the element helium was discovered – and curiously its existence was detected in the solar spectrum before it was discovered on Earth (which is why its name is based on the Greek word for Sun, *helios*). The element was discovered as a pure coincidence by Sir Joseph Norman Lockyer (1836–1920) the founder and editor of the famous journal Nature.
3. The Sun must never be directly viewed through a telescope without a solar filter as this can lead to severe eye injury and even blindness.

Facts

Mass	1.989 x 10^{30} kg
Radius	695,500 km
Density	1.409 g/cm^3
Rotation period	26.8 – 36 days

Image above: Sunspots in one of the active regions. *(© Royal Swedish Academy of Sciences)*

Image on the right: Oblong dark filament extending over one third of the Sun, a combination of three different wavelengths of extreme ultra-violet light. *(© NASA/SDO)*

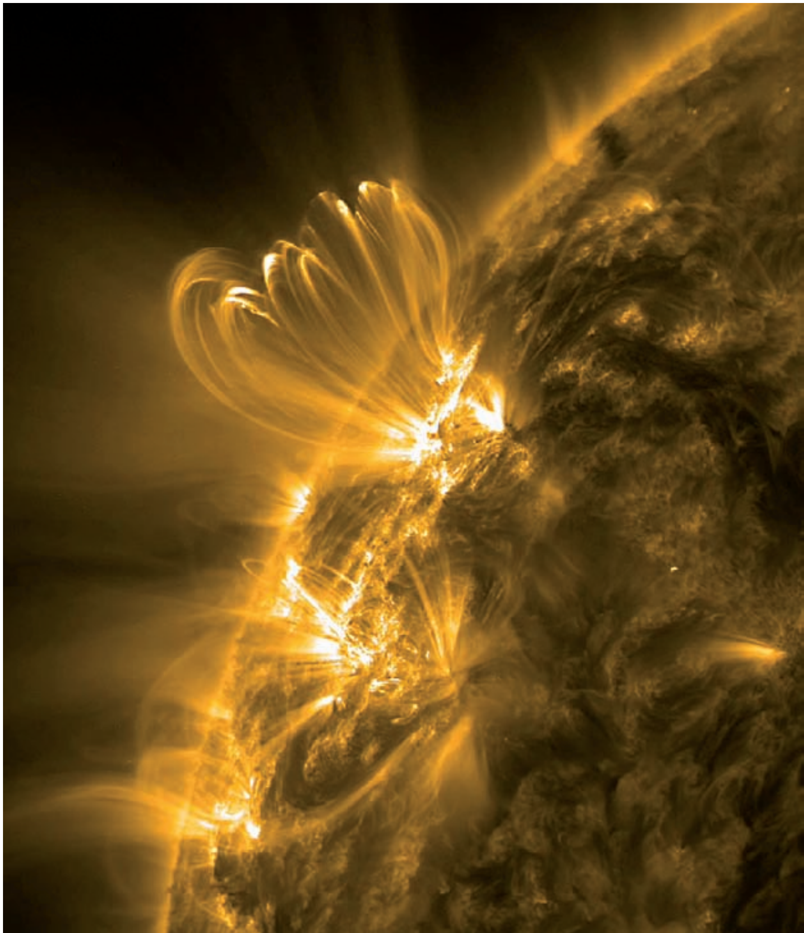


which are occasionally associated with climate changes on Earth, like the one in the second half of the 17th century. Extending over more than 20 Earth radii, the larger spots on the Sun may persist for several months. It is assumed that they develop when lines in the Sun's magnetic field are twisted by the speed differentials in its atmosphere, causing complex interactions with electrically charged hot gas particles. The resulting local 'zones of disturbance' appear on the outside as darker, colder spots. Recent research satellites have contributed some valuable new information to our knowledge on sunspots.

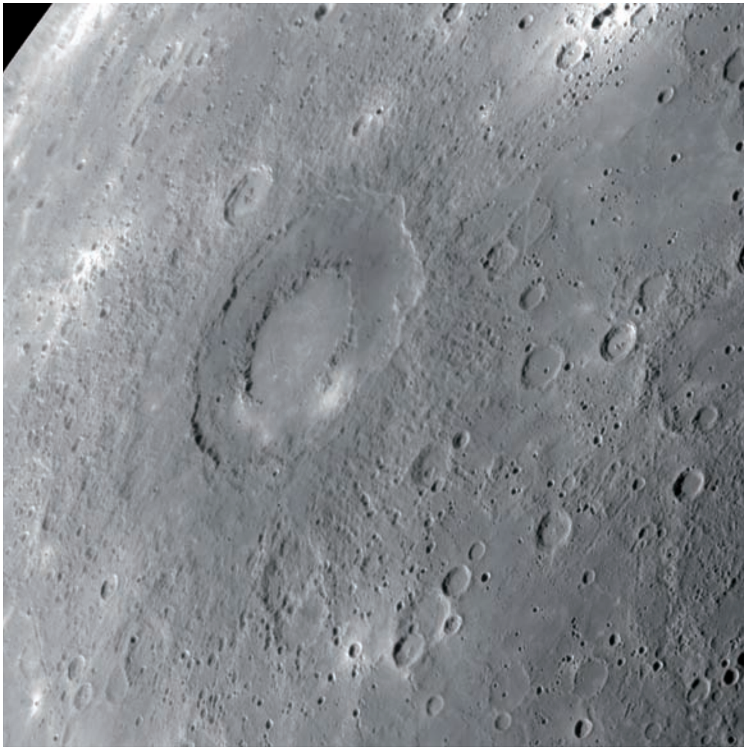
In physical terms, the sphere of the Sun may be subdivided into three zones. Within the innermost 20 percent of its radius, energy is generated by nuclear fusion, a process in which four hydrogen nuclei merge to form one helium nucleus. The process releases binding energy, i.e. the amount of energy that would have to be expended to split up a nucleus into its constituent protons and neutrons. If we apply Einstein's energy-mass equivalent, this means that the Sun loses about four million tons of its mass per second! For nuclear fusion to become possible in the first place, the center of the Sun must have a temperature of c. 15 million Kelvin and a pressure of 22 billion Pascal. In the space between 20 and 75 percent of the solar radius, the zone of energy generation is covered by the radiation zone where the energy quanta generated in the interior are scattered and reflected innumerable times, so that they reach the upper edge of the radiation center only after an average of 170,000 (!) years. Convection then carries them to the surface of the Sun within a few days, whence they spread at light speed through space in the form of light and radiation. A fraction of two billionths of that energy hits the Earth and manifests its effects.

Within the Sun, an energetic equilibrium prevails between the centrifugal pressure of gas (and, to a lesser extent, radiation) and the centripetal force of gravity. Trying to maintain this equilibrium throughout its entire life, the Sun, like any other 'regular' star, varies its shape so as to accommodate the changing fusion processes in its interior. This is why, in about six billion years from now, it will begin to pass through its Red Giant stage, during which it will gradually expand presumably to somewhere near today's orbit of Mars. As a result of the continuing loss in mass, the orbits of the inner planets will be significantly 'lifted' outwards: Planet Earth will be orbiting the Red Giant Sun near today's Martian orbit. Whether or not it will ultimately survive as an uninhabitable desert planet or whether, like Mercury and Venus, it will finally be 'incorporated' by the Sun is an open question and crucially depends on how much of its mass the Sun will lose as a Red Giant. At the end of its 12 million year lifespan, the Sun will shrink to form a White Dwarf the size of Earth. Its matter will be so compressed that a piece of it the size of a sugar lump would weigh as much as a small car. Over many billion years, the White Dwarf Sun will gradually cool down until it finally expires as a 'Black Dwarf'.

Image: Prominences in the corona, consisting of hot gas aligned along magnetic field lines. The image was taken in the extreme ultraviolet spectrum.
(© NASA/SDO)



MERCURY



Mercury is the innermost planet in our Solar System. Because it is so close to the Sun, it can be observed from Earth for only about two hours before sunrise and two hours after sunset, and that only if the ecliptic is very steeply inclined to the horizon. In a cycle of 217 years, observers on Earth may watch Mercury passing as a black dot before the bright disk of the Sun exactly twenty times in November and nine times in May. The next transit will be on 9 May 2016.

As Mercury's orbit is highly elliptical, its distance to the Sun differs greatly between aphelion and perihelion. At perihelion, the planet approaches the Sun to 46 million kilometers, counting from the Sun's center, while its distance grows to 70 million kilometers at aphelion. Because of its relative closeness to the Sun, it is fairly easy to demonstrate that the rotation of Mercury's perihelion is partly due to relativistic influences: it is the gravity pull of the Sun and, to a lesser extent, that of other planets that causes Mercury's perihelion to rotate slowly to the right around the center of gravity it shares with the Sun, so that in the long run the shape of its path around the Sun resembles a rosetta.

Mercury's rotation and orbital periods are linked, for it circles the Sun twice while it rotates three times around its axis. Consequently, a day/night period on Mercury extends over 176 terrestrial days. During that cycle, surface temperatures fluctuate between -180 and +430 degrees Celsius.

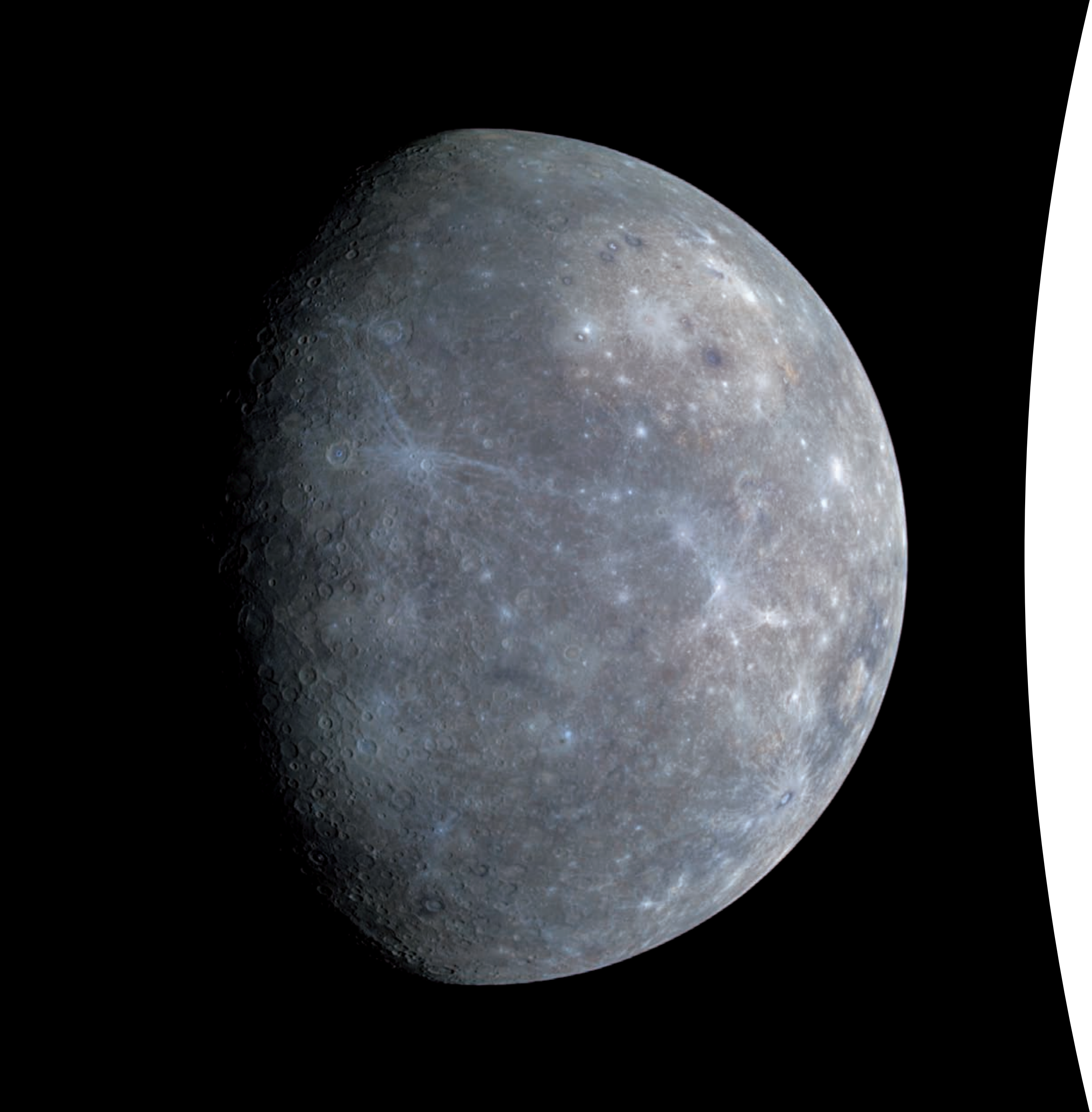
Among the terrestrial planets, Mercury is unique in more than one way. Its diameter of 4,880 kilometers makes it the smallest planet in the Solar System, in fact, smaller even than the Jovian moon Ganymed or Saturn's moon Titan. The gravitational acceleration at its surface is only a third of that of Earth but the same as that of Mars, a significantly larger planet. Despite the resulting low self-compression, its mean density is comparable to that of Earth. This leads scientists to assume that the core of Mercury must have a high metal content. Recent structural models assume there to be an extensive, iron-rich core about 4000 kilometers in diameter surrounded by a rocky mantle. The planet's high mean density and its closeness to the Sun give us important clues as to the origin and history of bodies in the inner Solar System.

The interior of Planet Mercury is subject to major tidal deformation given its extremely elliptical orbit and its coupled rotational motion. Deformations occur in combination with surface displacements and fluctuations of the planet's gravitational field, and can lead to increased seismic tremors. Mercury's tidal deformations will be the study object of the BELA laser altimetry experiment on board the European BepiColombo mission after 2022, from which scientists hope to receive further clues as to the nature of Mercury's interior.

Facts

Mass	3.302×10^{23} kg
Radius	2439.7 km
Density	5.427 g/cm^3
Rotation period	58.65 days
Orbital period	88 days
Mean distance from the Sun	57.91×10^6 km

Image: A view of Mercury. Notice the Rachmaninoff double-ring crater, a relatively recent formation with a diameter of 290 kilometers.
(© NASA/JHUAPL/Carnegie Institution of Washington)

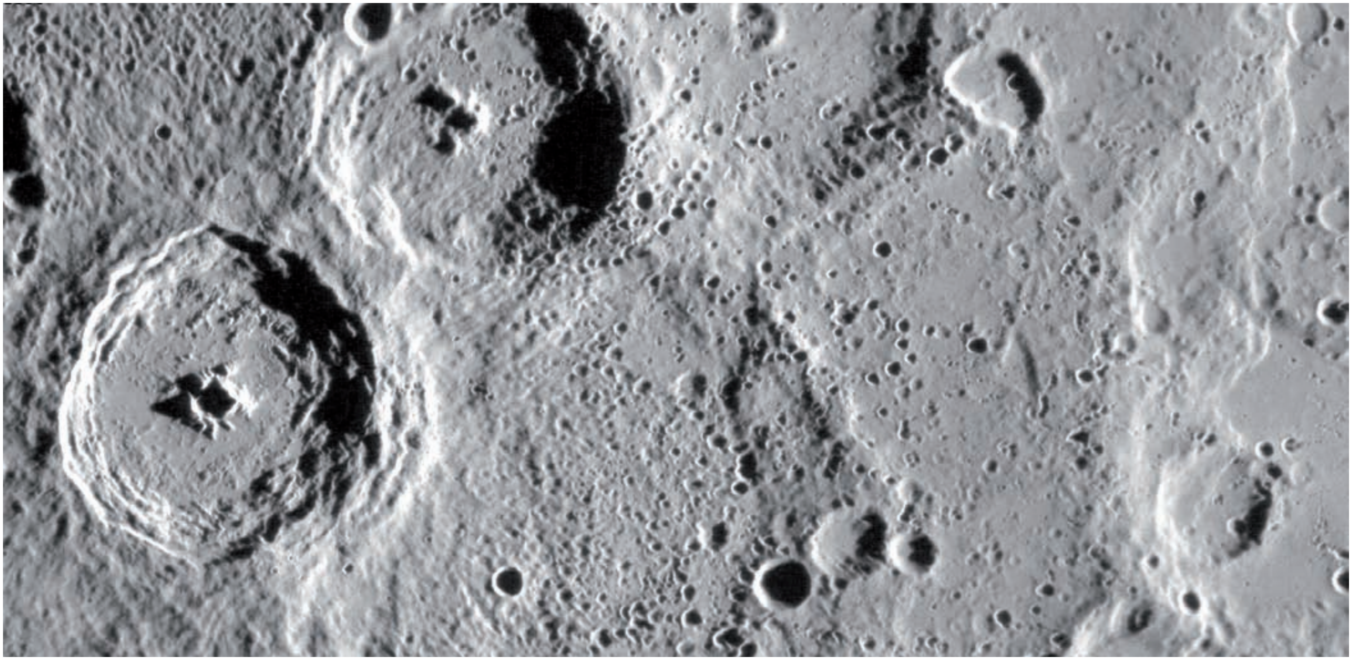


Being so close to the Sun, Mercury can be approached by spacecraft only via a complex route and with a considerable engineering effort. Both the gravitational pull of the central star and its enormous radiation levels have to be considered when approaching the planet. A first attempt to learn more about the planet's peculiarities based on the Mariner 10 flyby data in the mid-70s revealed a self-generated magnetic field in the interior of Mercury, measuring about one hundredth of that of the Earth. The MESSENGER space probe, having passed Mercury three times, swung into a highly elliptical polar orbit for a detailed exploration of the planet and its surrounding dynamic magnetic field and plasma. It was found that the prevailing north-south asymmetry of the magnetic equator results in the magnetic field lines opening up near the south pole, leaving a major area exposed to a bombardment by cosmic rays and solar wind. As a result, there is considerably more interaction between the cosmic surroundings and that part of Mercury's surface than near the north pole, leading to a much higher degree of weathering. This could also explain the existence of helium, hydrogen and oxygen atoms in the surroundings of the planet, which form a very thin 'exosphere', in which also sodium, potassium, nitrogen and argon have been detected meanwhile. The total mass of these volatile elements however is only about a thousand kilograms. Possibly some of these elements came directly from the Sun.

It is also certain now that some of the planet's deeper craters in the polar regions, which are never irradiated by the Sun and are therefore permanently cold, contain ice and other volatile compounds. The first indications were provided by radar observations

Image: The Spitteler and Holberg craters, about 65 kilometers in diameter, each with a central mountain and a terraced crater rim. *(© NASA/JHUAPL/Carnegie Institution of Washington)*

Image on the left: Global view of Mercury in true color, image taken by the MESSENGER space probe. The bright area at the top right corner of the image is the inside of the Caloris Basin. *(© NASA/JHUAPL/Carnegie Institution of Washington)*



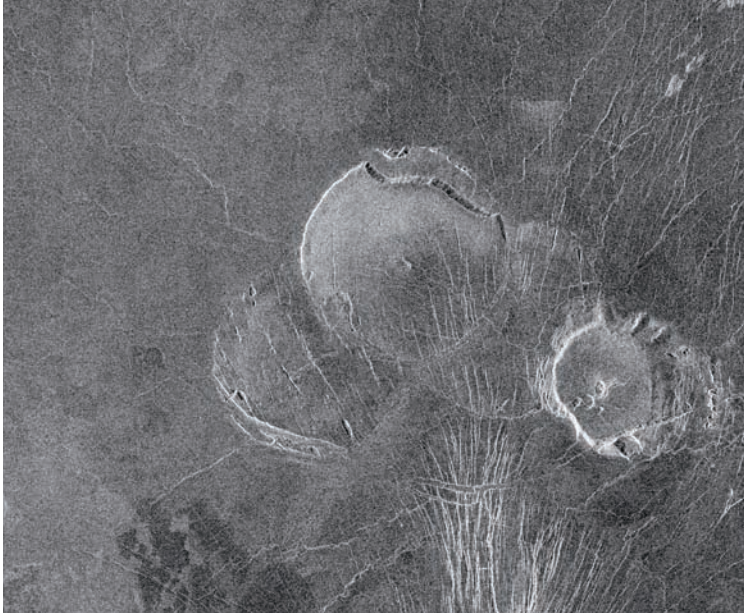
from Earth. Reflected laser pulses of MESSENGER fired into these deep craters have now confirmed these findings. Earth-borne radar observations of Mercury's surface show that the rotational axis is very slightly oblique relative to the normal of the planet's orbital plane, and that the planet on its revolution around the Sun is subject to major rotational oscillations caused by its libration. In combination with observation data now available on Mercury's extensive gravitational field, this permits the conclusion that the planet's outer, solid rock mantle is mechanically uncoupled from its solid, inner iron core through a (partly) molten layer of iron in the outermost core region. The existence of a liquid outer core region bears out the not-so-recent assumption that the planet's weak magnetic field is maintained by an active dynamo in its core.

Like the Moon, Mercury's surface is riddled with impact craters of all sizes, the most impressive surface structure being the Caloris basin with a diameter of 1,300 kilometers. During its formation, the body that struck the planet appears to have landed with so much force that the effects of the shock waves focused in the interior are apparent on the opposite side of the planet.

Another phenomenon of Mercury's surface is the large number of scarps, extending over hundreds of kilometers, which are possibly the result of a global contraction that took place during the planet's cooling phase. Another theory that has meanwhile been confirmed is that Mercury has seen a period of intense volcanism some billions of years ago. Long cracks gave way to liquid basaltic lava flows, filling valleys and crater basins on its surface. At least five percent of Mercury is covered by lava flows, extensive lava sheets on the north pole measure up to two kilometers in thickness. Given the relatively thin silicate mantle, the evidence of such heavy volcanic action comes as a surprise. MESSENGER's X-ray spectrometer detected considerable quantities of sulfur on Mercury. Also, the profuse quantity of magnesium and aluminum in comparison to that of silicon suggest that Mercury's crust in its composition must be rather heavy. This makes it resemble the upper mantle of Earth's ocean floors rather than the lighter, aluminum-rich primary crust of the Moon.

Image: One of the tallest and longest escarpments on Mercury, Beagle Rupes, deforming the elliptical Sveinsdóttir crater (bottom left). *(© NASA/JHUAPL/ Carnegie Institution of Washington)*

VENUS



Viewed from the Sun, Venus is the second planet as well as the one that is nearest to Earth. The mean distance between the orbits of the two planets is only about 41 million kilometers. After the Sun and the Moon, Venus is the brightest celestial body, reflecting a particularly great proportion of the sunlight because of its permanently closed cloud cover and its nearness to the Sun. It is often possible to observe the planet from the onset of dawn or dusk for up to four hours before sunrise and after sunset, respectively. With its diameter of 12,100 kilometers, Venus is almost as large as Earth.

Occasions when Venus passes before the disk of the Sun are rare; because the planets' orbits are not exactly on the same plane, Venus as well as Mercury, which is even closer to the Sun, do not pass before our central star at every opposition, a constellation in which the Sun, the Earth and the planet in question are on an imaginary straight line. For both planets, these rare events happen first after eight years, then after 121.5 years, then after another eight years and lastly after 105.5 years. Each time, the planets can be viewed through a specially-prepared telescope as small black dots before the Sun. A famous account of a Venus passage on 3 June 1769 is that of Captain James Cook on the island of Tahiti, which Cook visited specifically for the purpose. There was no single transit in the 20th century. The two most recent passages of Venus took place on 8 June 2004 and on 6 June 2012. The next transit visible from Earth will not occur until 2117.

Venus orbits the Sun in somewhat less than 225 days at an average distance of 108 million kilometers. Unlike Earth and most of the other planets, its own sense of rotation is retrograde, meaning that it rotates against the direction of its motion around the Sun. Because of this, one day on Venus (from one sunrise to the next) lasts 117 terrestrial days. As its axis of rotation is almost vertical to its orbital plane it has practically no seasons.

The landscape of Venus is very complex. 70 percent of its surface consists of extensive plains, called the regiones, which are elevated two kilometers above the reference level. 20 percent of the surface is classified as depressions with a depth of up to two kilometers. The remaining ten percent is Venusian highlands, called the terrae, which are mainly concentrated in two regions: Ishtar Terra in the North, with the eleven-kilometer Maxwell Montes at its eastern edge, and Aphrodite Terra with Ovda Regio and Thetis Regio in the equatorial zone; both are as large as continents on Earth. Aphrodite Terra also features an enormous valley called Diana Chasma that is two kilometers deep and almost 300 kilometers wide. Being of a size comparable to that of Valles Marineris on Mars, it is probably tectonic in origin, meaning that it was torn open by stresses in the crust of Venus. Beta Regio is an extensive volcanic area that rises as high as four kilometers.

More than three quarters of the surface of Venus are known to be of volcanic origin. All in all, more than a thousand volcanos and many bizarre-looking formations of volcano-tectonic origin have been detected on Venus, such as the coronae ('crowns'), ring-shaped structures with a diameter of up to 300 kilometers but elevated only a few hundred meters above the surface, which are uniquely to be seen on Venus. Impact craters have been found as well, although much fewer than on Mars, for example. From this observation, we may properly conclude that the Venusian surface is not very old. It is thought that roughly between 1,000 and 500 million years ago, a global disaster reshaped the landscape of Venus from the ground up. The reasons for this 'renewal process' are not yet fully understood. Conceivably, a series of widely disseminated volcanic eruptions covered nearly the entire

Facts

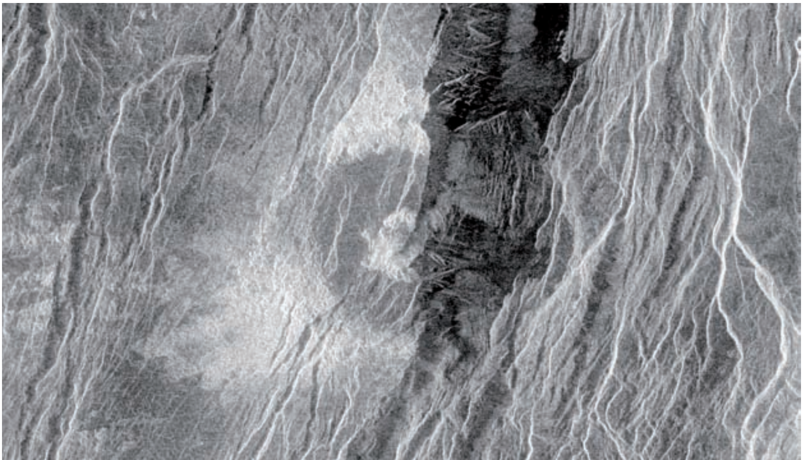
Mass	4.869 x 10^{24} kg
Radius	6051.9 km
Density	5.24 g/cm^3
Rotation period	243 days
Orbital period	224.7 days
Mean distance from the Sun	108.2 x 10^6 km

Image: Three unusual volcanos in the plains of Guinevere Planitia. *(© NASA/JPL)*

planet with lava, filling existing craters. The only part that has remained unaffected by these events is the highlands, which are considerably older than the volcanic lowlands of Venus, and which are thought to have been warped upward by tectonic forces.

From the global radar map generated by the Magellan space probe between 1990 and 1994 we know that the crust of Venus, unlike that of Earth, is obviously not subdivided into large continental plates. Scientists suppose, however, that the geological activity on Venus mirrors part of the Earth's early history, since we do not know precisely whether or not continental plates already drifted across the Earth's plastic mantle during the first two or three billion years. Soil samples taken by the Russian probes Venera 13 and 14 show that the composition of the ground roughly resembles that of the ocean floors on Earth: a large proportion of the Venusian crust consists of basalt, a dark, volcanic silicate rock. Both landers touched down on a volcanic slope. Measurements of ESA's Venus Express mission demonstrate that the rock composition of the Venusian highlands is slightly different from that of the volcanic lowlands. Data from Venus Express also suggest that volcanos were active well into the most recent geological history of the planet and may, in fact, still be active today.

Compared to Earth, the mass of the Venusian atmosphere is around 90 times greater. At ground level, the mean surface temperature is 477 degrees Celsius by day and by night, and the atmospheric pressure is 93 bar, which corresponds to the pressure prevailing in our oceans at a depth of one kilometer. The planet's troposphere, the region in which weather happens, extends to an altitude of 100 kilometers (versus 10 kilometers on Earth). Going up from ground level, temperatures continuously decline up to an altitude of 60 kilometers, after which they remain relatively constant to the upper edge of the troposphere. Unlike Earth's, the Venusian troposphere directly borders the thermosphere which, however, deserves its name only on the day side of Venus. On the night side, the thermosphere may be properly called a cryosphere because its temperature drops to -173 degrees Celsius.



Three thick cloud layers float at altitudes between c. 45 and 70 kilometers, completely shrouding the planet. Wind currents course through them in different directions, causing the upper cloud layer to rotate backwards against the equator. In fact, it circles the equator of the planet from east to west in four days at a speed of 360 kilometers per hour in a movement called super-rotation, in which the uppermost layer of the atmosphere rotates more quickly than the lower layers and even the planet itself. In addition, there are other zones where currents circulate between the equator and the poles, albeit at lower velocities; they probably transport heat to the poles. As a result, temperatures are nearly the same everywhere on the surface of Venus.

This extensive dynamism in the Venusian atmosphere is probably caused by the interaction of several factors. Venus itself rotates very slowly; this, combined with its relative proximity to the Sun and the warming associated with it – after all, it receives twice as much solar radiation as Earth – may cause large-scale convection or circulation currents in the atmosphere. On the surface of Venus, on the other hand, an almost perfect dead calm prevails.

Having hardly changed at all in more than four and a half billion years, the composition of the Venusian atmosphere reflects an early stage of planetary development. It contains 96.5 percent carbon dioxide (CO_2) and no more than 3.5 percent nitrogen (N_2). Other substances that can be found at various altitudes include sulfur dioxide (SO_2), water (H_2O) and, consequently, sulfuric acid (H_2SO_4). It is the carbon and sulfur dioxide as well as the modicum of water contained in the higher layers of the atmosphere that are responsible for the massive greenhouse effect on Venus: although

Image: Between Rhea and Theia Mons in the Beta region, a crater is 'cut in half' by numerous fracture lines.
(© NASA/JPL)

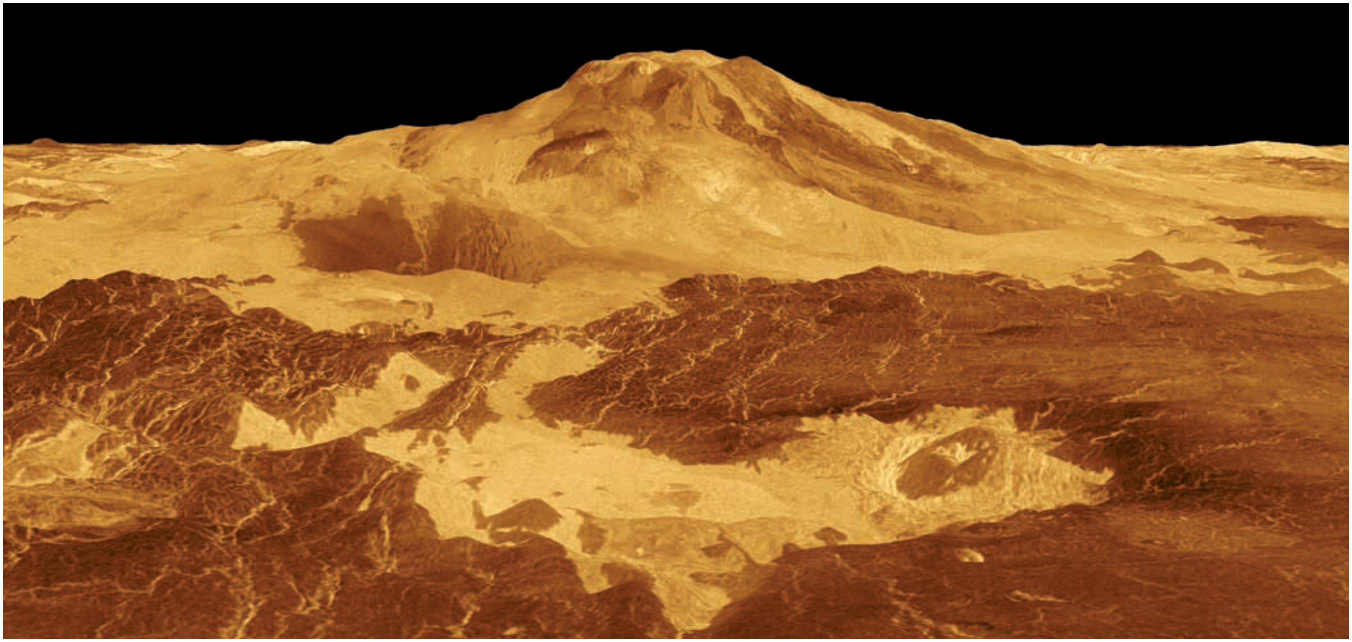
Image on the left: Computer simulation of global view based on radar data acquired by Magellan. *(© NASA/JPL)*

80 percent of the Sun's rays are reflected by the clouds, the remaining 20 percent are enough to heat up the planet, assisted by the intense greenhouse effect. If a similarly extensive greenhouse effect were to happen on Earth, it would have devastating long-range consequences for our planet's biomass.

Although nearly identical in size, Earth and Venus necessarily developed along different lines. The reason for this lies in the fact that the Earth's distance from the Sun is greater by a margin which, though comparatively small, is crucial. In the early days of the Solar System, both planets received approximately equal amounts of volatile elements like hydrogen. On both planets, water was transported to the surface by volcanic processes, a lesser amount being provided by comets and asteroids which, 4.5 to 3.8 billion years ago, struck both planets in much larger numbers than today. It was probably this water which formed the oceans that have been a salient feature of Earth ever since. Venus being warmer, the question is whether bodies of water ever formed on its surface; if they did, they certainly would not have existed for very long – the water would have evaporated, and much of it would have been lost to space.

Most of the carbon dioxide contained in the Earth's primal atmosphere was either converted into rock by sedimentation on the ocean floors or turned into oxygen and carbohydrates by photosynthesis and other organic processes. On Venus, on the other hand, the temperature, which had been somewhat more moderate initially, ultimately rose to a level high enough not only to evaporate any oceans that might have existed. Possibly the carbon dioxide that had once been fixed in ocean floor sediments may also have been released from the parent rock back into the Venusian atmosphere. At present, the Earth holds as much carbon dioxide as Venus, the only difference being that the molecule here is fixed in the limestone and carbonate rocks of the Earth's crust or dissolved in the water of the oceans.

Image: Perspective view of the 8,000 meter volcano Maat Mons, vertical scale is exaggerated 10 times.
(© NASA/JPL)



THE EARTH-MOON SYSTEM

Earth

Earth is the largest and heaviest of the four 'inner' planets of the Solar System, which are also called terrestrial or Earthlike because of their similarity to our home planet. Other than Earth, this group comprises the planets Mercury, Venus and Mars, but also the Moon is considered to be part of it. The Earth accounts for more than 50 percent of their total mass. Compared to the other Earth-like bodies, developments on Earth have been highly differentiated: in the course of four and a half billion years, the Earth produced more mineral and rock variants than any of its planetary neighbors. More importantly, it is unique because it provides all those physical and chemical conditions that are needed for the long-term survival and evolution of diverse highly-organized life forms. Earth is located in the 'habitable zone', a region around the Sun that can maintain water (H_2O) in a stable liquid phase.

The Earth orbits the Sun in 365.24 days at an average distance of 149.6 million kilometers – the 'astronomical unit' – and a mean velocity of 29.8 kilometers per second. The plane of the Earth's orbit is called the ecliptic. The inclination of the Earth's axis away from the vertical on the ecliptic is the reason why we have seasons, the onset of which is minimally but constantly delayed because of a very small 'rocking' motion of the Earth's axis itself, a phenomenon called precession. The Earth's proper rotation, in turn, causes the familiar alternation between day and night, whose respective length varies with the season and the latitude. The interplay between the Earth's rotation and the gravitational influence of the Sun and the Moon causes tides which affect not only the seas but also land and air masses.

Earth's inner structure is relatively well known. Studies investigating the propagation of quake shock waves within the Earth's body show that the Earth has a core of iron and nickel which, measuring nearly 6,000 kilometers in diameter, is solid on the inside and liquid on the outside. It is the moving, conductive metal core that generates the Earth's magnetic field which, although permanent, is subject to continuous change. At the center of the Earth, a temperature of more than 6,000 degrees Celsius and a pressure of several million bars prevail. The core is surrounded by a 3,000 meter thick mantle. Above the mantle, there is a thin crust less than 100 kilometers thick, the lithosphere, which is fragmented into six larger and several smaller plates. Following the Archimedean principle, the continents drift isostatically on these plates like icebergs float in the sea.

Germany's meteorologist and geophysicist Alfred Wegener (1880–1930) concluded from his studies of continental coastlines, crystalline sediments and rare fossils that

Facts

Mass	5.976×10^{24} kg
Mean radius	6378.1 km
Density	5.534 g/cm^3
Rotation period	23.93 h
Orbital period	365.24 days
Mean distance from the Sun	1.496×10^6 km

Image: The Rub' al Khali desert on the Arabian Peninsula, one of Earth's largest sandy deserts. *(© NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team)*

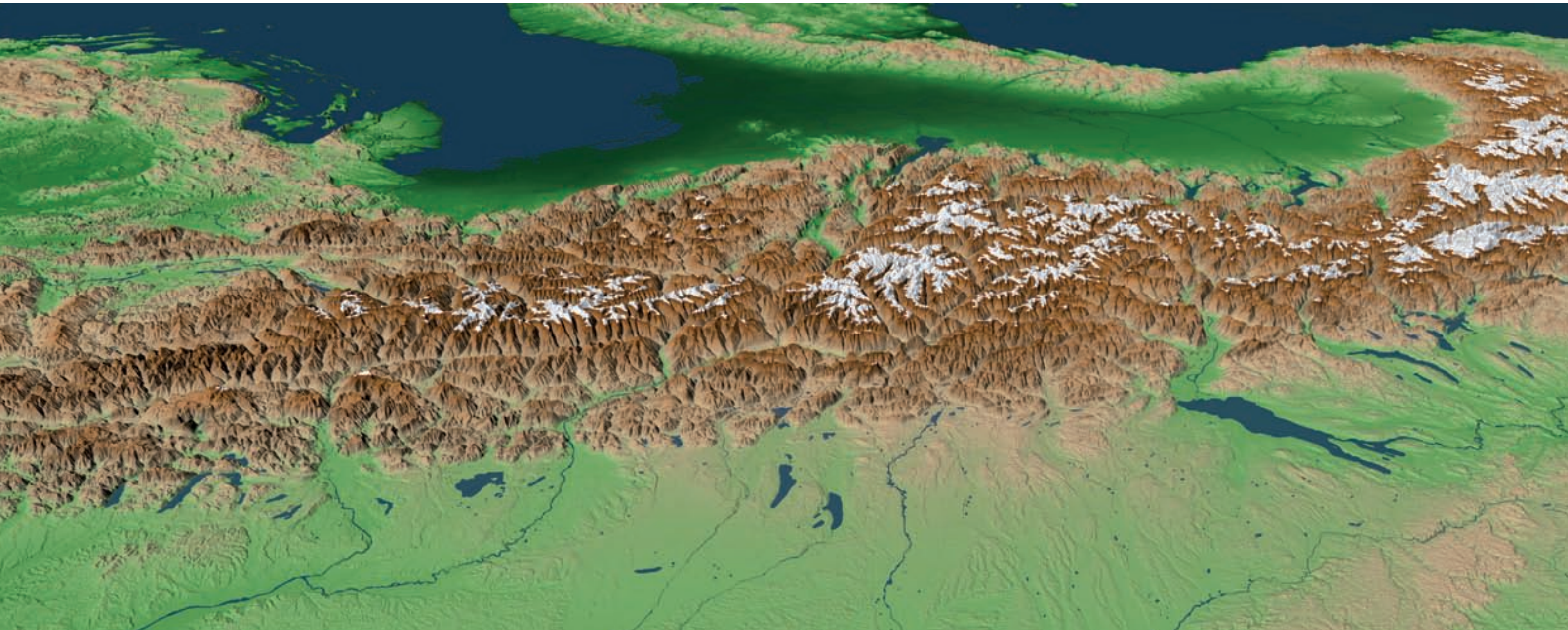
continents move relative to each other in various directions at a speed of a few centimeters per year. His observations provided the basis for today's plate tectonics models. As the mantle is denser than the crust, the plates of the lithosphere float on it, powered by currents in the upper mantle's convection cells. Where crustal plates drift apart, rifts – most of them submarine – open up, in which magma rises to the surface (as it does, for example, along the mid-Atlantic ridge). Where they collide, so-called subduction zones form along which the rock of the crust dives into the Earth's interior, as it does, for instance, off the west coast of South America. One consequence of such a head-on collision of two continents is that high mountain ranges fold up (such as the Andes or the Alps). Along a lateral displacement line of two tectonic plates, like the Saint Andreas Fault in California, and at the other two plate boundaries already mentioned, earthquakes are frequent and volcanism is very active. Thus, the Earth's crust changes and renews itself continuously, which is why the major part of it is now less than 200 million years old. Only when the decay of radioactive elements in the Earth's interior fades and the energy thus released is no longer enough to melt rock will the crust stop renewing itself. From then on it will be exposed to erosion by wind and water.

Nearly 71 percent of the Earth's surface is covered by oceans. These bodies of water are able to store large volumes of (heat)

Image above: Lake Manicouagan in the northern part of Quebec, Canada, the remnants of an impact crater. *(© NASA/GSFC/LaRC/JPL, MISR Team)*

Image below: Perspective view of the Alps and the Alpine foothills, the result of a collision between the Eurasian and African tectonic plates. *(© DLR)*

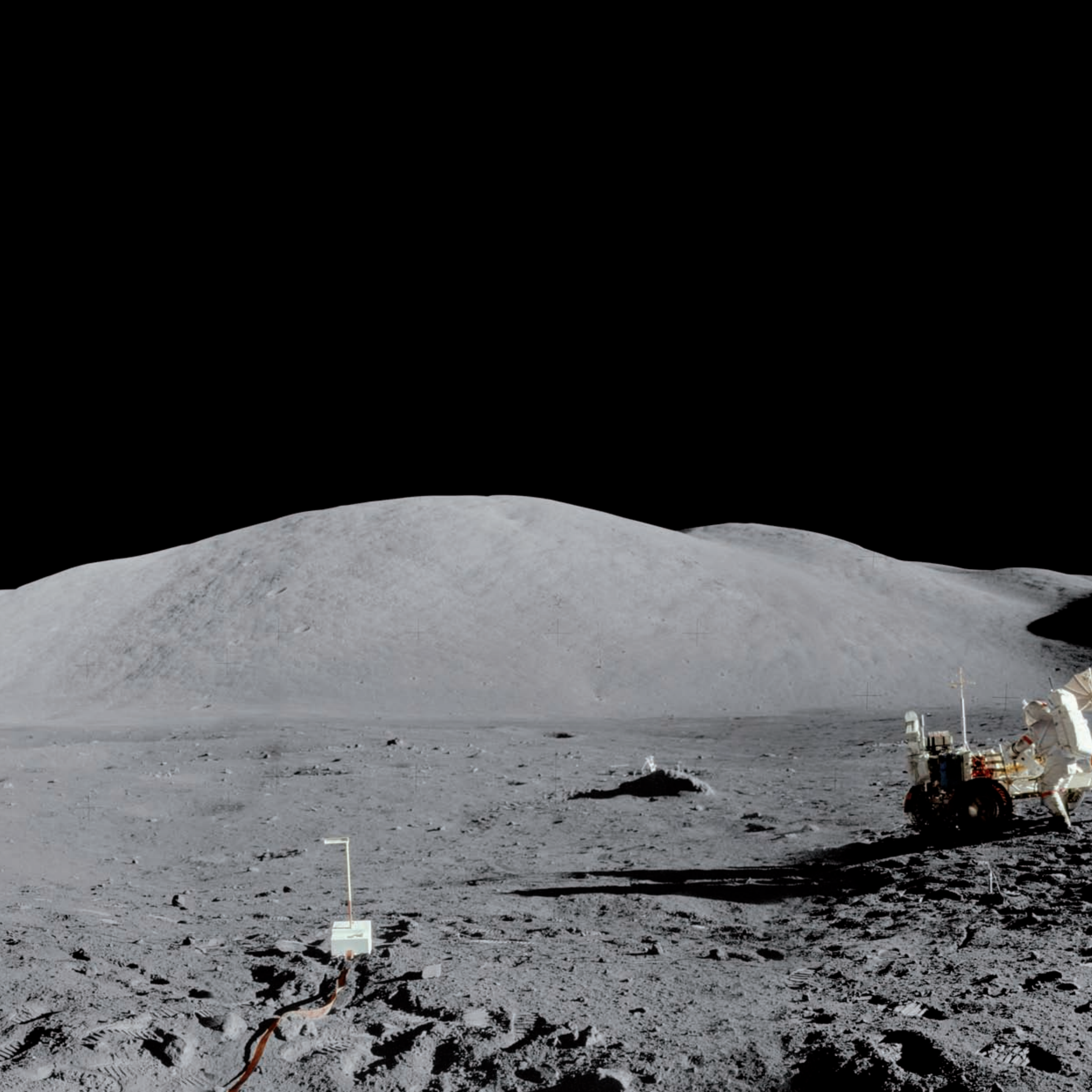
Image on the left: Global view of Earth, showing North and Central America, photographed by Apollo 16 on its way to the Moon. *(© NASA)*

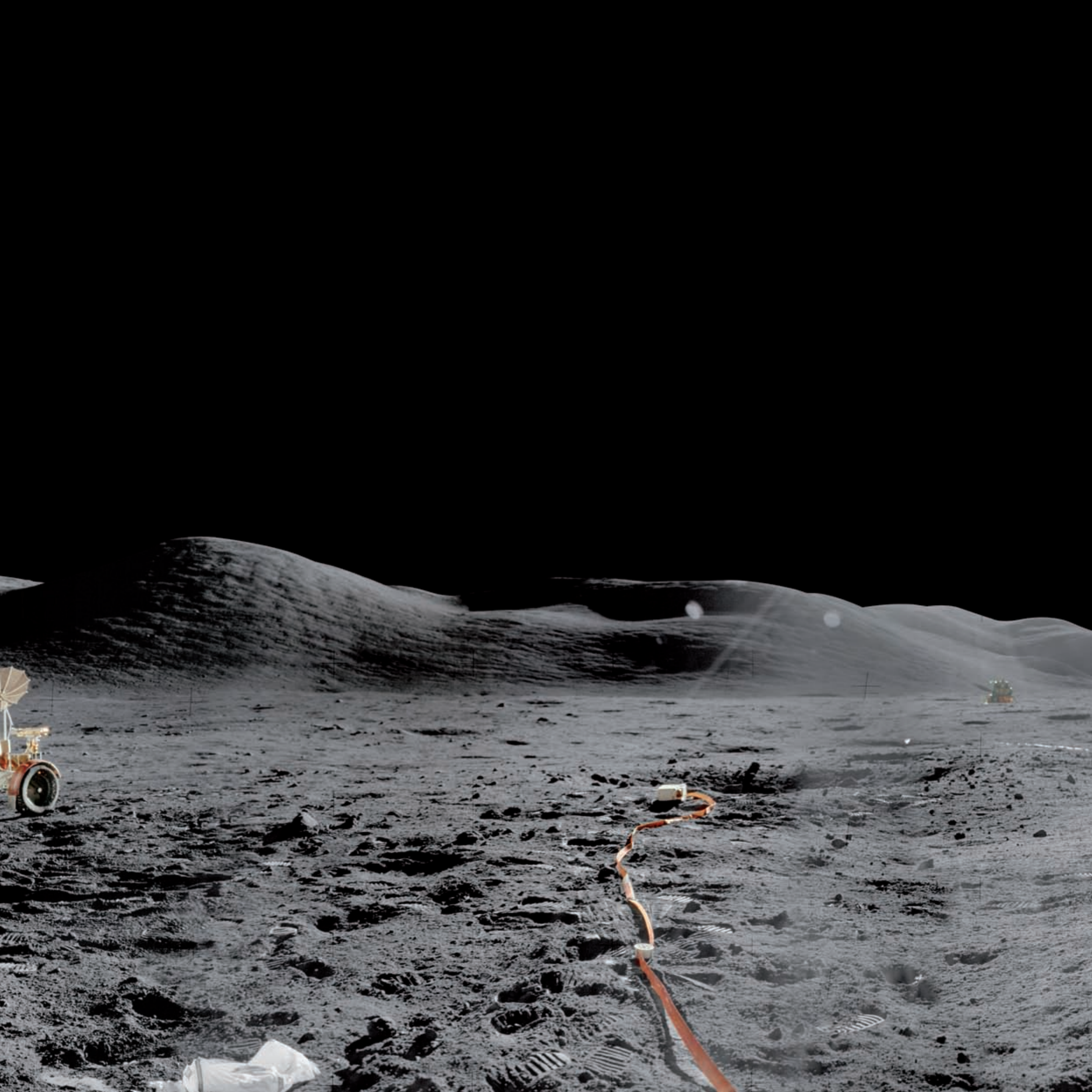


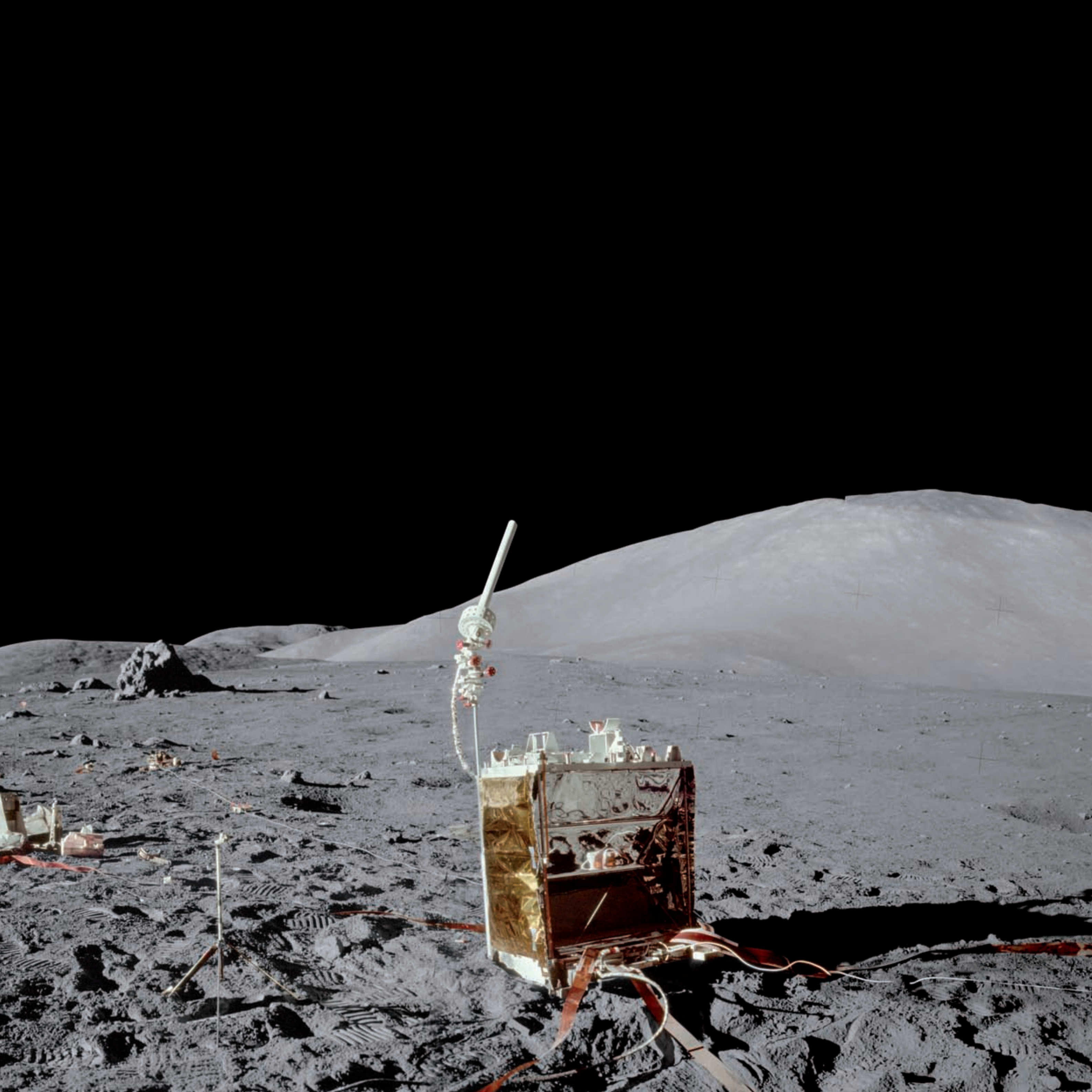
energy which they release again to the planet's air envelope and land masses after a certain delay – with fundamental consequences for the Earth's climate. Today, an increased greenhouse effect with its growing concentration of water vapor and CO_2 in the atmosphere would be powerful enough to transform the Earth's landscapes more rapidly than its fauna and flora could adapt to it. To keep tabs on this development, space-based remote sensing can deliver valuable information on climate trends and provide long-term forecasts. Next to atmospheric action such as wind, the other factor that significantly influences the erosion of Earth's surface is water. A theory discussed by scientists for some time now is that a large proportion of the Earth's oceanic water might have been provided by comets striking the young planet. The face of the Earth, especially during its earlier geological history, was frequently struck by meteors, which at that time were several orders of magnitude heavier than they are today. It can thus be assumed that at least some of these events were impacts by water-rich comets.

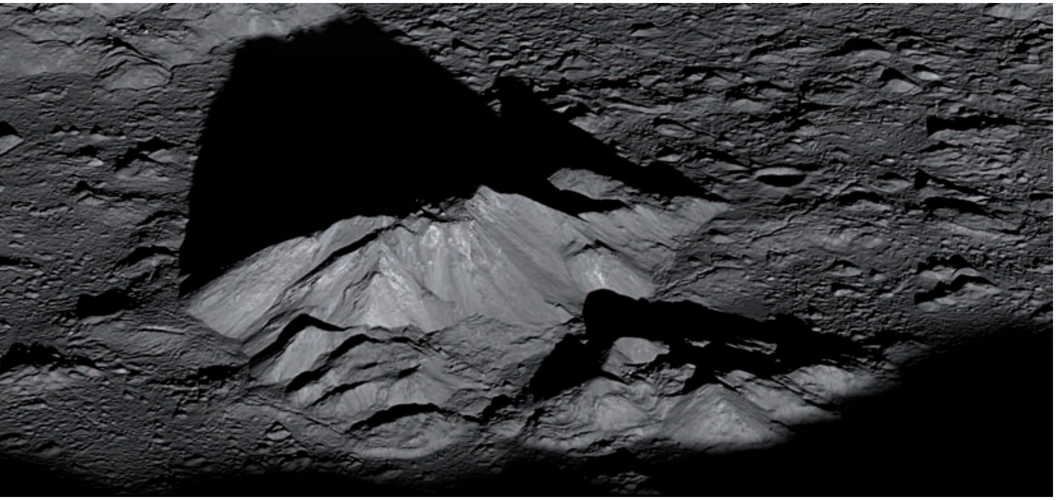
Thanks to its mass, Earth has a gravitational pull that is big enough to retain an atmosphere permanently. At present, Earth's 'lower' atmosphere, the troposphere, consists of 78 percent nitrogen (N_2),

Image: Clouds and weather events in the Earth's atmosphere above the Pacific Ocean, photographed from the ISS. *(© NASA)*









21 percent oxygen (O_2) and one percent of the noble gas argon; other gases are present in the form of traces only. Free oxygen, which is vital for all aerobic organisms, always was and still is generated exclusively by plants and algae through photosynthesis. If this process were to fail globally, free oxygen would disappear after about 300 million years, and the chemical balance would be restored to the status it had when life began. Extending to an altitude of ten kilometers, the troposphere is the zone in which our weather is made. Following above the troposphere are the stratosphere (up to an altitude of 50 kilometers), the mesosphere (up to 80 kilometers) and the thermosphere which, comprising the ionosphere and the suprasphere, extends to a height of c. 800 kilometers. Lastly, there is the ultra-thin exosphere. The terrestrial stratosphere produces ozone (O_3) which protects mainly the inhabitants of dry land from the Sun's death-dealing UV rays; at present, this layer is being depleted by harmful man-made influences, especially above the cold polar zones.

Image: A high-resolution, low-sun view of the central peak of Tycho crater. *(© NASA/GSFC/ Arizona State University)*

Image on previous page: Panoramic view of the Apollo 17 landing site, showing astronaut Harrison 'Jack' Schmitt examining Tracy's Rock. *(© NASA/JSC)*

Moon

The Moon is second to the Sun in terms of its prominence in the sky and, not least, its significance in the history of human civilization. Since the dawn of mankind, the Moon's phases, i.e. the 'monthly' return of a full moon, have been serving as a measure of time und have provided a basis of scheduled agricultural activities and the study of the laws of nature. In many civilizations and languages, the Moon is attributed a female gender and associated with fertility. Irregular events caused by the orbital movement of the Moon around Earth, such as solar and lunar eclipses, had a powerful mythological significance for our ancestors.

The Moon, so far, is the only terrestrial body that has been visited not only by a large number of space probes but also by humans. From 1969 until 1972, the U.S. Apollo missions sent 12 astronauts to the Moon, returning to Earth with about 382 kilograms of rock samples. Most of these samples are very old, i.e. over three and partly even four billion years. The exact analysis of their chemical and mineralogical composition enables us to take a look back at the early days of the Solar System and the history of the Earth-Moon system. They give us important clues as to the origins of the Solar System as such, and especially of the four terrestrial planets and the larger asteroids. At the same time, lunar research forms the basis of a better understanding of the early Earth and its development. The Moon may have played a crucial part in the evolution of life, since its gravity has helped to keep the Earth's rotational axis stable over billions of years.

The Moon revolves around Earth with respect to the stars in 27 days, 7 hours and 43.7 minutes, in the same sense of rotation as that of Earth orbiting the Sun. It takes the Moon almost precisely the same time to turn once about its own axis as it takes it to travel once around the Earth. This phenomenon is known as synchronous rotation, and is caused by the tidal locking effect between the Earth and the

Facts

Mass	7.3483×10^{22} kg
Mean radius	1737.4 km
Dichte	3.341 g/cm^3
Rotation period	27.32 days
Orbital period	27.32 days
Mean distance from Earth	384,000 km

Moon. Synchronous rotation makes the Moon always face the Earth with the same side, which, for this reason, is called the near side of the Moon. The far side can never be seen from Earth. It was photographed for the first time by the Soviet Union's Lunik 3 spacecraft in 1959. However, thanks to the Moon's librations, a small rocking motion it performs on its slightly elliptical path around Planet Earth, as much as 59 percent of the Moon's total surface can be seen from Earth.

Earth's moon is the smallest of the Earth-like, terrestrial bodies of the inner Solar System measuring about 3,475 kilometers in diameter, it has a surface of just under 3.8 million square kilometers, which is only one-fortieth of the surface of all of Earth's continents. Given its small size, the Moon's mass is too small to maintain an atmosphere. The Earth's satellite is surrounded by only – extremly – thinly distributed ten tons of atoms and ions of volatile elements in an ultra-thin exosphere whose total mass is estimated to be less than ten tons, which is very close to a vacuum. This exosphere contains sodium and potassium atoms stirred up by solar winds from the dust on its surface, called regolith. There is also helium (^{4}He) as part of the solar wind itself. Moreover, traces of argon (^{40}Ar), radon (^{222}Ra) and polonium (^{210}Po) have been detected – produced by the radioactive decay of the Moon's crust and mantle, and subsequently released into the exosphere in the form of gases.

When looking at the surface of the Moon, two regions can be immediately distinguished: the bright highland region, which constitutes over 80 percent, and the maria, regions which make up a little less than 20 percent. The highlands have a high albedo, and thus reflect a greater portion of the incident sunlight back into space than the mare regions which reflect much less light. Moreover, the highlands are riddled with a much larger number of craters, suggesting that this part of the Moon's surface is of a much higher age. Based on spectral data, the surface can be subdivided into at least three large areas, so-called 'terranes', each of which has its own specific mineralogical and/or geochemical composition. The structure of the Moon is far more complex than was assumed by scientists until a few years ago.

Image: View of the lunar surface with numerous craters, taken from Apollo 8, showing the 72-kilometer Goclenius crater (foreground) which was named after the German physicist Rudolf Gockel. *(© NASA)*

The maria are of volcanic origin and are mainly concentrated on the Earth-facing side. They are younger than the highlands, and fill three very large circular basins which have been created by the impacts of asteroids. The fact that there are more impact craters filled with lava on the near side rather than the far side of the Moon can be ascribed to the fact that the lunar crust is significantly thicker on the far side, which made it more difficult for magma to exude from the Moon's mantle.

The theory is that Earth's satellite came into being when, some 4.4 to 4.5 billion years ago, a planetary body about the size of Mars collided with Earth, which was young at the time but already differentiated into a crust, a mantle, and a core. As a result of this event, a major portion of the Earth's mantle evaporated and was ejected into space, where it condensed into a ring which orbited the Earth at the level of its equator. It was the accretion of this disc of dust particles and rock surrounding the Earth that eventually formed the Moon.

Most of the Moon's geological development ended relatively soon. Given the continuous bombardment of the early Moon by asteroids and comets as well as the decay of heat-producing radioactive elements in its interior, the early phase of the Moon's history saw the formation of a global, several hundred kilometers deep ocean of magma. As the bombardment and radioactive decay subsided, this magma ocean cooled down, leading to the crystallization of a sequence of rock-forming minerals. As a first stage, metallic iron sank to the bottom, to form a small core which was only a few hundred kilometers in size. Next, heavy minerals rich in magnesium and iron developed, which also sank to the bottom and formed a mantle. What followed next was the increasing formation of other minerals rich in iron, and finally the formation of a primary crust, consisting of light silicates rich in aluminum. Given their low density, these minerals, called anorthositic feldspars, floated to the top of the magma ocean that had meanwhile almost completely solidified, to form the lunar highland crust.

Elements such as potassium, rare earths and phosphor which are difficult to incorporate into the crystal lattice of rock-forming minerals, concentrated at the base of the anorthositic crust. A partial re-melting of the mantle finally led to an upwelling of iron and magnesium rich magmas, forming the basaltic rock which today covers the maria regions. All in all, the Moon, having a core, a mantle, and a crust, is a fully differentiated celestial body, which makes it only marginally more primitive than the planets of the inner Solar System. A question that has not been answered yet is why the crust of the far side is nearly twice as thick as that of the Earth-facing side of the Moon.

Image: Near-true color image of the north pole and the near side of the Moon, shot by Galileo.
(© NASA/JPL/USGS)

In the period that followed, the face of the Moon was scarred by frequent and violent impacts of meteorites and asteroids. The biggest impacts penetrated the crust deeply enough to enable basaltic lava flows to rise to the top and be released to the surface. Over several hundred million years, the huge impact craters filled with basalt, making them appear darker in color than the surrounding highland rock. Seen from Earth, these darker areas appeared like water oceans, an assumption that led to the basalt-filled impact craters being named 'seas' (or, in Latin, 'mare') to this very date: Mare Imbrium, Mare Serenitatis or the Oceanus Procellarum.

The volcanic evolution largely came to its end about three million years ago, and only sporadically, until about 1 – 1.5 million years ago, did any magma flows reach he surface of the Moon. Since then, the Moon is geologically almost completely inactive, a celestial body which is too small to keep an atmosphere of volatile gas molecules and has no major water resources. However, data from the lunar probe Lunar Prospector which orbited the Moon between 1997 and 1999 has nurtured the assumption that the deep craters at the north and south poles which are permanently shaded contain a considerable amount of water ice. A detailed study of these presumed water ice deposits was the objective of a number of recent international lunar missions. Data from a U.S.-built spectrometer installed on the Indian Chandrayaan-1 mission not only confirmed that ice deposits do, in fact, exist in the deep polar craters, but water was found to be present in the minerals and the regolith everywhere on the Moon's surface, albeit in very low concentrations.

The Moon has once again become one of the most important study objects in planetary research. Following a long pause in lunar research, the past 15 years have seen several orbiter missions, carried out by the USA but also by the emerging Asian spacefaring nations. Among the most scientifically prolific ones were the Japanese mission Kaguya-SELENE (2007 until 2009), the USA's LCROSS impact experiment (2009), India's orbiter mission Chandrayaan-1 (2008 until 2009), NASA's twin satellite mission GRAIL to measure the lunar gravity field (2011 until 2012) and above all the USA's Lunar Reconnaissance Orbiter, which has been in a low polar orbit around the Moon since June 2009, taking high-resolution photographs and creating a topographical map.

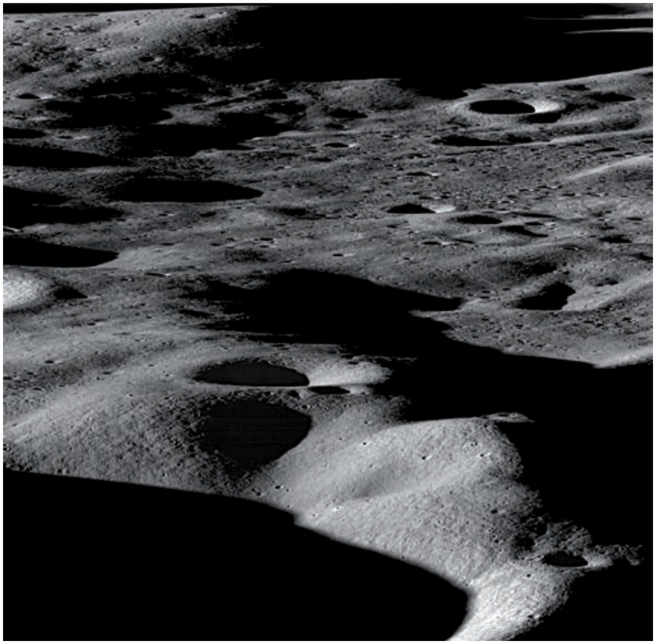
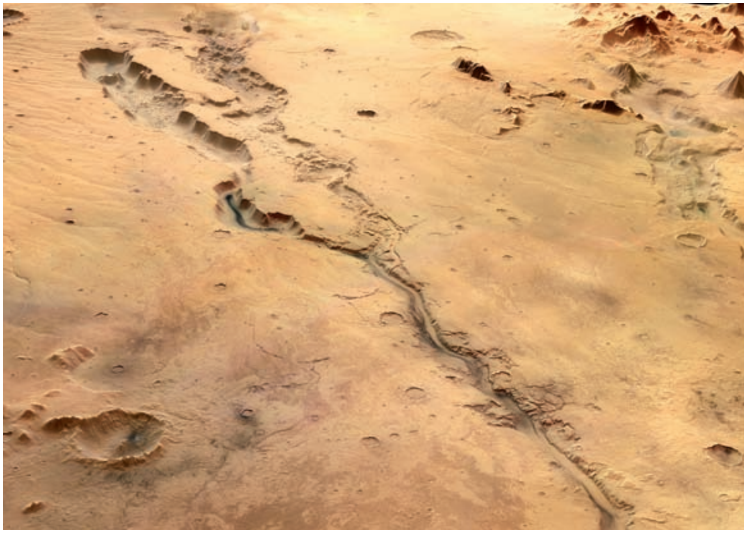


Image: A view of the northern rim of Cabaeus crater, photographed by the Lunar Reconnaissance Orbiter, target area of the LCROSS probe which impacted there in 2009. *(© NASA/GSFC/Arizona State University)*

MARS



The fourth planet from the Sun, Mars resembles Earth in many ways. Although it is only half the size of our globe and its ferrous core is smaller, it does have seasons which last about six months each because the planet takes longer to complete an orbit around the Sun. Moreover, Mars features ice caps at the poles and possesses a thin atmosphere. The small iron core of Mars is surrounded by a mantle of siliceous rock that is rich in iron. Circumstantial evidence indicates that in its early age, Mars had a magnetic field, weak though it probably was.

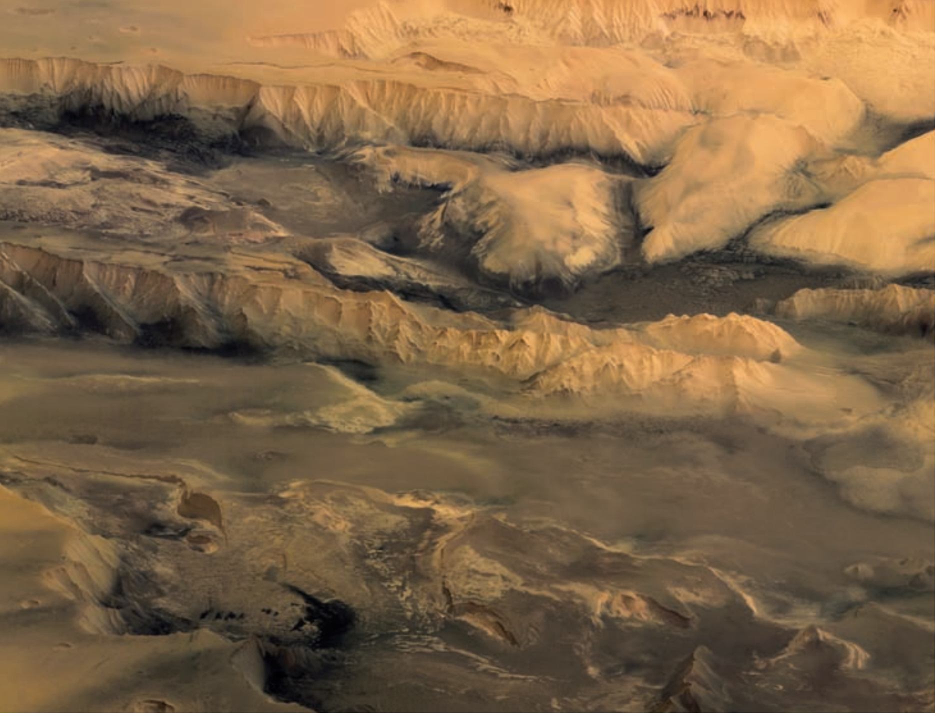
Observations of Mars can be traced back to the advanced civilizations of antiquity. Because of its reddish color that is vaguely reminiscent of blood, the ancient Egyptians called the planet 'Horus the Red', while the Greeks later on named it after Ares, the god of war. However, it is the Roman god of war, Mars, to which the planet owes its present name. Early in the 17th century, Johannes Kepler formulated the laws that describe the movements of the planets based on measurements of the position of Mars made by the Danish astronomer Tycho Brahe which, although few in number, were highly precise for their time. Throughout the last few centuries, moreover, it was common practice to compute the length of the astronomical unit (the distance between the Earth and the Sun) on the basis of trigonometric measurements of the distance between Earth and Mars whenever Mars was in opposition. In 1877, Schiaparelli fell for an optical illusion when he saw linear graben and rille formations on Mars which he mistook for channels, or 'canali' in Italian. For many of Schiaparelli's contemporaries, they simply had to be of artificial origin, and even much later, when the scientific world had long recognized the mistake for what it was, they led many to believe in an intelligent civilization on our neighbor planet.

Facts

Mars	Mass	6.4185×10^{23} kg
	Radius	3397 km
	Density	3.934 g/cm^3
	Rotation period	26.62 h
	Orbital period	687 days
	Mean distance from the Sun	227.9×10^{6} km
Phobos	Mass	1.063×10^{16} kg
	Size	26.8 x 22.4 x 18.4 km
	Density	2.0 g/cm^3
	Orbital period	0.3189 days
	Mean distance from Mars center	9378 km
Deimos	Mass	$2,38 \times 10^{15}$ kg
	Size	15 x 12.2 x 10.4 km
	Density	1.7 g/cm^3
	Orbital period	1.262 days
	Mean distance from Mars center	23,459 km

Six probes have landed on the planet by now, and although their analyses rule out any form of life or even organic substances on Mars so far, the planet remains the most important destination in international space flight in the context of the search for existing or extinct life on another celestial body in the Solar System. Having landed in the Gale crater on 6 August 2012, the Mars Science Laboratory mission carrying the Curiosity rover will examine a thick layer of sediment for traces of habitats that have vanished long since. Curiosity is equipped to identify carbon compounds but not traces of life. This task will be left to another mission to be implemented by ESA a few years

Image: Dao and Niger Valles, taken by Mars Express.
(© ESA/DLR/FU Berlin, G. Neukum)



later. Its rover will be capable of drilling down to a depth of five meters for the first time.

Thanks to numerous missions to Mars, such as Mariner 9, Viking 1 and 2, Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter, we are fairly familiar with conditions and formations on the surface. Roughly speaking, the surface of Mars may be subdivided into two large regions: a lowland area in the north and highland area in the south which displays numerous impact craters. Particularly conspicuous features close to the equator include Olympus Mons, a shield volcano measuring 24 kilometers in height and 600 kilometers in diameter, and its three neighbors, Arsia Mons, Ascraeus Mons, and Pavonis Mons which, sitting on top of the six-kilometer-high region of Tharsis, are only a little smaller.

Another outstanding landmark is the enormous canyon system that form Valles Marineris (named after the Mariner 9 probe) which is nearly 4,000 kilometers long and up to 200 kilometers wide. The deepest rifts go down to a depth of almost eleven kilometers. Meanwhile, the southern hemisphere harbors the Hellas and Argyre impact basins, the largest impact structures that are visible today on Mars. Depending on the season, the poles are covered by a thick layer of water and/or carbon dioxide ice. Near to the Equator, daytime temperatures may rise close to +27 degrees Celsius in summer, while night-time temperatures at the poles may drop to –133 degrees Celsius in winter. On the equator, average daytime temperatures range below the freezing point.

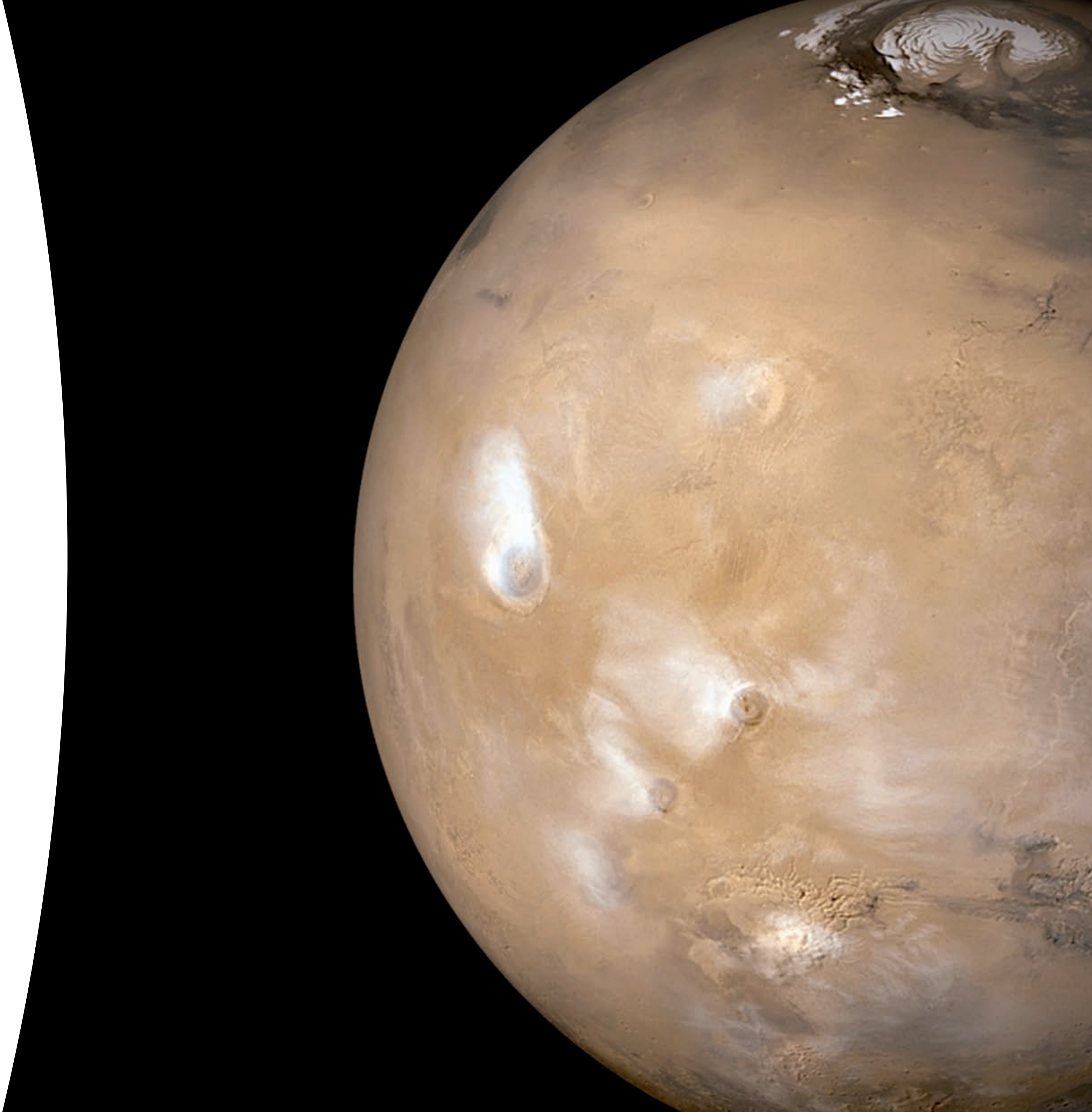
Volcanism left its mark on the planet during much of its development. In many places on the surface, minerals have been identified that are typical of basaltic volcanism, the type that most frequently occurs on all terrestrial planets in the Solar System. On Earth, some of the largest volcanos, such as the Hawaiian islands, are basaltic in nature, but what is much more important is that the floors of the oceans also consist of this volcanic rock that is rich in iron and magnesium. Basalts originate whenever relatively primordial material of the planetary mantle is melted, forming magma that rises in large bubbles and emerges on the surface as lava. It is generally assumed that the crust of Mars consists essentially of basalt which, however, is no longer present in its original context in many places because of processes like meteorite impacts, weathering, and erosion.

There are only a few places where volcanos, extinct today, can be found in large numbers. The province where they are most conspicuous is Tharsis, where about a dozen big and hundreds of smaller volcanos have been discovered, some of which were active even in the very recent past. Another volcanic region is Elysium, where some lava flows probably congealed only a few million years ago. As this practically coincides with our present day in geological terms, the question arises whether there may still be some volcanic activity on Mars.

However, the surface of Mars was shaped not only by volcanism but also by tectonic processes. Satellite images show numerous faults like fracture-related deformations in the lithosphere (the brittle outer shell of the planet). Swarms of such faults may often extend over several hundred or even a thousand kilometers in

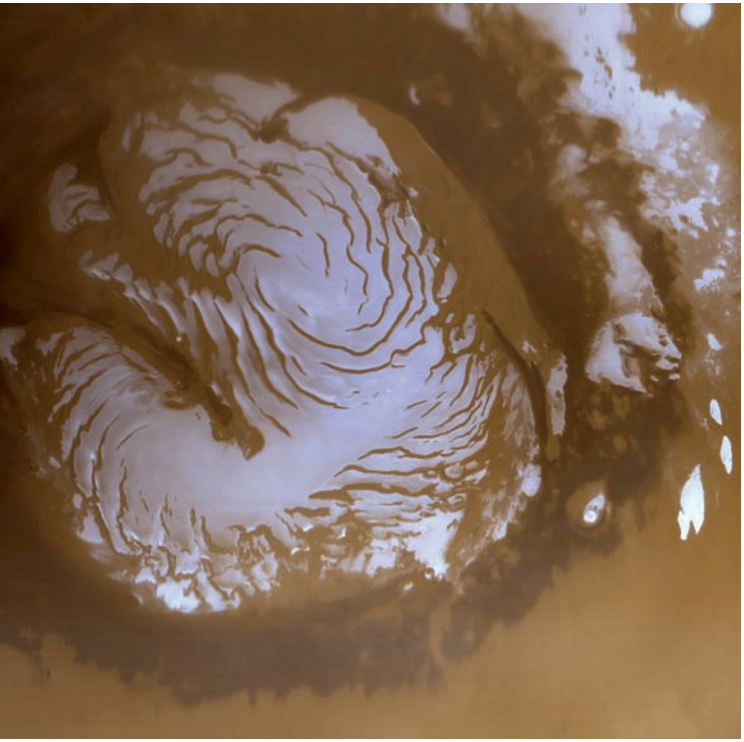
Image above: Mars Express mosaic of the central section of Valles Marineris. *(© ESA/DLR/FU Berlin (G. Neukum))*

Image on the Right: Dust storm in Syria Planum south of Labyrinthus Noctis. The great volcano Olympus Mons appears in the center, the somewhat smaller Tharsis volcanos to the right of it. *(© NASA/JPL/Malin Space Science Systems)*



length. Both tensile and compression faults are known, but only a few lateral displacements. This is not surprising because on Earth, these are mainly caused by plate tectonics. Mars, on the other hand, is a ‘single-plate planet’ whose lithosphere, unlike that of Earth, does not consist of numerous individual plates that rub against each other.

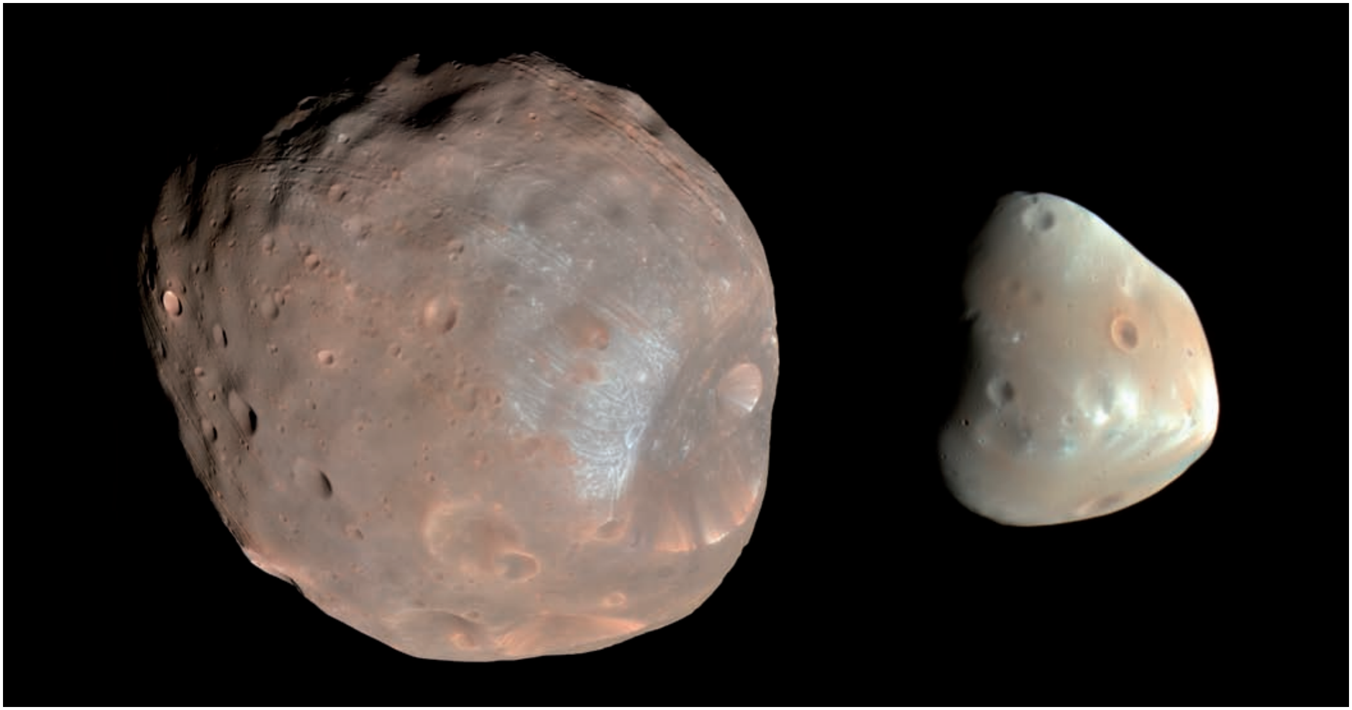
The surface of Mars has been shaped and overprinted by fluvial (involving water), glacial (involving ice and glaciers), and aeolian (involving wind) processes of varying intensity and duration. Ramified valley systems extend over vast areas, bearing witness to the former activity of water on Mars. One of the best-known valley systems is Ma’adim Vallis which formerly drained into the Gusev impact crater where the Mars rover Spirit looked for traces of water. Moreover, next to rivers and streams there were also crater lakes that were filled with water. Called paleolakes today, these are often accompanied by deltas, characteristic mineral deposits, and inflow and/or outflow channels. In the more recent past, a short-lived mobilization of water in conjunction with flows of mud or rubble may have caused the characteristic erosion grooves that are to be found on the slopes of many craters.



There are many places on the surface of Mars where traces of glacial processes can be observed which can be dated to the very recent past. On the north-western slopes of the big Tharsis volcanos, for example, flow structures can be found that recall the rubble-covered rock glaciers we know from the mountains and polar regions of Earth. These structures are thought to be remnants of Martian glaciers. Particularly in the middle and high geographical latitudes, there are many surface phenomena that resemble periglacial structures in permafrost areas on Earth. And in point of fact, ice has been found close to the surface in some places.

Widespread dark dunes bear witness to the activity of wind on Mars, whose impact was much greater in the distant past, when the atmosphere was denser. Comparatively gigantic dune fields can be found especially in the interior of impact craters. However, these dunes differ from those on Earth in that they consist not of quartz sand but of volcanic ash that was deposited about three to four billion years ago. Today, the activity of the wind manifests itself particularly impressively in dust storms and whirlwinds called ‘dust devils’ that move across the surface of Mars at great speed. Like that of Venus, the atmosphere of Mars preponderantly (95 percent) consists of carbon dioxide (CO_2), but the atmospheric pressure on the surface is no higher than six millibars (on Earth: 1013 millibars). In the Martian atmosphere, clouds of water and CO_2 ice may form, and enormous seasonal storms may blow up which raise dust and sand to altitudes up to 50 kilometers so that it spreads across the entire planet, causing the sky to assume a dull yellowish-brown color and forming extensive dune fields. Many dust storms are regionally confined, but every five to ten years they assume global proportions. Spectrometers on board the Mars Express space probe have discovered traces of methane and formaldehyde in the atmosphere above some of the major volcanic provinces, giving rise to speculations that the release of these gases might have been caused by remnants of heat in the interior of the volcanos.

Image: Ice cap on the north pole of Mars in summer, taken by Mars Global Surveyor. *(© NASA/JPL/MSSS)*



The moons of Mars

Discovered in 1877 by Asaph Hall, the two Martian moons, Phobos and Deimos, share certain characteristics. Both have a highly irregular shape and a very dark surface that reflects only about five percent of the Sun's light. Phobos features some impact craters, the largest being Stickney with a diameter of twelve and Hall with a diameter of five kilometers.

It is not clear how the two Martian moons originated. It may well be that Phobos and Deimos did not evolve together with Mars as its moons. There are also some doubts about the theory that the two bodies might be fragments thrown up by the impact of a large asteroid in the early age of Mars. Quite probably, they are minor bodies that originated in the asteroid belt between Mars and Jupiter and were later trapped by the gravity of Mars.

When the pictures taken by the Mars Express probe were evaluated, it was found that Phobos was approximately five kilometers ahead of the orbital position projected for the time when the images were taken. This may be a sign of orbital acceleration that would cause the tiny moon to spiral ever closer to Mars. If this were so, Phobos might be torn apart by the planet's gravitational forces in about 50 million years and turned into a short-lived ring around Mars, or else it might crash on the planet. The Russian probe Phobos Grunt, which was supposed to investigate the moon in some detail, was destroyed during take-off at the end of 2011.

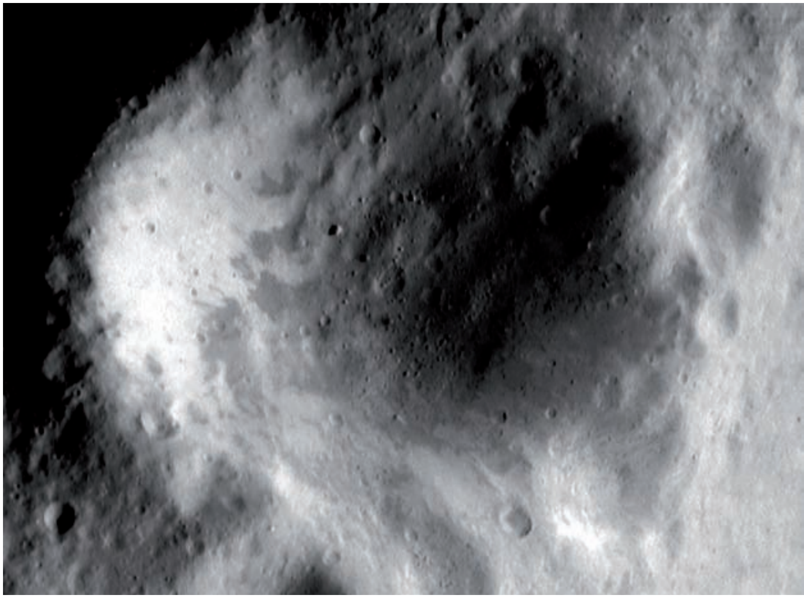
Image: The two Martian moons, Phobos (left) and Deimos (right). *(© NASA/JPL-Caltech/University of Arizona)*

THE ASTEROIDS

The first asteroid was discovered on New Year's Eve of 1801 by Giuseppe Piazzi (1746–1826), then director of the Palermo observatory. While he was drawing up a map of the sky, he noted that an object had changed its position since the previous observation. The new 'wandering star' turned out to be a small planet which Piazzi named after the goddess of vegetation and patron saint of Sicily, Ceres.

Particularly from the German point of view, the events that preceded the discovery of the first asteroid are interesting because they had a lasting influence on the exploration of the Solar System and the discovery and exploration of the asteroids. In 1781, William Herschel discovered a new planet – Uranus, raising the issue of whether the planetary family might have yet more members. Two German researchers, Johann Daniel Titius and Johann Elert Bode, developed a simple mathematical formula which describes the distances between the planets' orbits and the Sun. As the newly-discovered planet Uranus fitted in quite well with this so-called Titius-Bode law, this was regarded as proof that the formula was correct. More than that, however, the formula predicted another planet somewhere between the orbits of Mars and Jupiter, which now had to be found.

For this reason, Franz Xaver von Zach, working from a new observatory near Gotha, organized what he called the 'celestial police': the firmament was subdivided into 24 zones, each of which was to be systematically searched by different European observatories to track down the suspected missing planet. When it emerged that the orbit of the 'planet' discovered by Piazzi was indeed at the projected distance from the Sun, everybody was overjoyed. But the joy did not last: in the spring of 1802, Heinrich Wilhelm Olbers of Bremen discovered another planet on a similar orbit around the Sun. Two years later, Karl Ludwig Harding of Lilienthal found another one, and yet another was discovered, again by Olbers, in 1807; they were christened Pallas, Juno, and Vesta. And there was another problem: all four were far too small! They could not be observed at all with the naked eye, revealing themselves only in a telescope.



However, a tentative explanation was soon found for this multitude of small 'planets': they were thought to be fragments of a larger body that had been destroyed somehow or other. Today, we know that no major planet has ever formed between Mars and Jupiter. Instead, the latest theories about the origin and early evolution of our planetary system indicate that the planets did not originate where we find them today but 'migrated' after their formation. The reason: the

The Titius-Bode Law is a simple mathematical series which fairly precisely indicates the distances between the planets and the Sun – and triggered the postulate that a planet is 'missing' from the region between Mars and Jupiter. Towards the end of the 18th century, the law was formulated by Johann Daniel Titius (1729–1796) and Johann Elert Bode (1747–1826). Another similarly simple series (Venus: no moon; Earth: one moon; Mars: two moons; Jupiter: four moons) induced Jonathan Swift (1667–1745) to speak in his 'Gulliver's Travels' of two Martian moons – 100 years before they were discovered by Asaph Hall (1829–1907) in 1877. Neither the Titius-Bode Law nor the rule concerning the number of moons orbiting the planets is universally valid.

Image: The asteroid Eros: view of the crater Psyche which, measuring 5.3 kilometers in diameter, is the largest on the asteroid. *(© NASA/JHUAPL)*

Image on the right: The size of the asteroid Vesta (left) compared to that of Lutetia, Mathilde, Ida, Eros, Gaspra, Šteins, and Annefrank (from top to bottom).
(© NASA/JPL-Caltech/JAXA/ESA)

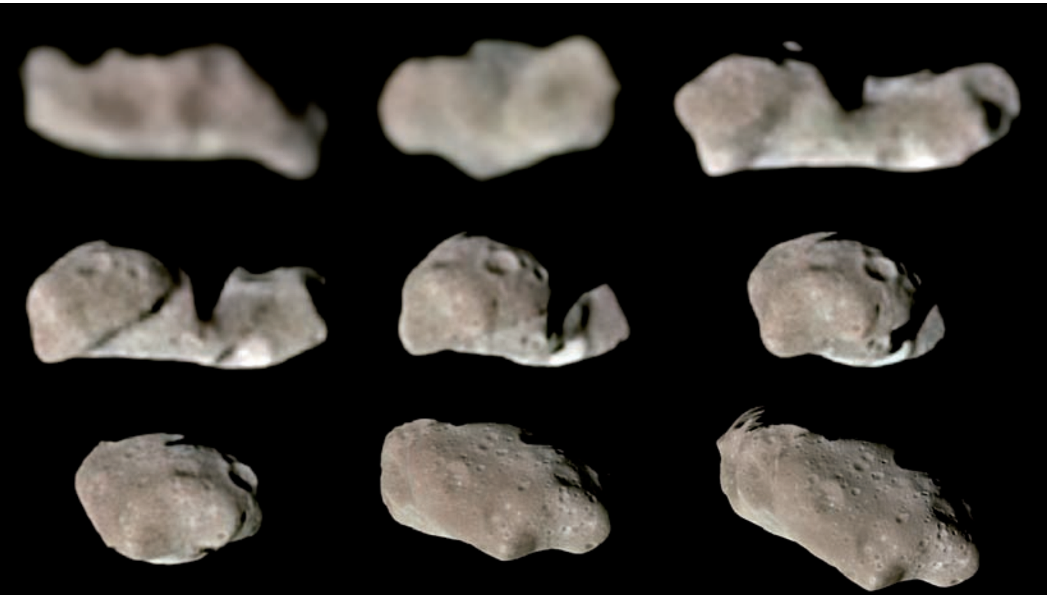


Image: **Nine different images of the asteroid Ida in true color, taken by the Galileo probe during its approach to the asteroid.** *(© NASA/JPL)*

interaction between the quickly growing planets and the remnants of gas that still existed in the circumsolar accretion disk, another being the effects of the gravitational forces exerted mainly by the large planets, Jupiter and Saturn. So the Titius-Bode law has no physical meaning whatsoever. Yet the fact that it was thought – and seemingly proven to be correct – intensified the search for more planets, which led to the discovery of the asteroids.

Almost 40 years went by before further asteroids were discovered, but then they arrived thick and fast. Several were known by the end of the 19th century. Today, in 2013, we know about 615,000 asteroids, of which most are concentrated between the orbits of Mars and Jupiter in the so-called asteroid belt. As far as we know today, most asteroids were produced by collisions between the original ‘building blocks‘ of the planets. 4.6 billion years ago, the Sun was still in its formative phase and surrounded by a rotating disk of gas, ice, and dust. Dust particles gently collided, forming ‘fluffballs’ which, in turn, gathered together into ever-larger bodies. After some more millions of years, kilometer-sized objects called planetesimals had formed, the original building blocks of the planets. After about 10 to 100 million years, collisions between these planetesimals and the absorption of the residual gas and dust remaining in the disk led to the formation of planets. The asteroids and comets of today‘s Solar System are the remains of the planetary building materials.

The distribution of asteroids in the asteroid belt is determined mainly by the gravitational influence of the giant planet, Jupiter. There are several zones in the belt where the number of asteroids is practically nil, while elsewhere they occur in great numbers. It is conceivable that the two small Martian moons, Phobos and Deimos, once belonged to their number but approached too closely to the planet Mars and were trapped by it at some time.

The diameters of most known asteroids range between 20 and 100 kilometers. Measuring about 1,000 kilometers in diameter, Ceres is the largest object in the asteroid belt and has meanwhile been promoted to the status of dwarf planet. Because collisions between asteroids are so frequent, the population of the asteroid belt is gradually being ground down into more and more fragments. There is no lower limit to their size: millions and millions of pebble-sized fragments of rock and dust particles circle around the Sun together with the larger asteroids.

The orbits of some asteroids are highly eccentric, crossing the orbit of Mars, the Earth, and even Mercury. More recently, activities to study the Near-Earth Asteroids (NEAs) have been intensified to determine the long-term probability of collisions with Earth and their possible effects. The largest NEA has a diameter of about 40 kilometers. NEAs having a diameter greater than one kilometer number about 1,000. The impact of an object of this size on Earth would have worldwide effects.

Programs to search for asteroids

Programs tailored to search for asteroids have been implemented since about 1980, particularly at the Mt Palomar observatory in the USA. One crucial factor in the discovery of NEAs was the invention of the digital camera (with CCD detectors) and its use in astronomy. Not only did this new technology enable astronomers to find much fainter and therefore smaller objects (which are much more numerous than large ones), the images could also be processed on a computer directly after they were taken. By comparing the positions measured in several photographs taken at different times, asteroids can be identified as objects moving against the starry sky.

Together with an enormous increase in computing power, these new observation methods permitted implementing quite a number of NEA search programs, particularly in the USA. The number of known asteroids increased dramatically: by 2000, more than 100,000 objects had already been identified, and by November 2011, the head count had increased to more than 570,000. There are also figures to reflect the motive force, i.e. the search for NEAs: at the millennium, 1,000 of them had been discovered; today, their number has risen to almost 8,500. Vigorously taking part in the search programs in close co-operation with observatories in France, Sweden, and Italy, DLR's Institute of Planetary Research in Berlin succeeded in discovering six new NEAs and nearly 4,000 new asteroids, chiefly in the main belt, between 1996 and 2002.

Worldwide observation campaigns supplied measurement data that permitted determining the rotation characteristics and the shape of the bodies observed. Measurements at various wavelengths enable scientists to find out the surface color of these bodies and even establish their surface condition and mineralogical composition. The heat radiation emitted by an asteroid is of particular importance in determining its size. Such measurements not only permit calculating its diameter; as well as its brightness in visible light, they can also be used to determine its so-called albedo (the reflectivity of its surface material).

Space probes to asteroids

However, the most detailed and spectacular examinations of asteroids were supplied by space missions. In the last few years, several asteroids were inspected by space probes on the spot. In 1991 and 1993, the Galileo space probe, which was on its journey to Jupiter, flew close by two asteroids, (951) Gaspra and (243) Ida, taking glances at their surface from various angles and discovering that Ida, which is 60 kilometers in length, has a satellite somewhat more than 1 kilometer in size that was given the name Dactyl. What had previously been known from photometric light curves now emerged clearly: asteroids are irregularly shaped rotating lumps of rock which are pitted by craters and may even have tiny moons.

Image: The asteroid Vesta displaying a large slope in the south polar region, photographed by the Dawn probe. *(© NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)*

Late in June 1997, the asteroid (253) Mathilde, which measures about 50 kilometers, was visited by the American space probe NEAR (Near-Earth Asteroid Rendezvous) on its way to the near-earth asteroid Eros, around which it circled for a year from February 2000 onwards. Although the asteroid Mathilde is three times as large as Eros, NEAR's measurements show that it is only half as dense. Mathilde's mysteriously low density, only 30 percent greater than that of water, hints at a curiously porous structure. It may be that Mathilde is a loose agglomeration of rock fragments resembling a 'rubble pile' whose constituent elements were created by a collision between two asteroids and are held together only by their own weak gravitation. By now, further circumstantial evidence has emerged indicating that numerous asteroids are of similar composition.

Another small NEA was examined by the Japanese space probe Hayabusa which took off for (25143) Itokawa in May 2003. After its arrival in 2005, Hayabusa supplied detailed images and scientific data about Itokawa. About 350 meters in size, the object is shaped like a lengthy potato and looks exactly like the mental picture asteroid researchers had of a 'rubble pile': a collection of fragments created by a collision of two asteroids earlier on. Hayabusa even touched down on Itokawa's surface to collect dust particles. After a journey of more than seven years, Hayabusa returned to Earth on 13 June 2010. A small capsule in which the dust particles from Itokawa's surface were brought back to Earth was recovered in Australia. It is the first-ever return of a probe which had previously landed on an asteroid. The analysis of the dust particles yielded important information about the mineralogy and history of the asteroid.

The flight path of the European comet probe Rosetta was arranged so that it could fly by the asteroids (2867) Šteins on 5 September 2008 and (21) Lutetia on 10 July 2010. In both cases, close-ups were taken. More importantly, the surface of the 100-kilometer asteroid Lutetia was mapped in great detail. The same asteroid was extensively surveyed and observed from Earth as well.

The Dawn mission

One of the reasons why studying these bodies is so important is than many of them mirror the earliest stages in the evolutionary history of our Solar System, and that analyses of their surface morphology and composition yield information about the time at which our Solar System originated. This is why the American space probe Dawn was developed. In 2007, it was sent on a journey to the asteroid belt where it was to explore the asteroid Vesta which, measuring about 500 kilometers in diameter, is the third largest and second heaviest planetoid. Dawn examined Vesta for 14 months from three different orbits, radioing images of the asteroid's surface and data about its condition and structure back to Earth.

As a result, it was found that Vesta is a kind of proto-planet – a planet, in a manner of speaking, that was arrested in its development before it could become a terrestrial body. Similar to Mars or the Moon, Vesta is differentiated, featuring a small metal-rich core, a rock mantle, and a crust. No traces of volcanism have been identified as yet, although there are clues suggesting its existence which, however, may also be interpreted in other ways. Vesta's surface is marked by traces of numerous collisions with other bodies in the asteroid belt. The impact that left a 500-kilometer basin at the south pole nearly destroyed the asteroid. Spectrometer measurements confirmed that a certain group of meteorites on

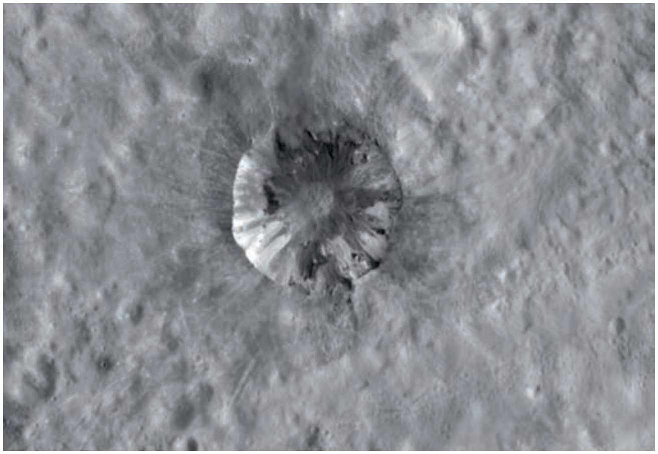


Image: The Cornelia crater on Vesta with conspicuous areas of bright and dark material in its interior.
(© NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)

Earth originally came from Vesta or from fragments of the asteroid. Having concluded its experiments, the probe flew on to the dwarf planet Ceres which it will reach in 2015.

Earth-crossing asteroids

Near-Earth Asteroids (NEAs) enjoy more and more attention, not only because of the impact threat but also because some of them make interesting targets for crewed space missions. NASA especially regards the planet Mars as a potential long-term objective. To gather the requisite technical experience with extended, sophisticated crewed space missions, NASA believes that the NEAs are suitable springboard on the way towards these targets. Some of the smaller NEAs are relatively easy to reach because their orbits resemble that of Earth. Another point is that because the gravitation of an NEA is weak, you can land on its surface and take off again into space after your visit without having to carry large amounts of fuel. Such missions might serve to gather not only technical space experience but also valuable scientific data about the physical properties of NEAs.

Impacts of asteroids and comets are an on-going natural phenomenon that has been marking the surface of planets since their formation. Asteroids continually cross the orbit of Earth. Through-out its history, there have been repeated collisions which permanently influenced the biosphere and the course of evolution. Today, the impact rate is much lower than it was four billion years ago, when our planet was still in the development stage. Nevertheless, the next major impact on Earth is only a question of time. This is why the possible consequences which asteroid or comet impacts might have on our Earth and other planets are being investigated. One particular item of study is the part played by such impacts in the development of life.

These days, we keep hearing speculative news about asteroids that appear to be on course for Earth. In reality, however, there is no object known so far that represents an immediate threat to our planet. To be sure, the astronomers' search programs have only discovered a fraction of the entire NEA population to this day. At present, NASA is developing the OSIRIS-REx mission under which a probe will be launched to the near-earth asteroid 1999 RQ_{36} (Bennu) in 2016. Next to studying the asteroid with cameras and spectrometers on the spot, the probe is supposed to land on it and bring back about 60 grams of material to Earth. Japan is planning – with extensive German participation – a sequel to the Hayabusa mission for 2019 which will take samples on the asteroid 1999 JU_3 and return them to Earth.

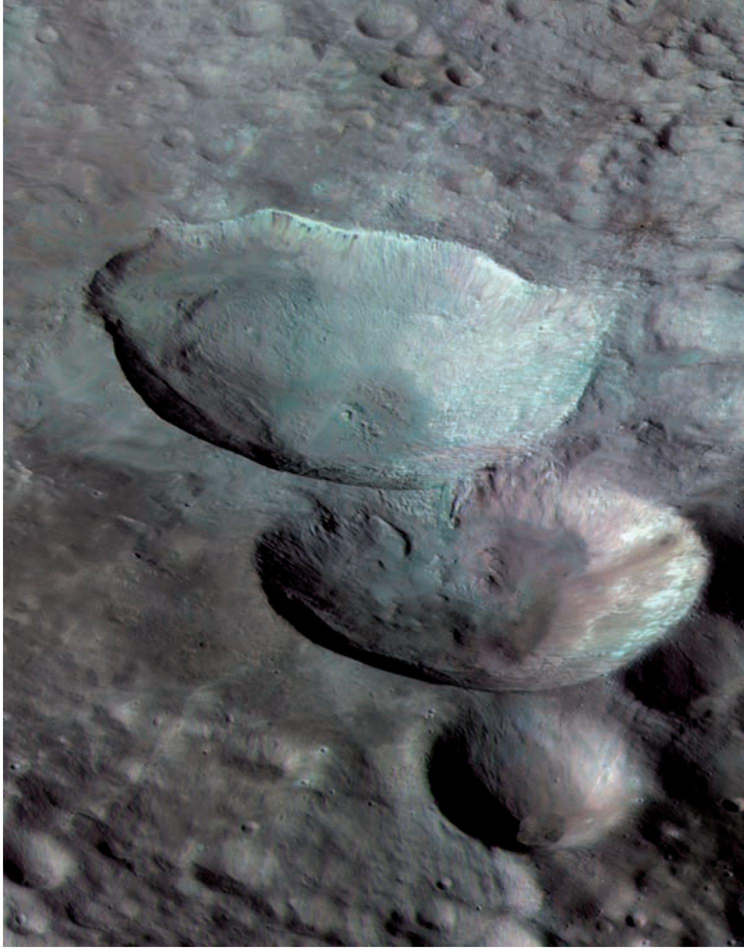


Image: The 'Snowman' craters Marcia, Calpurnia, and Minucia on Vesta. *(© NASA/JPL-Caltech/UCLA/MPS/DLR/IDA)*

JUPITER

Jupiter is the largest planet in our Solar System. With a mass equivalent to one thousandth that of the Sun or 318 times that of Earth and a composition that partly resembles that of the Sun, it almost might have turned into a second Sun if its mass had been a little greater. Jupiter is the second brightest planet in the night sky after Venus. Even a small telescope reveals its typical colored cloud bands, the Great Red Spot that has been known and observed since 1664, and the dance of the four moons that have been named after their discoverer, Galileo.

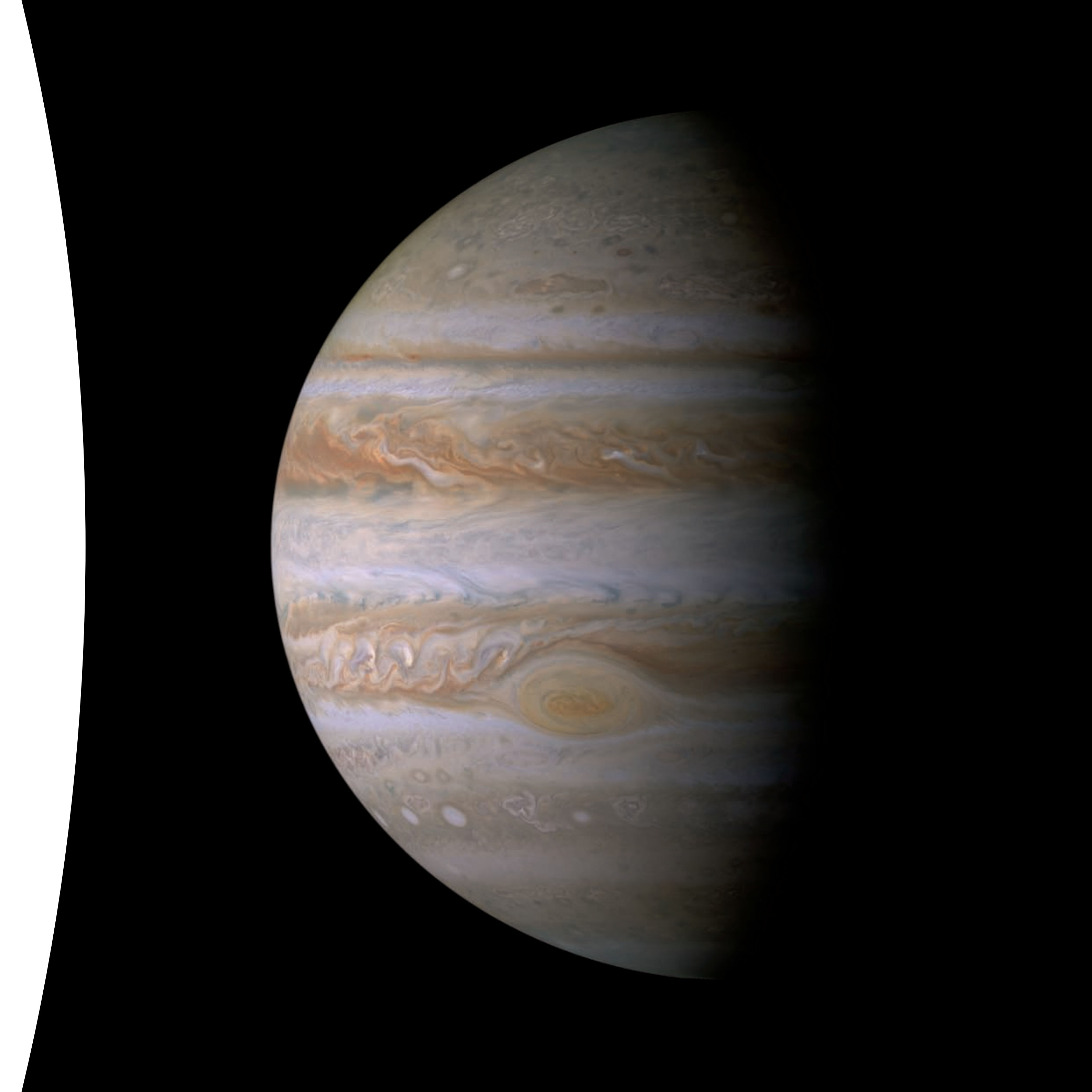
Jupiter takes nearly twelve years to orbit the Sun, travelling at an average velocity of 13 kilometers per second. Because of its enormous mass, the giant planet influences the paths of all the other bodies in the Solar System. Thus, for example, it is Jupiter's gravitational influence that caused the gaps in the asteroid belt, diverts comets from their original flight path and even traps some of them, and interferes with the orbits of the other planets – an effect that must always be figured into the exact calculation of any orbit. Furthermore, we make use of its powerful gravitational field to accelerate space probes and change their course noticeably (Voyager, Ulysses, Cassini-Huygens, New Horizons). Jupiter's equatorial radius (R_J) measures 71,500 kilometers and its rotation period falls just short of ten hours. This high rate of rotation has markedly flattened the giant planet at the poles, a phenomenon that is clearly visible even in a small telescope. Jupiter's polar radius measures 66,850 kilometers, about 6 % less than the equatorial radius. Jupiter's low mean density of 1.33 g/cm³ is due to the high proportion of hydrogen and helium in its interior.

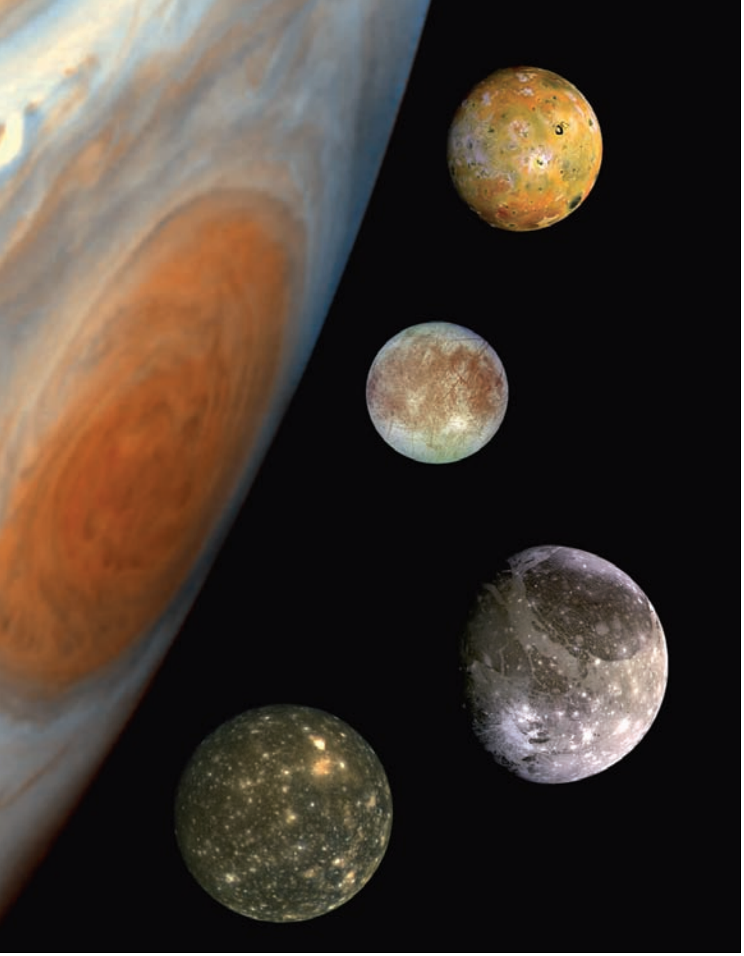
Wind velocities at the equator rise to 150 meters per second (540 kph). The conspicuous Great Red Spot (GRS) is thought to be an isolated giant cyclone which moves more slowly than the other atmospheric structures in the vicinity. Contrary to other, smaller vortex systems, the GRS has remained stable since it was first documented more than 300 years ago. Measurements taken by spectroscopes on Earth as well as on space probes have revealed details about the composition of the atmosphere. Additional information about Jupiter's uppermost cloud layers was supplied by Galileo: in December 1995, Galileo launched its own probe carrying six scientific experiments, the first to enter the cold atmosphere of one of the outer planets. The uppermost layers of Jupiter's dense atmosphere consist mostly of hydrogen (H_2), helium (He), crystals of ammonia ice (NH_3), ammonium hydrogen sulfide (NH_4HS), and ice crystals and droplets of water (H_2O). Models predict that at a depth 1.0 to 0.75 R_J, the planet consists of a molecular mix of hydrogen and helium which at 0.75 to 0.2 R_J becomes metallic because of the high pressure. This highly conductive metallic hydrogen which rotates around Jupiter's core is regarded as the source of the planet's enormous magnetic field. It is expected that only the innermost center of the planet (0-0.2 R_J) is occupied by a small compact core about ten times the size of Earth. Further information about Jupiter's atmosphere, its internal structure, and its magnetic field will be supplied by the Juno space probe (NASA) which has been on its way to Jupiter since August 2011 and will reach it in 2016.

Facts

Jupiter	Mass	1.8987×10^{27} kg
	Radius (equatorial)	71,492 km
	Radius (polar)	66,854 km
	Density	1.33 g/cm³
	Rotation period	9.925 h
	Orbital period	11.86 years
	Mean distance from the Sun	778.4×10^6 km
Io	Mass	8.93×10^{22} kg
	Mean radius	1821 km
	Density	3.55 g/cm³
	Orbital period	1.769 days
	Mean distance from Jupiter	422,000 km
Europa	Mass	4.79×10^{22} kg
	Radius	1562 km
	Density	3.01 g/cm³
	Orbital period	3.551 days
	Mean distance from Jupiter	671,000 km

Image on the right: Jupiter with the Great Red Spot, a giant storm system.
(© NASA/JPL/Space Science Institute)





Io is the innermost of the Galilean moons. It resembles the Moon both in volume and density. Io orbits the giant planet at a distance of less than six times the radius of Jupiter. Jupiter's enormous attraction combined with the effect of Io's slightly elliptical orbit to produce tides which, many times more powerful than the influence of the Moon on Earth, generate heat in the interior. Gravitational interaction with two other moons, Europa and Ganymede – the so-called Laplace resonance – forces Io into a slightly elliptical orbit which reinforces the tidal effect and maintains it over geological periods. This, in turn, causes intense volcanic activity. More than a dozen active volcanos and more than 100 volcanic ejection centers were registered during the Voyager flybys and the observations of Galileo. Reaching a height of up to 17 kilometers, Io's mountains are probably also of volcanic origin, as are its stratified structures which are up to 1.6 kilometers high. Io is a body whose surface is constantly being renewed by volcanic activity. Erupting volcanos eject material to a height of several hundred kilometers, from which it spreads over large areas on the surface. The moon's movement through Jupiter's strong magnetic field induces powerful electric currents which ionize large parts of the volcanic ejecta, which are then irre-trievably lost in interstellar space.

The second of the Galilean moons, Europa, is somewhat smaller than the Moon. Its icy surface displays hardly any impact craters. The upper layers of the surface consist mainly of water ice with admixtures of rock and mineral fragments and possibly salts. Although elevation differences on Europa are not particularly extreme, its icy crust displays a marked structure and remarkable phenomena. Its most conspicuous features are elongated mountain ridges that extend across vast plains and show up in nearly all medium and high-resolution images. The mountainous features that occur most frequently

Image: Comparison of the relative size of the Galilean moons and Jupiter's Great Red Spot. *(© NASA/JPL/DLR)*

The Jovian moons

At present, the Jovian system is known to comprise 67 moons. Discovered by Galileo in 1610, Io, Europa, Ganymede, and Callisto were named 'Galilean moons' after their discoverer. When Galileo spotted satellites orbiting a larger body, he confirmed the theory that it is not Earth which stands at the center of the universe – or at least of the Solar System as it was then known – and that the Sun forms the hub of a planetary system within which the Earth orbits it as one of several planets.

Facts

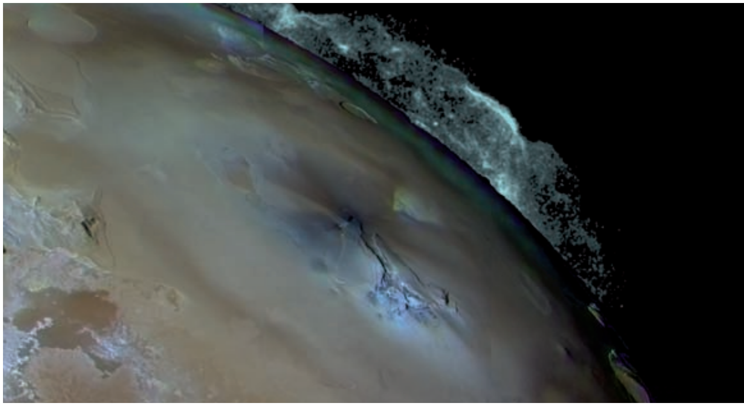
Ganymede	Mass	1.48 x 10^{23} kg
	Radius	2632 km
	Density	1.94 g/cm^3
	Orbital period	7.155 days
	Mean distance from Jupiter	1,070,000 km
Callisto	Mass	1.08 x 10^{23} kg
	Radius	2404 km
	Density	1.86 g/cm^3
	Orbital period	16.69 days
	Mean distance from Jupiter	1,883,000 km

on Europa are so-called double ridges which consist of two crests separated by a central valley. Moreover, there are numerous areas where fragments of plains with mountain ridges ranging in size from a few kilometers to several tens of kilometers have been shifted relative to each other by tectonic forces on ground that is probably mobile (plastic or even partially liquid) and are now embedded in a matrix of rough hilly material. Called chaotic terrains, these areas recall terrestrial icebergs which, drifting in the sea, have frozen to the ground. Compared to the craters on the terrestrial Moon, those few impact craters that are to be found on Europa are relatively shallow and never measure more than 45 kilometers in diameter.

It is highly probable that beneath Europa's icy crust, an ocean of liquid water exists that might be up to 200 kilometers deep. Scientists so urgently wanted to know whether this hypothetical ocean exists that the extension of Galileo's mission was dedicated exclusively to Europa. In point of fact, the interaction between electrically conductive salts dissolved in the ocean and Jupiter's outer magnetic field that was discovered by the Galileo probe provided indirect clues to the existence of an ocean in our day. It is not least because of this ocean, whose volume of water is markedly greater than that of the terrestrial seas, that Europa is now a preferred destination in our search for potential habitats of organisms outside the Earth.

Viewed from Jupiter, Ganymede is the third of the Galilean moons and also the largest. Measuring 5,265 kilometers in diameter, it is in fact the largest moon in the Solar System. Ganymede's density is low (1.942 g/cm³), indicating that it contains a large proportion of water ice that accounts for more than half of its volume. Several close flybys of the Galileo probe confirmed that Ganymede's structure is highly differentiated, comprising a core of iron or iron sulfide, a rock mantle, and an outer layer of ice. Moreover, it was demonstrated that Ganymede is surrounded by a magnetic field generated by a dynamo at its core. This makes Ganymede the only moon in this Solar System with its own magnetic field.

About one third of its surface is occupied by old, dark areas that are dotted with craters. Parallel curved furrows several kilometers wide represent the remnants of old, large, highly eroded ring basins caused by impacts of large comets or asteroids in the moon's early



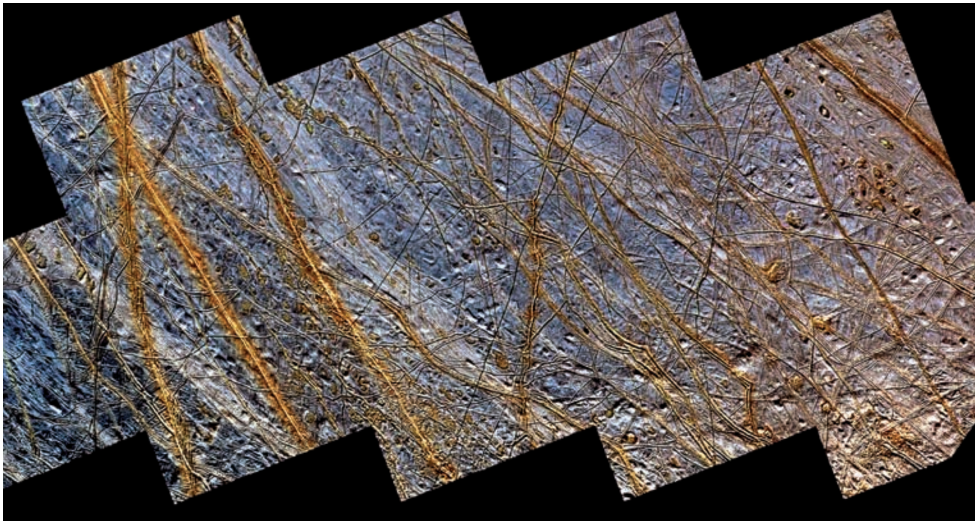


Image above: An eruption of the Pele volcano on Io. The ejecta reached altitudes of up to 300 kilometers. *(© NASA/JPL/USGS)*

Image below: Typical surface structures on Europa: double ridges, dark stains, and smooth plains of ice. *(© NASA/JPL/DLR)* age several billion years ago. The dark areas are intersected by so-called grooved terrain, light, furrowed areas that cover about two thirds of the surface. These light areas were formed by tectonic forces emanating from the dark areas. At the surface, they consist chiefly of relatively pure water ice. Crater density, which is relatively low in the bright compared to the dark areas, indicates that the former are comparatively recent. The shape of craters on Ganymede differs markedly from that of the craters on the lunar surface. Craters featuring central depressions occur frequently, while central peaks are comparatively rare. Generally speaking, Ganymede's craters are much shallower than those on the Moon. Bright, pancake-like, nearly circular, and very shallow formations constitute a special feature. Analogous with the papyrus manuscripts of antiquity that were covered with several layers of writing, these flattened impact structures are called palimpsests.

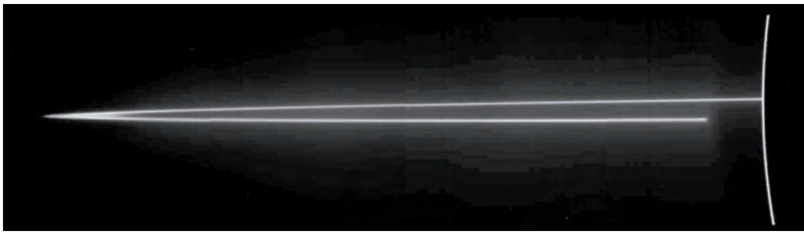
Callisto is the outermost of the Galilean moons. Having a diameter of 4,818.6 kilometers, it is only a little smaller than the innermost planet, Mercury. At 1.834g/m³, its mean density is the lowest of all four large Jovian moons. Together with its large diameter, this suggests that Callisto, too, contains great quantities of water ice. Strewn with craters like the dark areas on Ganymede, its surface shows little geological development. Consequently, a number of big old impact basins have been preserved which are surrounded by a multitude of concentric rings, formed mainly by furrows. The biggest basin of this kind is Valhalla whose ring system measures up to 4,500 kilometers in diameter. High-resolution images show that Callisto's surface is covered by a dark powdery substance in many places. Very probably, this substance was produced by a process of erosion whereby relatively volatile constituents of Callisto's icy crust, such as frozen CO_2, were sublimated by the Sun's rays, leaving on the surface a growing deposit composed of other ingredients like carbon compounds or silicates. At present, Callisto is geologically inactive. However, measurements of its magnetic field performed by the Galileo space probe may be interpreted as indicating that oceans exist under the icy crusts of Ganymede and Callisto as well. Compared to the ocean of Europa, however, these would be located at much greater depth, below an ice shield about 100 kilometers thick.

In addition to the Galilean moons, the Jovian system includes Metis, Adrastea, Amalthea, Thebe, Leda, Himalia, Lysithea, Elara, Ananke, Carme, Pasiphae, Sinope, and 48 other small moons, some of which were discovered only in the last few years. With the exception of the inner moons, Metis, Adrastea, Amalthea, and Thebe, which fly around the giant planet within the orbit of Io, all these moons are far beyond Callisto on orbits that are highly elliptical and steeply inclined relative to Jupiter's equatorial plane. Most of these moons measure only a few kilometers in diameter and are therefore difficult to find.

The ring system

In addition to its moons, Jupiter has an equatorial ring system consisting of three separate rings. Being extremely dark, the ring system was only discovered in the image data radioed back by Voyager 1 during its flyby in March 1979. However, it was also identified belatedly in older measurement data sent by the Pioneer 11 probe from its Jupiter flyby in 1974. The system consists of three parts: (1) A main ring having a radial width of c. 6,000 kilometers and a thickness of between less than 30 and 100 kilometers that includes the orbits of the two smaller moons, Metis and Adrastea. The main ring is chiefly composed of tiny, micrometer-sized dust particles of siliceous and/or carbonaceous composition. (2) Both above and below its plane, this main ring is surrounded by a halo in the shape of a torus 20,000 to 24,000 kilometers thick. (3) The darkest part of Jupiter's ring system is formed by two so-called gossamer rings outside the main ring, with the inner of these rings approximately reaching the orbit of Amalthea and the outer ring that of Thebe. The gossamer rings are fainter than the main ring by a factor of about 30. Next to Io's ejecta, it is thought that most of the ring particles come from the small inner moons. Material that has been thrown up by the bombardment of micrometeorites cannot be retained by the gravitation of these lightweight moons and so enters an orbit around Jupiter as ring material.

Image: Jupiter's main ring in visible light. *(© NASA/JPL)*



SATURN

Having a radius of about 60,000 kilometers, Saturn is the second largest planet in our Solar System. It is also the most distant planet that can be seen with the naked eye. Until 1781, when Uranus was discovered, it was thought to be the outermost planet. From the time when the telescope was invented, a conspicuous system of rings has been observed around Saturn, which is why it is also known as the 'ringed planet'. Being about twice as far away from the Sun as Jupiter, Saturn takes nearly 30 years to complete an orbit. Every 20 years, Jupiter and Saturn appear quite close together to observers on Earth as a particularly distinctive bright light in the sky. Such a close constellation may be one of several explanations for the famous 'star of Bethlehem'.

Its gravitational force, which is equal to that of 95 Earth masses, enables Saturn – like Jupiter – to divert comets from their paths and entrap them in its 'family'. Saturn's structure resembles that of Jupiter, although it is assumed that its outer comparatively lightweight shell of hydrogen and helium extends to a much greater depth, an assumption that is supported by Saturn's low density of no more 0.70 g/cm³. This means that, being even lighter than water, Saturn would float like an iceberg in a hypothetical giant basin of water. The gravity that prevails at the upper edge of the cloud cover is only a little lower than on Earth. Because Saturn rotates very quickly (in no more than ten hours or so) and has the lowest mean density of all the known planets, it displays a marked polar flattening of 1 in 10 that can be observed even in a low-powered telescope.

Facts

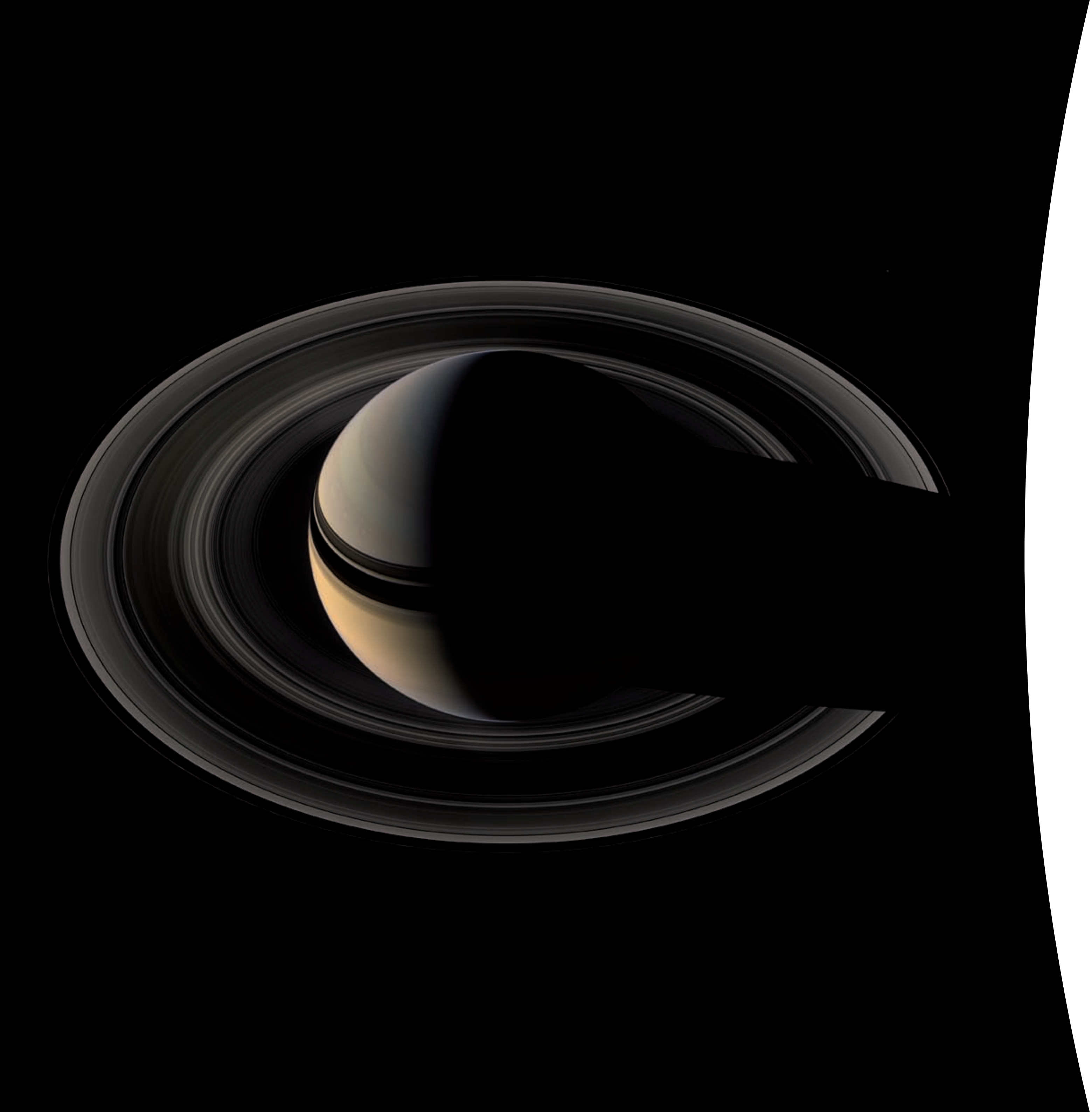
Saturn	Mass	5.688×10^{26} kg
	Radius (equatorial)	60,268 km
	Radius (polar)	54,364 km
	Density	0.70 g/cm³
	Rotation period	10.233 h
	Orbital period	29.4 years
	Mean distance from the Sun	1.429×10^{9} km
Mimas	Mass	3.8×10^{19} kg
	Mean radius	196 km
	Density	1.17 g/cm³
	Orbital period	0.942 days
	Mean distance from Saturn	185,520 km
Enceladus	Mass	8.4×10^{19} kg
	Mean radius	247 km
	Density	1.24 g/cm³
	Orbital period	1.370 days
	Mean distance from Saturn	238,020 km
Tethys	Mass	7.55×10^{20} kg
	Mean radius	523 km
	Density	1.21 g/cm³
	Orbital period	1.888 days
	Mean distance from Saturn	294,660 km

Wind velocities in the equatorial zone may reach 500 meters per second (1,800 kph). Since 1876, astronomers have been watching a cyclone in Saturn's northern hemisphere which regularly appears at intervals of about 30 years. Named the Great White Spot in the literature, it is a seasonal phenomenon. Like Jupiter, Saturn radiates more heat than it receives from the Sun.

The ring system

According to the classical subdivision, Saturn's ring system comprises seven groups designated as D, C, B, A, F, and G as their distance from the planet increases. Another ring, the E ring which is situated outside the G ring, was formed by a process which differs from that of the six inner rings, being related to geological activity on the Saturnian moon, Enceladus. The letters A through G (E included) refer to the order in which the individual ring segments were discovered.

Ever since the flybys of the Voyager probes in 1980/81, it has been known that Saturn's equatorial plane, which is inclined almost 27° to the ecliptic, is really occupied by more than a thousand individual rings whose shape, dynamics, and origin have been investigated since 2004 by a number of instruments, including in particular the two cameras and the spectrometers aboard the Cassini probe. The two brightest and most conspicuous rings are those designated A and B, which have been known since the 17th century. They are 14,800 and 24,500 kilometers wide, respectively. Between the two, there is the Cassini Division that is about



4,500 kilometers wide and contains other rings which, however, are markedly darker. In 1850, the 17,500-kilometer C ring (also known as crepe ring) was discovered within the B ring. The flybys of Voyager 1 and 2 produced evidence of the 8,000-kilometer innermost ring, D, whose existence had been suspected as early as 1967. In 1979, even before the Voyager flybys, Pioneer 11 discovered the two outermost rings, F and G. The F ring is only about 50 kilometers wide, while the diffuse G ring extends across c. 7,000 kilometers.

Varying from ring to ring, the size of the ring particles mostly ranges between that of a grain of dust (a few micrometers) and a few centimeters. Spectrometry evidence suggests that more than 90 % of the ring matter is water ice, at least at the surface of the ring particles.

There is intense gravitational interaction between the rings and their nearest moons. Moreover, there are so-called shepherd moons to keep the ring particles on track.

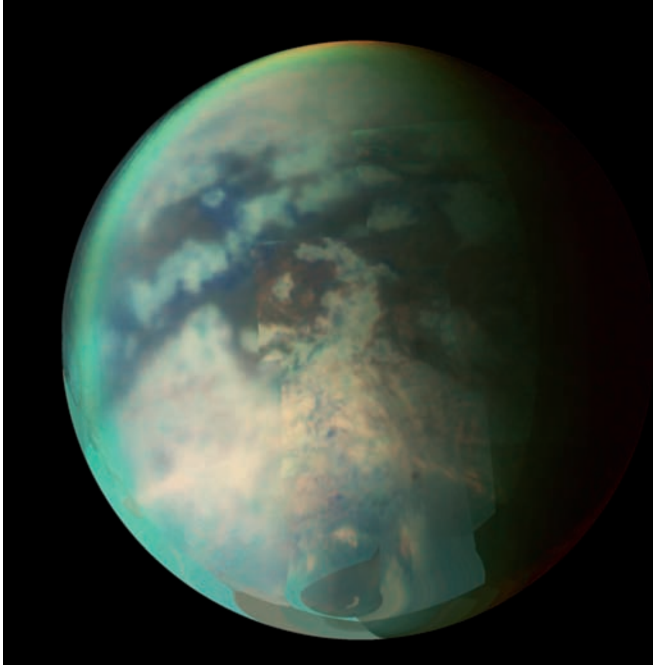
There are as yet no satisfactory answers to the questions about the origin and age of the rings. Their total mass approximately corresponds to that of the 400-kilometer moon, Mimas. It may be that the rings are remnants of the material from which Saturn and its moons formed 4.5 billion years ago. Then again, it may be that there was once a moon in the space now occupied by the rings which was struck and broken up by an asteroid or a comet. The icy lumps that remained were gradually ground into dust by successive asteroid or comet impacts and mutual collisions. A third possible explanation would be that an object measuring c. 300 kilometers in diameter that came from the Kuiper-Edgeworth Belt flew so close by Saturn that it was broken apart by tidal forces. However, the two last-named events are extremely rare and could have happened only in the early period at least 4.0 to 3.8 billion years ago, a period in which large comets and asteroids crashed much more frequently on planets and their moons. However, the assumption of great age is opposed by the dynamic processes within the rings which suggest an age of no more than a few tens to one hundred million years.

The ring system reaches out into space across four planetary radii, and because its orbital plane is inclined to the ecliptic we normally see it from Earth either obliquely from above or obliquely from below or, very rarely, edge-on. The ring system is less than one kilometer thick, and when it appears edge-on it vanishes even when viewed through the most powerful

Left: Global view of Saturn in true color, looking from above on the unlit side of the rings. *(© NASA/JPL/Space Science Institute)*

Facts

Dione	Mass	1.05×10^{21} kg
	Radius	560 km
	Density	1.43 g/cm^3
	Orbital period	2.737 days
	Mean distance from Saturn	377,400 km
Rhea	Mass	2.49×10^{21} kg
	Radius	765 km
	Density	1.33 g/cm^3
	Orbital period	4.518 days
	Mean distance from Saturn	527,040 km
Titan	Mass	1.35×10^{23} kg
	Radius	2575 km
	Density	1.88 g/cm^3
	Orbital period	15.9454 days
	Mean distance from Saturn	1,221,850 km
Hyperion	Mass	1.77×10^{19} kg
	Size	205 x 130 x 112.5 km
	Density	1.4 g/cm^3
	Orbital period	21.277 days
	Mean distance from Saturn	1,481,100 km
Iapetus	Mass	1.88×10^{21} kg
	Radius	730 km
	Density	1.21 g/cm^3
	Orbital period	79.33 days
	Mean distance from Saturn	3,561,300 km



terrestrial telescopes. The last time the planet was observed in its ‘ringless’ state was in August 2009, when the Earth crossed Saturn‘s ring plane from south to north and Cassini made use of this unusual lighting condition to take important measurements in the ring plane.

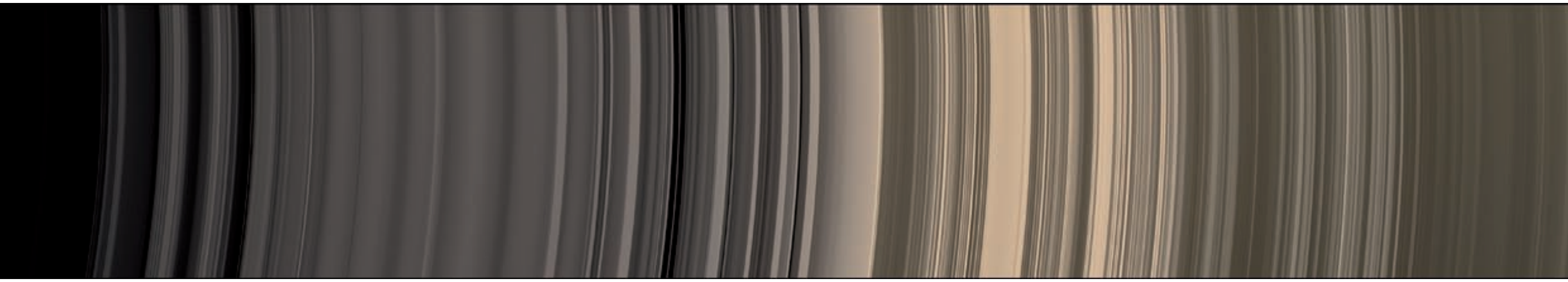
The moons of Saturn

There are nine relatively large moons circling around Saturn. Starting with the innermost and moving outwards, they are called Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, and Phoebe. All of them were known before Pioneer 11 first flew by Saturn in 1979. About one year earlier, the tenth and eleventh minor moons that had been discovered in1966 were assigned to two moons almost on the same orbit: called Janus and Epimetheus, these so-called co-orbital moons circle around Saturn within the orbit of Mimas. Pan, Atlas, Prometheus, and Pandora are some of the so-called shepherd moons that were discovered in the rings by Voyager 1 and 2 during their flybys. Before the flyby of Voyager 1, two smaller moons, Telesto and Calypso, were discovered with telescopes. Travelling on the same orbit as Tethys, these so-called Lagrangian moons or ‘Trojans’ are 60° (measured from Saturn at the center of the circle) ahead and/or behind Tethys. In the same year, the moon Dione was also found to have a Trojan which, called Helene, precedes Dione by 60° on its orbit around Saturn. Another 43 small moons have been discovered since 1980, either by Cassini or by observers on Earth using a telescope.

Measuring 5,150 kilometers in diameter, Titan is the largest Saturnian moon and the second largest moon in the Solar System, after the Jovian moon Ganymede. It was discovered in 1655 by Christiaan Huygens. At 1.88 g/cm³, its density is the highest of all Saturnian moons, and its interior consists not only of ice but also contains a high proportion of heavy substances such as silicates. It is the only satellite in the Solar System that has a dense, extensive atmosphere displaying a reddish-orange tint. Titan‘s gaseous envelope consists mainly of nitrogen, augmented by 1.4 percent of methane, and traces of ethane, acetylene, propane, diacetylene, methylacetylene, hydrogen, cyanide, and cyanoacetylene as well as carbon dioxide and monoxide. Titan, Triton and Earth are the only bodies in the Solar System whose atmospheres consist mainly of nitrogen. Opaque in visible light, it obscures our view of the

Image above: The moon Titan, global view showing an old impact basin. Mosaic of several infrared images taken by Cassini. *(© NASA/JPL/Univ. of Arizona)*

Below: Top view of Saturn‘s ring system. *(© NASA/JPL/Space Science Institute)*



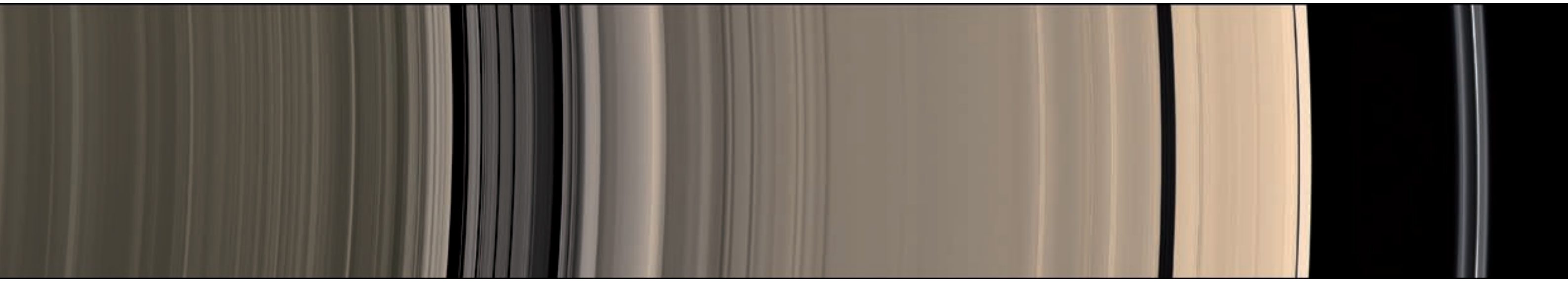
surface. Only radar and sensors that respond to light in the infrared spectral range, like the VIMS spectrometer installed on Cassini, are able to take pictures of the surface and map it in detail. Titan was the target of the European lander probe Huygens which was released by its parent probe Cassini on 25 December 2004, floated for several hours through Titan's atmosphere on 14 January 2005 and finally descended and landed on the surface of the enigmatic Saturnian moon.

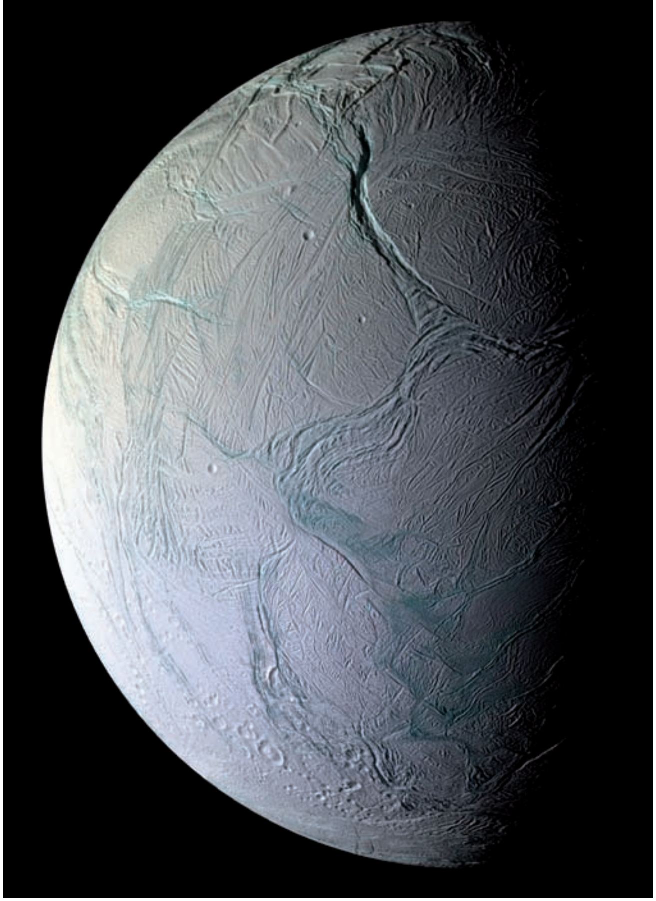
Titan's surface formations resemble those of Earth in many ways, although Titan's surface consists mainly of ice. There are few impact craters, indicating that the surface is quite young. Some areas appear to have been changed by intense erosion, similarly to the karst landscapes on Earth. Long-drawn-out dunes of dark material, probably carbonaceous particles, bear witness to the intense action of the wind. Elongated mountain ridges, caldera-like features, and nearly circular shield-like formations resembling the volcanos on Hawaii hint at tectonic and volcanic activities. Cassini-Huygens identified river valleys draining into lake basins on Titan. In contrast to the Earth, however, Titan's surface is -180 °C cold, so it is not water that flows in the rivers but a mix of liquid methane and ethane. Huygens landed in a dry lake basin featuring the mouths of several rivers. Cassini's observations of reflecting surfaces showed that some of the lakes are filled with liquid hydrocarbons.

Mimas, the innermost of Saturn's nine big moons, has a diameter of 396 kilometers and consists chiefly of ice. It was discovered in 1789 by William Herschel. At 1.15 g/cm³, its mean density comes close to that of water ice. Its surface is thickly strewn with impact craters. Major craters measuring 20 kilometers and more in diameter all have central peaks, the most distinctive being Herschel Crater with a diameter of about 130 kilometers. It is ten kilometers deep and has a central peak 6,000 meters high.

Enceladus (diameter: 504 kilometers) is second closest to Saturn among the planet's large moons. Like Mimas, it was discovered by William Herschel in 1789. Its surface displays a wide variety of terrains: old cratered landscapes featuring craters that are eroded or tectonically deformed, smooth plains with only a few craters, and furrowed plains featuring parallel fissures up to one kilometer deep. Even before the Cassini mission, it was supposed that Enceladus is responsible for the origin of the diffuse E ring because the particle density of that ring is greatest along the moon's orbit. Ultimately, Cassini's camera data proved beyond doubt that so-called cryovolcanoes at the south pole of Enceladus raise icy material from fissures which spreads along the moon's orbit. It may well be that tidal forces are responsible for this volcanic activity. Next to Earth, the Jovian moon Io and the Neptunian moon Triton, Enceladus is now the fourth body in the Solar System on which active and sustained volcanism has been found. Generated by the volcanism on Enceladus, the E ring extends farthest of all the rings of Saturn both radially and vertically, reaching inward to the orbit of Mimas and outward to the orbit of Titan. Like Titan and Phoebe, Enceladus contains not only ice but also a relatively high proportion of heavy substances, as evidenced by its density of 1.61 g/cm³, which is quite high for an icy moon.

Discovered in 1684 by Giovanni Cassini, Tethys has a diameter of 1,066 kilometers. Having a mean density of 0.97 g/cm³, the body is lighter than water ice. It resembles Mimas in some ways: its surface is densely covered with impact craters, including Odysseus, an impact basin several hundred kilometers in size that resembles the Herschel Basin on Mimas. A great rift valley system called Ithaca Chasma which extends over about three quarters of the moon's circumference was formed by tectonic forces in the early ages, either by a distension of the crust or a deformation caused by the great impact that shaped the Odysseus Basin.





Also discovered in 1684 by Giovanni Cassini, Dione is the fourth biggest of the nine large moons, having a diameter of 1,124 kilometers. Having a mean density of 1.47 g/cm³, Dione is one of Saturn's icy moons, together with Titan, Phoebe, and Enceladus. Its surface shows the most extensive geological development after that of Enceladus and Titan: plains with a high crater density, partially criss-crossed by long linear mountain ridges or faults, alternate with relatively smooth plains featuring fewer craters and areas with more extensive tectonic deformations. In the south polar region, there is the Evander Basin which measures several hundred kilometers in size. The hemisphere that is averted from the moon's orbital movement shows a distinctive network of tectonic faults running in different directions which originated at different times. On the bright steep slopes of these parallel faults, fresh water ice has been exposed which could not be identified as such on the less well-defined images taken by Voyager, which is why the first impression was of a dense network of fine and very bright filaments of entirely unknown origin.

Image: The moon Enceladus. The Labtayt Sulci, which are about one kilometer deep, appear in the upper part of this color-enhanced image. *(© NASA/JPL/Space Science Institute)*

Measuring 1,528 kilometers in diameter, Rhea, yet another moon discovered by Giovanni Cassini in 1684, is Saturn's second biggest moon. The inner neighbor of Titan has a density of no more than 1.23 g/cm³, which is why it is thought to consist mainly of water ice. Rhea's surface resembles that of Dione, although Rhea is less well developed geologically than its inner neighbor. The hemisphere that leads in the direction of the moon's movement around Saturn is pockmarked by craters, including a number of very large impact basins measuring several hundred kilometers. This is also the hemisphere in which Inktomi is situated, a conspicuous, very bright ray crater. Like that of Dione, the moon's trailing hemisphere features long-drawn-out faults that essentially run from north to south. Rhea's tectonic history was markedly less eventful than that of Dione, and the moon's activity probably ceased somewhat earlier.

Hyperion is an irregularly-shaped triaxial body measuring 410 by 260 by 220 kilometers, which corresponds to a mean diameter of 268 kilometers. In 1848, Hyperion was discovered independently by three astronomers, William Lassell, William C. Bond, and George P. Bond. Hyperion's rotation is chaotic, i.e. the direction of the north pole changes continuously in the course of a few days. At 0.57 g/cm³, its mean density is the lowest of all nine large Saturnian moons. Hyperion is pockmarked by craters formed by impacts on this porous body that make it look like a sponge. Depressions and crater floors contain deposits of dark, spectrally-red carbonaceous material.

Measuring 1,471 kilometers in diameter, Iapetus is Saturn's third largest moon after Titan and Rhea. Since its discovery by Cassini in 1671, it has been known that Iapetus has two hemispheres that differ extremely in brightness: the one facing in the direction of the moon's orbital movement is the darkest of all known moons in the Solar System, while the brightness of the trailing hemisphere and the polar regions is comparable to that of the other Saturnian moons. Cassini's image data show that both hemispheres are very densely marked by craters and feature a comparatively great number of very large impact basins, so that they must be older than the surfaces of the other moons of Saturn. Along the equator, the moon is encircled by a mountain ridge extending

along almost half its circumference. In some places, this ridge is not coherent but consists of isolated mountains or massifs arranged in line. The elevation of the ridge above its environment may reach 20 kilometers. Although the origin of this structure is most probably due to tectonic deformations, the exact mechanism has not yet been clarified.

Phoebe is the farthest out of the nine major moons, circling around Saturn at a distance of almost 13 million kilometers. Contrary to all the other moons, Phoebe runs around Saturn in a clockwise direction. Together with its surface characteristics and its density, which at 1.6 g/cm³ is comparatively high in view of its small size, this fact suggests that Phoebe did not originally form as a satellite of Saturn but is really a small body from the Kuiper-Edgeworth Belt beyond Neptune that was forced by Saturn's gravity into a retrograde orbit around the planet.

Image: Saturn and its large moons, not to scale. *(Individual images: © NASA/JPL/Space Science Institute; Composite: DLR)*

URANUS

In 1781, William Herschel discovered the seventh planet of our Solar System that was given the name Uranus soon afterwards. However, the planet was probably observed earlier than that because it is just bright enough to be seen with the naked eye. Circling around the planet in the equatorial plane, the five biggest moons of Uranus (Miranda, Ariel, Umbriel, Oberon, Titania) have been known for quite some time. In 1977, occultation observations made with an airborne telescope revealed the existence of a system of five individual rings whose number has meanwhile grown to 13. Since the flyby of the Voyager 2 probe in January 1986, we have known that Uranus is a globe shining in a bluish-green tint which, unlike Jupiter and Saturn, generally does not display any marked cloud bands and atmospheric structures.

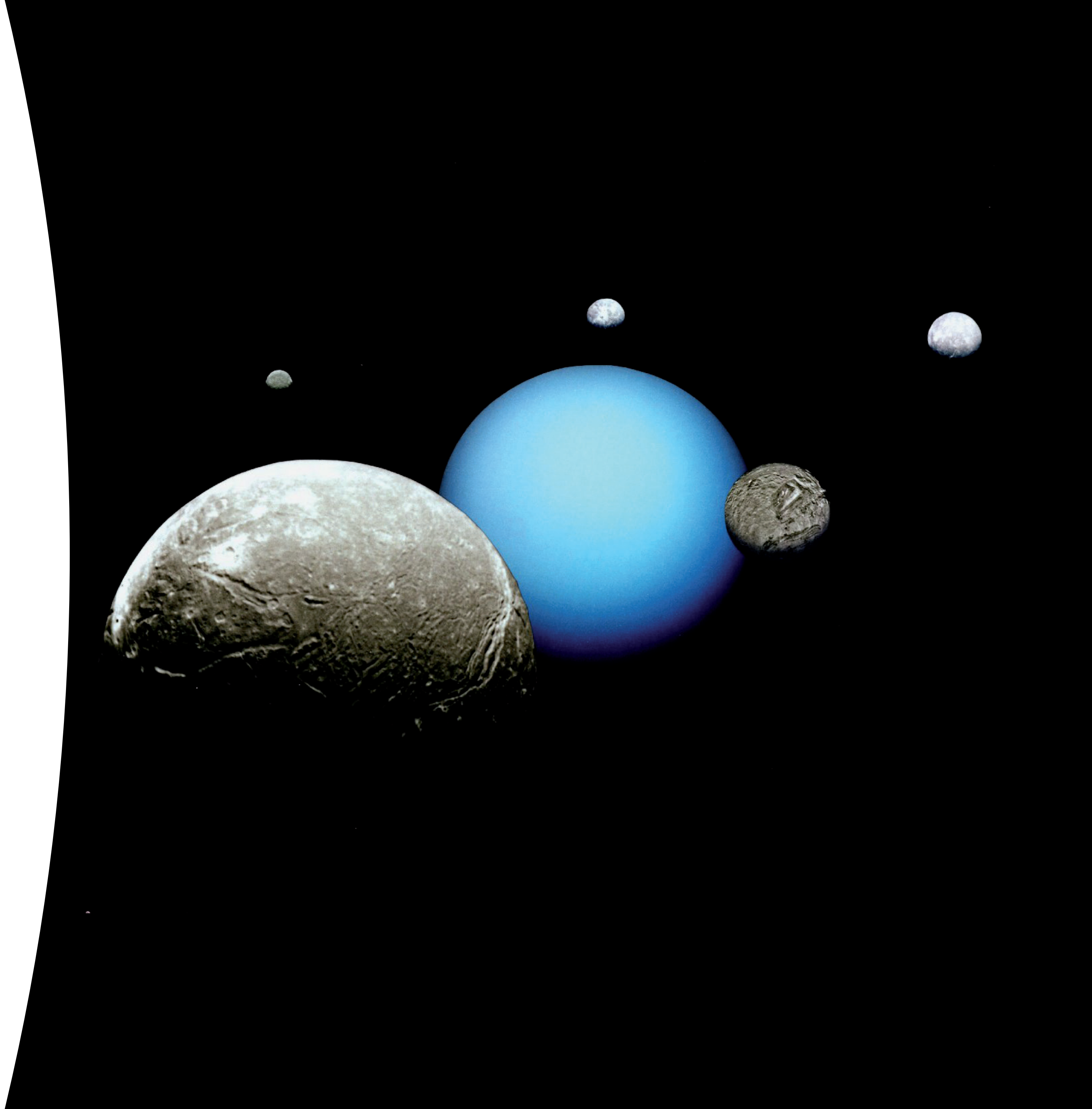
Uranus takes 84 years, approximately the lifespan of a human being, to orbit the Sun from which it is about 20 times more distant than Earth, twice the distance of Saturn and four times the distance of Jupiter. Uranus rotates around its axis once in 17.3 hours and has a relatively powerful, asymmetric magnetic field that forms an angle of 60° to the planet's spin axis which, in turn, is inclined at 98° so that it runs almost parallel to the planet's ecliptic. Therefore, Uranus 'rolls' around the Sun, in a manner of speaking. Consequently, the planet is exposed to seasonal fluctuations in solar irradiation that are fairly unusual compared to the other planets. It is thought that the conspicuous inclination of Uranus' spin axis to the ecliptic may be due to a disastrous collision with a compact body of high mass that took place in the early age of the Solar System.

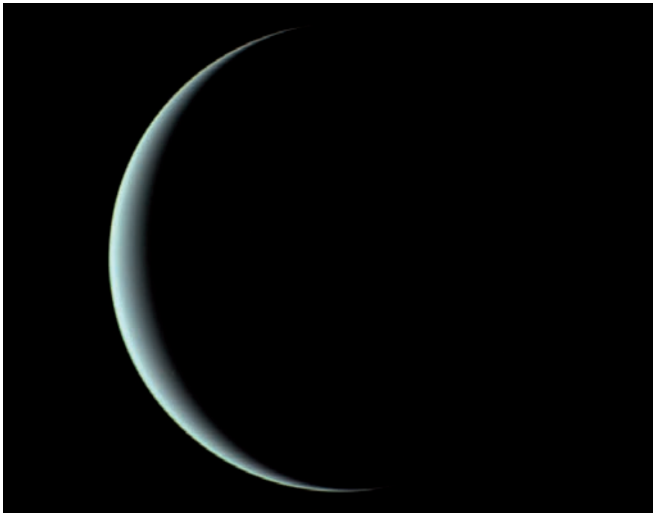
Facts

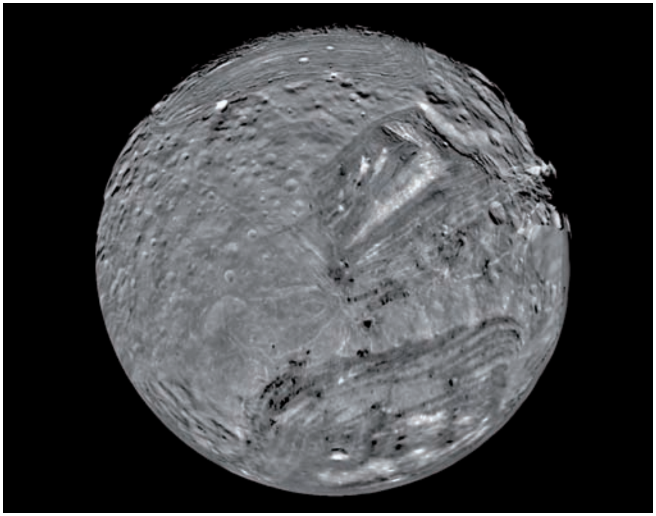
Uranus	Mass	8.684×10^{25} kg
	Radius (equatorial)	25,559 km
	Radius (polar)	24,973 km
	Density	1.30 g/cm^3
	Rotation period	17.24 h
	Orbital period	84.02 years
	Mean distance from the Sun	2.870×10^9 km
Miranda	Mass	6.6×10^{19} kg
	Density	1.15 g/cm^3
	Radius	240.4 x 234.2 x 232.9 km
	Orbital period	1.413 days
	Mean distance from Uranus	129,872 km
Ariel	Mass	1.35×10^{21} kg
	Density	1.56 g/cm^3
	Radius	581.1 x 577.9 x 577.7 km
	Orbital period	2.52 days
	Mean distance from Uranus	190,945 km
Umbriel	Mass	1.17×10^{21} kg
	Density	1.52 g/cm^3
	Radius	584.7 km
	Orbital period	4.144 days
	Mean distance from Uranus	265,998 km

The mass of Uranus is 14.54 times that of Earth. Measuring 51.118 kilometers in diameter at the equator, the planet has room enough to accommodate 64 terrestrial globes. The interior itself essentially consists of a mix of ice and rock under elevated pressure and temperature conditions. Consisting chiefly of water (H_2O), methane (CH_4), and ammonia (NH_3) ice, the core may account for up to 85 % of the planet's total mass. Because of the extreme ambient pressure, the properties of the material in the ice-rich core region resemble those of a liquid. At greater depth, phase transitions may even cause the precipitation of helium drops and diamond crystals. In contrast to Jupiter and Saturn, however, the planet's magnetic field is probably generated by an outer liquid layer which, rendered conductive by a relatively high concentration of ions, is covered by a relatively shallow water ocean. Given these circumstances, it is only to be expected that the magnetic field of Uranus varied noticeably since the flyby of the Voyager 2 space probe. The water ocean is shrouded in a dense atmosphere consisting mainly of molecular hydrogen, helium, and water with a measurable admixture of methane (CH_4) which gives Uranus its bluish-green tinge. While the

Image on the right: Uranus and its largest moons, Ariel, Miranda, Titania, Oberon, and Umbriel (from big to small). *(© NASA/JPL)*







condensation of methane in the planet's troposphere occasionally leads to the formation of clouds, layers of mist in its stratosphere are chiefly formed by hydrocarbons like acetylene (C_2H_2) and ethane (C_2H_6).

Because of its great distance to the Sun, the amount of solar energy that Uranus receives per unit of area and time is four times less than that received by Saturn and sixteen times less than that received by Jupiter. Because of the unusual orientation of its spin axis, the north and south poles each receive intense solar irradiation for a period of 21 years, while the equatorial zones and middle latitudes of the planet receive a relatively great share of the Sun's energy for another two 21-year periods. These inequalities in the length of the insolation periods should cause noticeable atmospheric dynamism at the various planetary latitudes. According to the measurements taken by Voyager, however, this holds true only for the uppermost layers of the atmosphere, where preponderantly zonal cloud circulation movements were observed. Moreover, Uranus does not appear to possess a source of heat in its interior, in which it differs markedly from all the other giant planets.

Located without exception at the equatorial plane, Uranus' 13 rings are at a distance of 39.000 to 97.000 kilometers from the planet's center. Rich in dust, the rings reflect only a scant five percent of the Sunlight, meaning that they are extremely dark and colorless. It may be that they contain a high proportion of carbon.

Facts

Titania	Mass	3.53×10^{21} kg
	Density	1.70 g/cm^3
	Radius	788.9 km
	Orbital period	8.706 days
	Mean distance from Uranus	436,298 km
Oberon	Mass	3.01×10^{21} kg
	Density	1.64 g/cm^3
	Radius	761.4 km
	Orbital period	13.463 days
	Mean distance from Uranus	583,519 km

Image on the left: The crescent of Uranus in true color. *(© NASA/JPL)*

Image on the right: The Uranian moon Miranda showing conspicuous structures. *(© NASA/JPL/USGS)*

The moons of Uranus

The five biggest moons of Uranus resemble the medium-sized icy moons of Saturn as far as their size and arrangement are concerned. On the other hand, the planet's satellites have a higher mean density of about 1.5 g/cm³, suggesting that their interior contains a higher proportion of rock and, consequently, produces more radioactive heat. Dotted with impact craters, the moons' surfaces accordingly display traces of resurfacing driven by tectonic or even volcanic forces which, especially on Miranda and Ariel, are linked to the thermal evolution of the interior of each satellite. It is probable that, like the moons of Jupiter and Saturn, the evolution of the moons of Uranus was additionally influenced by tidal effects and their interaction with the relatively powerful and noticeably inclined magnetic field of Uranus.

Miranda is the innermost and smallest of Uranus' known moons. The structure of its surface is astonishingly diverse, featuring craters, furrowed landscapes, embankments, scarps, and three large ring formations which may have been formed by lightweight material rising from the satellite's warm interior.

Ariel is the second biggest moon of Uranus. Its surface shows many craters, suggesting that it is of great age, and displays a network of numerous rifts and ridges which suggest that the icy crust was tectonically deformed by changes in the satellite's volume. At the same time, Ariel's surface is the brightest of all the moons of Uranus, indicating that it is somewhat younger in geological terms than the others because it was not as much darkened by micrometeorites and charged particles. Recent evaluations of the images taken by Voyager 2 of some rift structures have supported the evidence indicating that the moon was resurfaced by active cryo-volcanism.

Measuring more than 1,500 kilometers in diameter, Titania and Umbriel, the two largest moons of Uranus, might even now harbor extensive oceans of liquid water in their interior, formed in their early age when the satellites were periodically heated more intensely by tidal forces so that water melted. Umbriel is the third largest of Uranus' moons. Its relatively dark surface shows only a few bright spots. The largest of the moons of Uranus, Titania, has a surface that is covered by impact craters. It features a number of conspicuous straight depressions or valleys which, caused by tectonic stress in the icy crust, occasionally stretch over hundreds of kilometers.

Oberon, the outermost of Uranus' moons, resembles Titania in that its surface is covered by impact craters, some of which show dark material of unknown origin in their depths.

Voyager 2 discovered another ten relatively small satellites (Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Belinda, and Puck). In the last few years, yet more moons (Caliban, Stephano, Sycorax, Prospero, Trinculo, and Setebos) have been added to the list together with a few tiny satellites, Francisco, Margaret, Ferdinand, Perdita, Mab, and Cupid. A total of 27 moons are known so far.

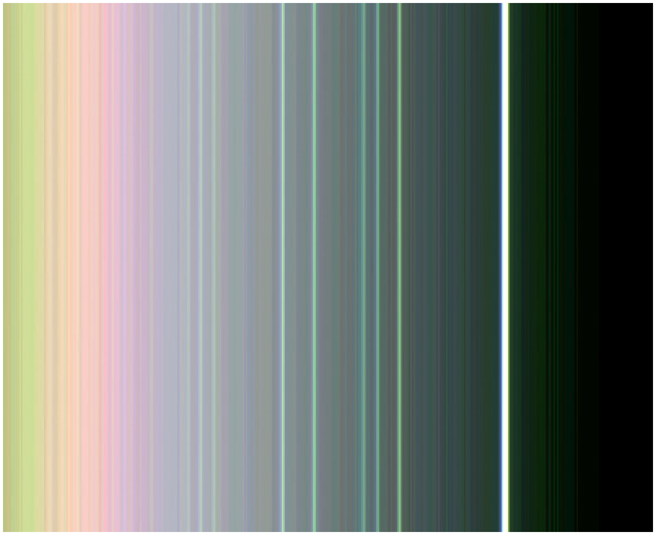
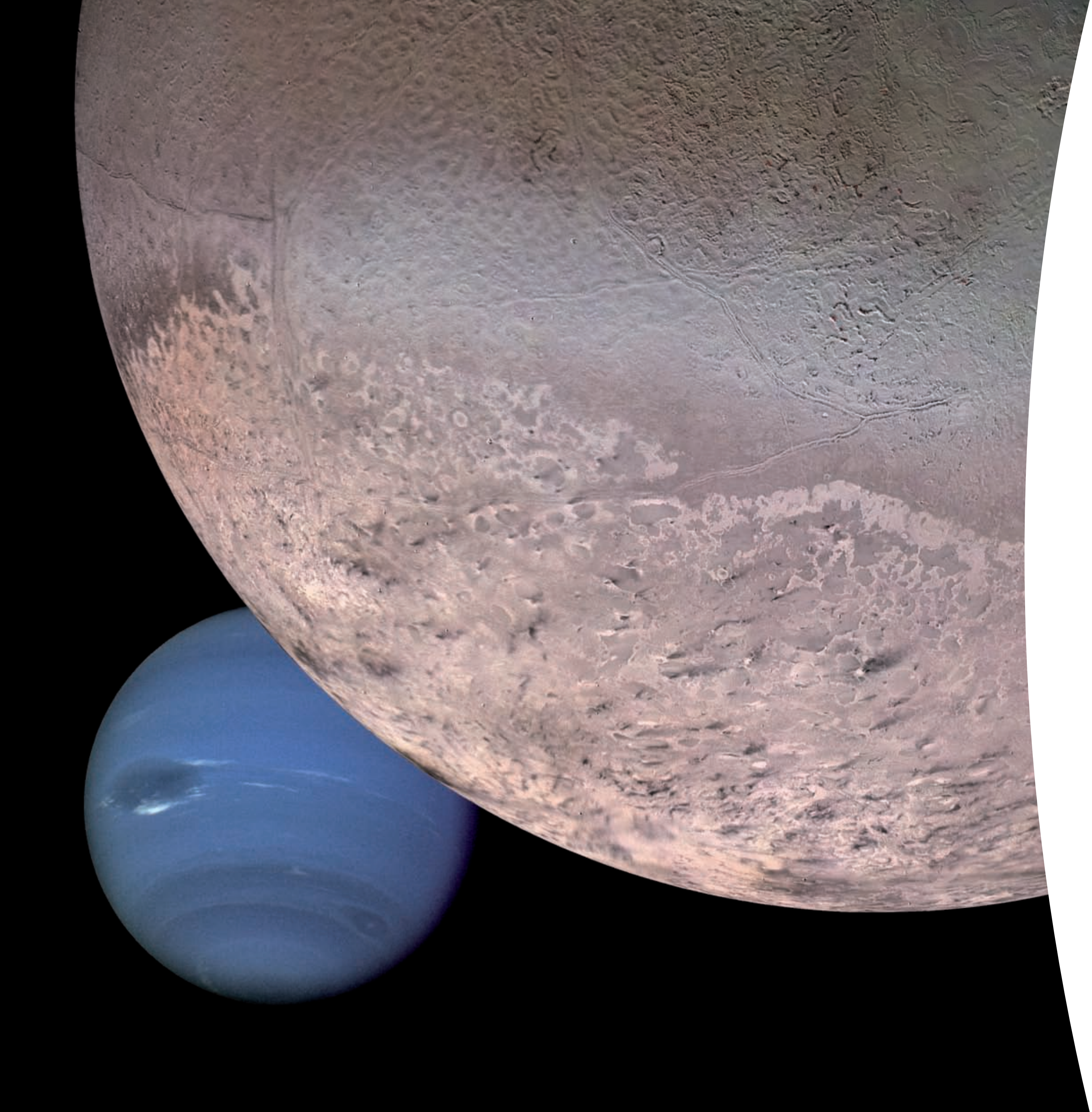


Image: The ring system of Uranus in false color.
(© NASA/JPL)



NEPTUNE

The outermost of the giant planets, Neptune, was discovered in Berlin as late as 1846 by Johann Galle and Heinrich Ludwig d'Arrest on the basis of irregularities in the orbital movement of Uranus. The planet was possibly seen 233 years earlier by Galileo who, however, failed to recognize it as a 'wanderer'. From the images taken by the Voyager 2 probe, which passed the planet in August 1989, we know Neptune as an aesthetic, shining blue sphere featuring a large and a small dark spot as well as conspicuously bright structures and clouds in its upper atmosphere that recall terrestrial cirri.

Like the other giant planets, Neptune has moons and a ring system. To a terrestrial observer, it appears to remain for a long time in one and the same constellation because it is far away from Earth and moves slowly in its orbit. Neptune takes nearly 165 years to circle around the Sun, from which it is about 30 times as far away as Earth. The planet rotates around its axis in somewhat more than 16 hours. Its spin and magnetic-field axes are set at an angle of 47°; moreover, its magnetic field is offset by 0.4 planetary radii from the planetary center, which leads to complicated interactions with the solar wind.

Neptune's mass is equal to 17.15 Earth masses. The planet has a diameter of 49,492 kilometers at the equator, and its interior is spacious enough to accommodate about 60 terrestrial globes. It consists of a partially or entirely separated mix of ice and rock under enhanced pressure and temperature conditions. Dominated by water ice, the core region may occupy as much as 70 % of the planetary radius. It is covered by a thin, liquid, conductive layer which generates the magnetic field. This 'ocean of ions' is shrouded in a dense atmosphere that mainly consists of molecular hydrogen and a small proportion of helium (10 to 15 %). The condensation of methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), and water (H_2O) produces changing cloud patterns and widespread haze. The great dark spot observed by Voyager 2 is an atmospheric vortex whose life, according to recent observations by the Hubble space telescope, is materially shorter than that of its long-lived counterpart, the Great Red Spot in the atmosphere of Jupiter.

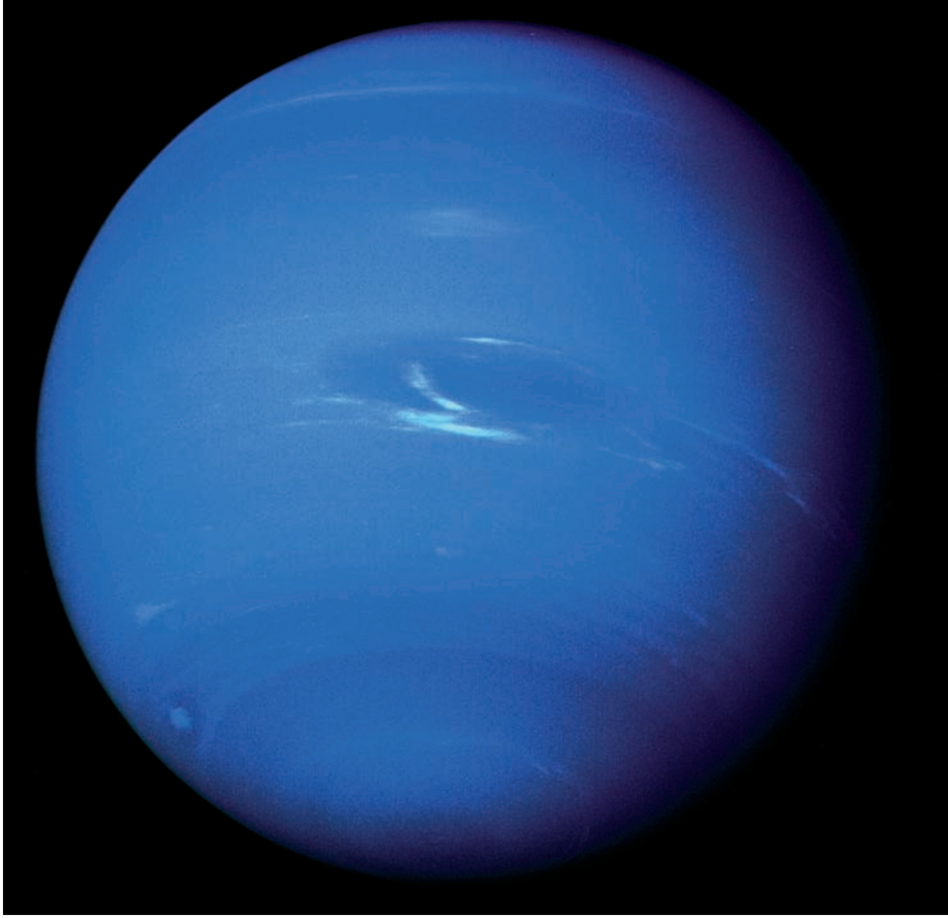
Although Neptune only receives a fraction of one twentieth of the energy that Jupiter receives from the Sun per unit of area and time, the wind velocities observed by Voyager 2 on its flyby are the highest ever measured in the Solar System – 560 meters per second or 2,060 kilometers per hour. This might be due to the fact that, in contrast to Jupiter and Saturn, Neptune's atmosphere is practically free from large-scale turbulences which obstruct and slow down high-speed atmospheric currents. Furthermore, Neptune probably has another source of energy deep in its interior because the planet radiates almost 2.6 times more energy in the thermal infrared wavelengths than it receives from the Sun. Moreover, the existence of compact, abnormally hot regions ('hot spots') has been proven in the vicinity of the south pole. Such local high temperatures are likely to influence the frequency of chemical reactions and the formation of aerosols in the atmosphere of Neptune.

Ever since stellar occultation revealed rings arching around Neptune in 1984, it was firmly believed that Neptune has its own ring system. And indeed, the images taken by Voyager 2 showed two narrow, complete, sharply

Facts

Neptune	Mass	1.024 x 10^{26} kg
	Radius (equatorial)	24,746 km
	Radius (polar)	24,341 km
	Density	1.76 g/cm^3
	Rotation period	16.11 h
	Orbital period	164.79 years
	Mean distance from the Sun	4.498 x 10^9 km
Triton	Mass	2.14 x 10^{22} kg
	Density	2.07 g/cm^3
	Radius	1352 km
	Orbital period	5.877 days
	Mean distance from Neptune	354,800 km
Nereide	Mass	2 x 10^{19} kg
	Density	unknown
	Radius	170 km
	Orbital period	360.14 days
	Mean distance from Neptune	5,513,400 km

Image on the left: Neptune and its largest moon, Triton (foreground). Composite image. *(© NASA/JPL/USGS)*



delimited main rings with radii measuring 63,000 and 53,000 kilometers and a width of 10 to 15 kilometers each. In addition, two or three fainter rings were discovered which are wider and probably consist of minor particles with a low albedo.

The moons of Neptune

Neptune has 13 moons, of which Triton and Nereid were known before Voyager 2 flew by. Neptune's largest moon, Triton, has a thin atmosphere of nitrogen and methane. Measuring 2,705 kilometers in diameter, it is somewhat smaller than the Moon, yet its surface structures are surprisingly diverse. Nereid is the smaller and more distant of the two moons that have been known for a long time. It moves along an orbit that is extremely elliptic. Voyager 2 was unable to observe Nereid at close range. However, light-curve fluctuations have given rise to the assumption that the shape of the satellite is not spherical but oblong; alternatively, its surface may be composed of materials of varying reflectance (albedo).

The cameras on Voyager 2 discovered another six moons, the largest of these newly-discovered objects being Proteus with a diameter of 420 kilometers. The diameters of the other five moons, Naiad, Thalassa, Despina, Galatea, and Larissa vary between 60 and 200 kilometers. In 2002 and 2003, telescope observations of the Neptune system revealed five more moons measuring between 40 and 65 kilometers (Halimede, Psamanthe, Sao, Laomedeia, and Neso).

Triton is probably the only major satellite in the Solar System that was not born together with its central planet: on its nearly circular orbit that is inclined about 23 degrees to the equatorial plane, Triton runs against Neptune's direction of rotation around the Sun. This suggests that Triton was originally a dwarf planet like Pluto which originally came from the inner Kuiper-Edgeworth Belt and was 'trapped' by Neptune very early on when it crossed the planet's orbit. Moreover, it is to be expected that Triton's rotation and orbital periods were synchronized by tidal effects at an early time. Thus, Triton's orbit, which had been highly eccentric in the beginning, quickly assumed its present circular shape, and Triton constantly turns the same hemisphere towards Neptune.

There is a great deal of evidence indicating that Triton's interior was sufficiently warmed by tidal friction to completely separate its two main constituent elements, rock and ice, in accordance with their density. Current models suggest that about 75 % of Triton's total mass are accounted for by a central rocky core and about 25 % by the icy shell that surrounds it. Like Jupiter's moon Europa, Triton might hide under its icy crust an ocean of water that is in contact with the rocky core.

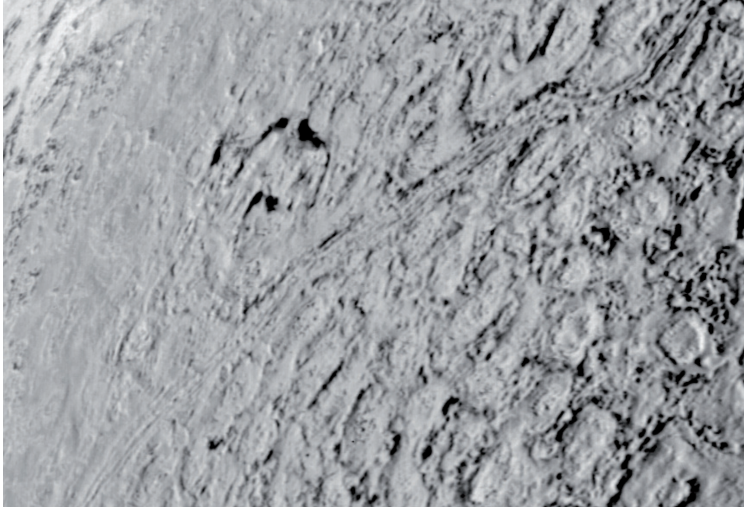
The mean temperature at the surface of Triton is as low as -240 °C, the lowest ever measured on any planet or large moon with a rigid surface. Triton's surface is composed of water ice and frozen nitrogen and methane, mixed with frozen carbon monoxide and dioxide as well as with rock and organic elements (more hydrocarbon

Image: Global view of Neptune showing the great dark spot and atmospheric band structures.
(© NASA/JPL)

compounds). Next to Titan, Triton is the only heavenly body to possess a nitrogen-based atmosphere like Earth, although Triton's is much thinner. Because the highly volatile substances on its surface interact with Triton's atmosphere, their spatial distribution on the surface changes drastically in the course of a Triton year. Because of the length of time it takes to orbit the Sun and the extreme inclination of its spin axis, each pole is exposed to the Sunlight for 82 years and subsequently remains in the dark for the same length of time. On the summer hemisphere, nitrogen and methane ice evaporate, exposing the dark icy crust below. On the cold winter hemisphere, on the other hand, the precipitation of ice with its higher albedo makes these regions appear brighter.

The only pictures we have of Triton's surface were taken by the Voyager 2 space probe in 1989. They show a geologically complex surface which also features enigmatic structures like the 'cantaloupe terrain' that has only been seen on Triton so far. The name is borrowed from the rind of certain honeydew melons. The pictures show comparatively few impact craters, and what is more, the craters on Triton are small compared to those on the satellites of Jupiter or Saturn, for instance. The largest crater in the region photographed by the cameras on Voyager (only 40 percent of the surface was imaged) measures no more than 27 kilometers in diameter. As the age of a surface can be judged by the number of its impact craters, the small number of craters on Triton appears to indicate that its surface is relatively young, and that marked changes on it have been initiated by geological processes that may still be active today. Next to the Jovian moon Europa and the Saturnian moons Titan and Enceladus, Triton is the only large icy moon that is thought to be still geologically active today.

The evidence for the action of erosion and the aeolian transport of surface material includes linear dark deposits which, criss-crossing the surface particularly in the vicinity of the south pole, indicate the prevalent wind direction by their orientation. It is supposed that the cantaloupe terrain, this network of depressions and hills, was produced by the sublimation of highly volatile substances in Triton's icy crust, triggered by temperature differences in the course of the day. Tidal effects may have caused deformations in the surface in the form of linear scarps and mountain ridges which probably originated fairly recently. With regard to their morphology and spatial extent (10-25 kilometers wide, up to 1,000 kilometers long, around 200 meters high), the mountain ridges resemble comparable formations on the Jovian moon Europa.



Next to Earth, the Jovian moon Io, and the Saturnian moon Enceladus, Triton is the fourth body in the Solar System that is known to be volcanically active today. However, Triton's volcanism cannot compare in intensity with that of the three other bodies. That volcanism is still active on Triton was established by observations of geyser-like eruptions in the south polar region where dark clouds resembling the trunk of a tree rise up vertically and then spread out horizontally at an altitude of about 8 kilometers, where they probably meet an inversion layer in the atmosphere. These volcanic blasts may occur when sub-surface bubbles filled with gaseous nitrogen are heated by the Sun so that they expand and ultimately explode. However, the phenomenon may also be explained by the comparatively sedate evaporation of ice on the surface, a process that grows more intense as solar irradiation increases. Other regions on Triton possibly display calderas (eruptive centers) up to 200 kilometers wide that are filled with plane material which is probably viscous when it emerges on the surface but consists not of lava, as on Earth, but of a mix of water and ammonia.

Image: Cantaloupe terrain on Triton. *(© NASA/JPL)*

COMETS

Since time immemorial, comets have been enthralling people by the way in which they appear in the sky suddenly and unexpectedly. Many myths surround these fascinating shiny phenomena bearing a long tail. Thought to be harbingers of bad luck, they often spread fear and terror. Even the murder of Julius Caesar more than 2000 years ago was linked to the appearance of a comet. When the comet Halley appeared in 1066, it was held responsible for the defeat of the army of King Harold II by the troops of William the Conqueror near Hastings in England. Even when it returned in 1910, the same comet caused parts of the population to fear that the end of the world had come.

For a long time, it was not clear where comets come from. Aristotle located these shining objects in the outermost layer of the terrestrial atmosphere, thinking them to be a kind of weather phenomenon. Martin Luther thought they infringed the divine order by their sudden appearance. It was only in 1577 that Tycho Brahe was able to prove by parallax measurements that comets had to be farther away than the Moon. Subsequently, astronomers frequently used these impressive, conspicuously bright tailed stars to refine their analytical methods for calculating orbits. Famous mathematicians like Gauss and Euler were involved in these endeavors.

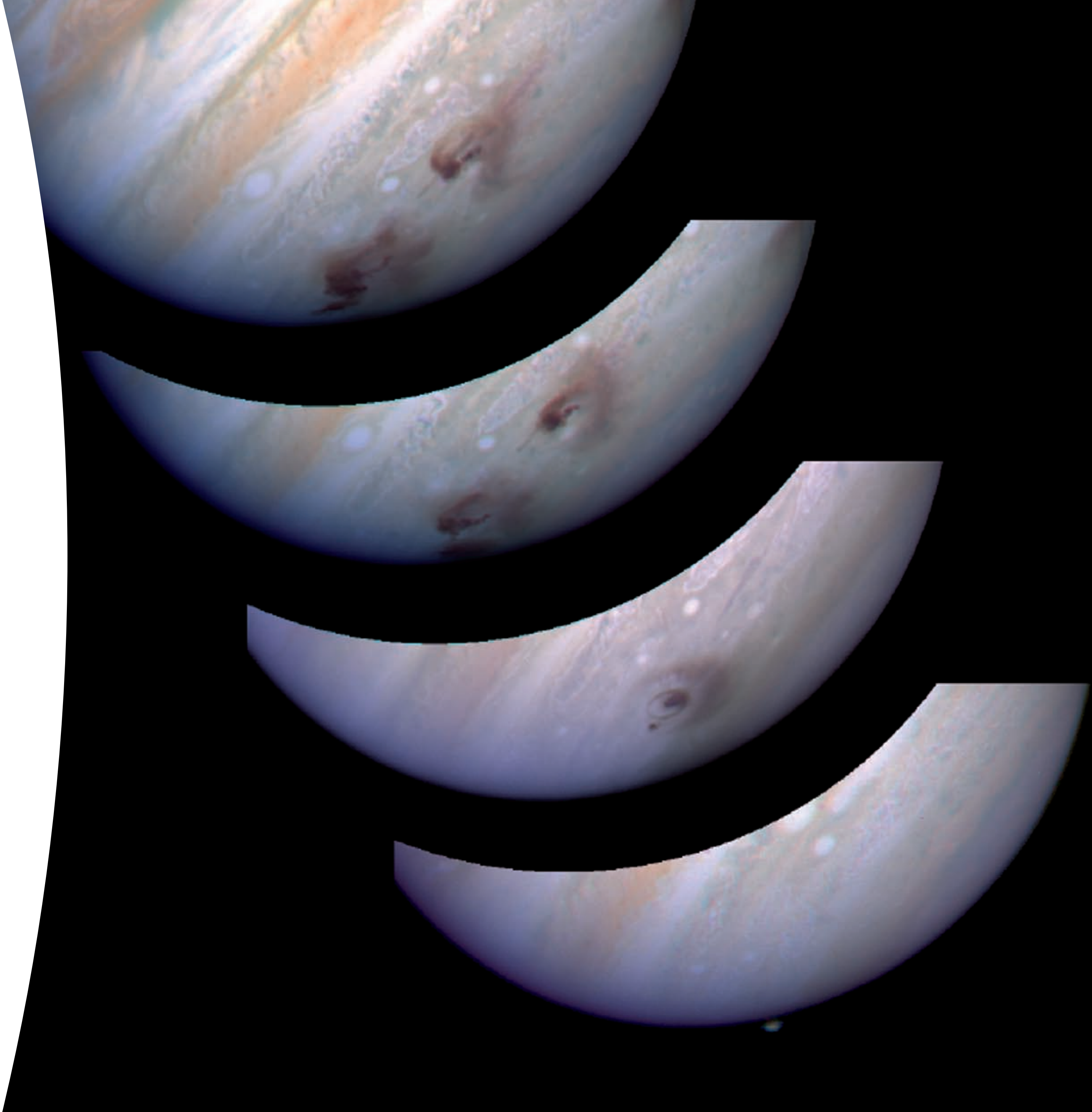
Today we know that comets are small bodies whose diameters range from a few hundred meters to some tens of kilometers. Their original home is on the distant outskirts of the Solar System, a place where the cold is extreme. In the Solar System, there are two important reservoirs of comets: first, there are the so-called Trans-Neptunian Objects to which Pluto belongs. These TNOs are located in a torus outside the orbit of Neptune at a maximum distance of about 100 astronomical units (AUs). Second, there are the bodies that form the spherical Oort Cloud. Spreading over a distance between a few thousand AUs to almost one light year from the Sun, the cloud reaches the limits of the Solar System. The Oort cloud is supposed to contain many billions of cometary nuclei which either come from the region of the outer planets or have been trapped from somewhere in the Milky Way, so that their origin lies outside the Solar System.

Because of their great distance so the Sun, around which they move very slowly, comets remain extremely cold, which enables them to preserve even highly volatile components for a very long time in the form of ice. Occasionally, slight gravitational disturbances in its orbit may cause one of these bodies to enter a path that brings it closer to the Sun. On the way, its originally frozen gases will gradually thaw and flow into space, carrying dust particles from the surface along with them. Through this so-called cometary activity, the small nucleus will be gradually surrounded by a hazy, diffuse atmosphere, the coma, which measures between 10,000 and 100,000 kilometers in diameter. From it, a conspicuously bright tail will begin to grow as soon as the comet reaches the vicinity of the orbit of Mars. Always pointing away from the Sun, such a tail may reach a length of 2 astronomical units (300 million kilometers) in extreme cases.

In physical terms, tails can be classified as gas or dust tails, the latter being conspicuous for their curvature. Spectroscopic measurements prove that many molecules we know from the interstellar medium are also present in the coma and the gas tail of a comet. Consequently, it is assumed that comets are small, not overly altered relics from the earliest age of the Solar System. They owe their original condition to their gravity, which is low compared to that of the planets, the slight probability of collisions and the low impact velocities in the outer Solar System, and their low temperature. This is

Image above: The comet Hale-Bopp with two tails, photographed in April 1997. *(© Observatory Slovenia)*

Image on the right: Traces of the impact of the G fragment of the Shoemaker-Levy 9 comet in the Jovian atmosphere over a five-day period. *(© R. Evans, J. Trauger, H. Hammel and the HST Comet Science Team and NASA)*



why the results of cometary research are so important for statements about the early evolution of our planetary system. Even the asteroids were exposed to relatively high temperatures and have thus been modified more extensively than the comets.

Thus, the chief feature that distinguishes comets from asteroids is their higher content of volatile molecules like water ice. At the same time, researchers have recently found out that the differences between the two classes of objects are not as great as was formerly thought. Even in the asteroid belt, objects have been discovered that display cometary activity, albeit at a low level. On the other hand, there are old comets whose icy components have completely evaporated from their surface, so that outgassing has ceased.

Shortly after the planetary system had formed, comets (as well as asteroids) were diverted towards the Sun in much greater numbers and thus crashed more frequently on the inner planets and the Moon. Certain components that are important for life, like water and organic molecules, were probably transported to Earth by comets whose impacts thus influenced the development of a biosphere in the early age of the Solar System.

Comets have little internal coherence. They break up occasionally, particularly when they come too close to the Sun, and some even plunge into it. When a comet disintegrates, its debris spreads out along its trajectory. Whenever such a cloud of debris comes close to Earth, its small particles enter the Earth's atmosphere and burn up in it as meteors. Many well-known showers of meteors or shooting stars, as they are often called, can be traced back to broken-up comets or comet effluvia.

About 20 years ago, an outstanding event happened: in 1992, the comet P/Shoemaker-Levy 9 (SL9) was shattered by the tidal forces of Jupiter. Ranging between 50 and 1,000 meters in size, its 21 fragments arranged themselves around Jupiter in a chain several million kilometers long. They were discovered in March 1993 by astronomers Carolyn and Eugene Shoemaker and David Levy of the Californian Mount Palomar observatory. Very soon, it emerged that all fragments were on a collision course with the planet. In July 1994, they successively crashed into a part of the southern Jovian hemisphere that was facing away from Earth at a velocity of about 60 kilometers per second (216,000 kph).The phenomena that subsequently occurred in the atmosphere of Jupiter formed the object of one of the greatest globally coordinated observation campaigns in the history of astronomy. The evaluation showed that the energy released by the impact was equivalent to about 50 million atom bombs of the Hiroshima type. The traces left behind by the impacts in Jupiter's atmosphere were larger than the diameter of Earth and could be observed in telescopes for a long time afterwards.

In the last few decades, comets were visited by several space probes. The measurement results gathered by them did a great deal to improve our understanding of these heavenly bodies. The first missions to comets in the history of space flight culminated when a probe flew closely by the famous comet Halley in 1986. Returning regularly and featuring a splendid tail, this is the most popular of all periodic comets. It has probably been observed for more than three thousand years and certainly since the year 240 B.C. It orbits the Sun on an elongated elliptical path which is inclined to the Earth's ecliptic. Its mean orbital period is 76 years. The comet reaches its aphelion, the greatest distance from the Sun, beyond the orbit of Neptune, passing through its perihelion, the point closest to the Sun, between the orbits of Mercury and Venus, which makes it one of the so-called short-period comets. In March 1986, the Soviet probes Vega 1 and Vega 2 flew past the comet's nucleus at a speed of c. 78 kilometers per second, keeping a distance of somewhat less than 9,000 and 8,000 kilometers, respectively, and communicating numerous photos and measurement

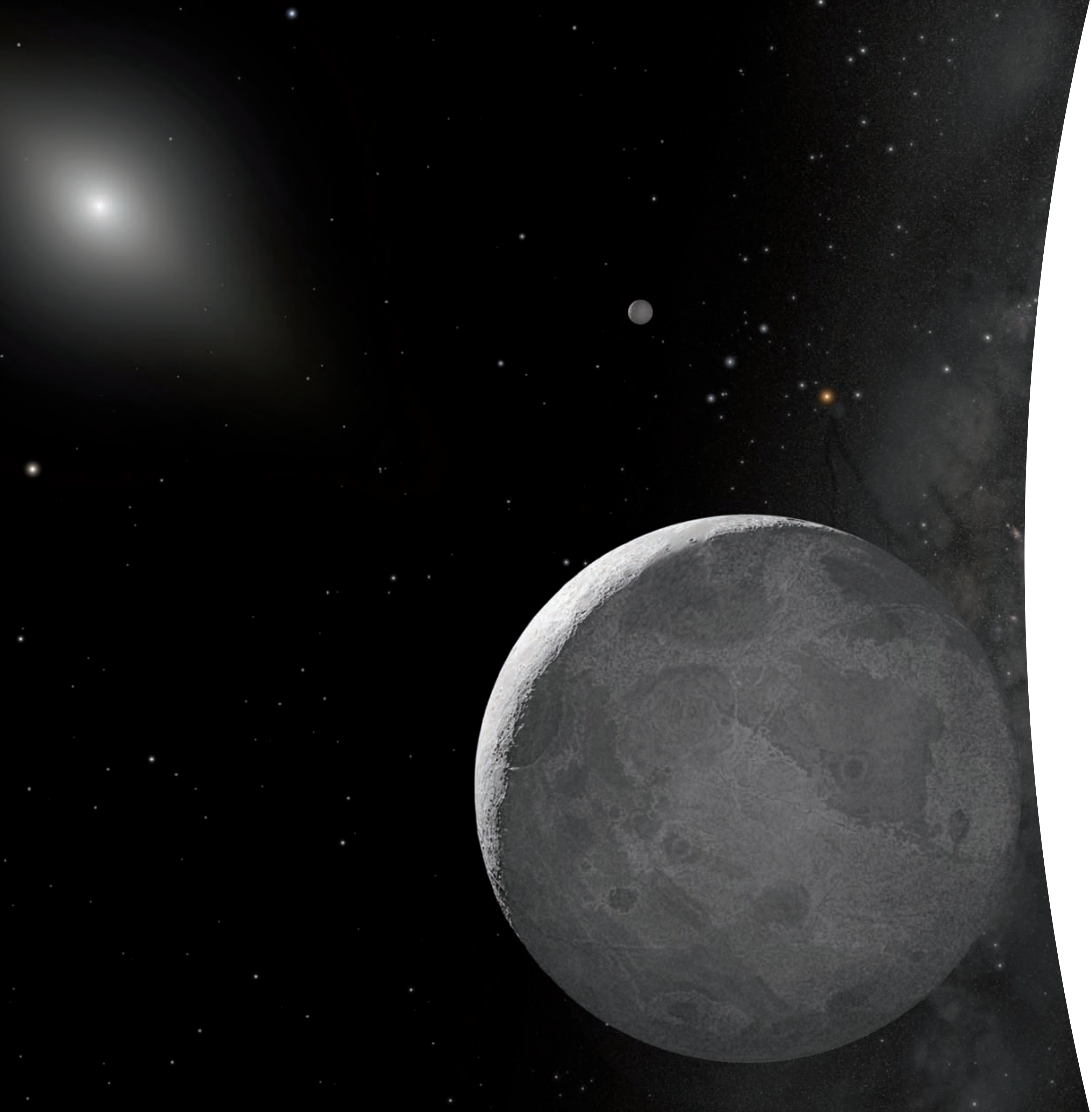
Image: Nucleus of the comet Tempel 1. *(© NASA/JPL/UMD)* data. Shortly afterwards, ESA's Giotto probe, which had been launched on 2 July 1985, approached Halley to a distance of 600 kilometers, delivering well-defined pictures together with other data. In 2001, NASA's Deep Space 1 mission flew past the comet 19P/Borelly at a distance of no more than 2,200 kilometers, mainly for the purpose of testing new technologies. Two genuinely scientific missions were launched by NASA a few years later. In 2005, the Deep Impact probe paid a visit to the short-period comet Tempel 1, which originally comes from the Kuiper-Edgeworth Belt. It was discovered by astronomer Ernst Wilhelm Leberecht Tempel of Saxony on 3 April 1867. An essential feature of the space experiment was the impact of a copper projectile weighing 372 kilograms which hit the comet at a speed of 37,000 kilometers per hour, creating a crater about 100 meters in size and throwing material into space, which was then examined by the instruments on the probe and by telescopes on Earth. This was the first-ever successful analysis of material from regions below a comet's surface. It was impossible to detect the crater itself because of the cloud of dust that was raised. Having completed its primary mission, the probe, re-named EPOXI, flew by the comet 103P/Hartley in November 2010 at a distance of no more than 700 kilometers to conduct measurements there.

In 2004, after a flight of almost five years, the Stardust space probe passed the comet Wild 2 at a distance of 240 kilometers, taking numerous pictures and gathering coma material. In January 2006, the lander capsule containing the dust samples returned to Earth on a parachute. Examined in laboratories all over the world, the dust samples supplied fresh insights into the composition and origin of comets. Having passed Wild 2, the probe was re-named Stardust-NExT and sent on to the comet Tempel 1. In February 2011, it passed the nucleus of the comet at a distance of 180 kilometers and radioed images back to Earth. Some of these show the region around the Deep Impact crater that was almost six years old by then. However, it is still difficult to specify the original size of the crater precisely because the surface has been changed in the meantime by cometary activity.

Thanks to the great endeavors undertaken in the last few decades, involving observations from Earth as well as space missions, our knowledge about comets has expanded considerably. Today, we know that comets are porous bodies of low density whose physical and chemical properties differ widely – meaning that there is no such thing as a 'standard comet'. We also know that the composition of comets is not homogenous. Their constituent elements, dust and ice, contain numerous organic molecules. Driven by water ice as well as by frozen carbon dioxide, the activity of a comet is highly direction-dependent and inhomogeneous. Despite the enormous gains made in scientific knowledge in the last few years, some important questions still remain partially or entirely unanswered, such as, for example, the one about the significance of comets in the evolution of our planetary system and of life. Another moot question is why the properties of comets differ so greatly, why their composition is so heterogeneous, and why so little ice is found on their surface. We would like to know more about how cometary activity actually operates, why it changes drastically on occasion (outbursts) and why comets break apart so frequently (splits).

It is hoped that ESA's Rosetta mission will answer these questions in detail. Launched in 2004 and carrying eleven measuring instruments and a lander module, it is now on its way to the comet 67P/Churyumov-Gerasimenko, which measures nearly five kilometers. In 2014, it will be the first space probe to orbit a comet for several months at a distance of a few kilometers, releasing the Philae lander which will carry out numerous examinations on the comet itself.

Image: The Rosetta lander Philae on the nucleus of the comet 67P/Churyumov-Gerasimenko, artist's impression. *(© ESA/AOES Medialab)*



DWARF PLANETS

On 24 August 2006, the members of the International Astronomical Union (IAU) present at its 25th general assembly in Prague adopted the first-ever definition of the term 'planet' in our Solar System. The decision was prompted by continuous observations, the discovery of large trans-Neptunian objects, and fresh knowledge about planetary systems. The IAU resolved that planets and other bodies in our Solar System, moons excepted, should belong to one of three categories that are defined as follows:

1. A planet is a celestial body that itself is not a star and a) is in an orbit around the Sun, b) has sufficient mass for its own gravity to give it a nearly spherical shape (meaning that it is in a so-called 'hydrostatic equilibrium'), and c) has cleared the environment of its orbit of foreign cosmic matter.
2. A dwarf planet is a celestial body that a) is in an orbit around the Sun, b) has sufficient mass for its own gravity to give it a nearly spherical shape (meaning that it is in 'hydrostatic equilibrium'), c) has not cleared the environment of its orbit from foreign cosmic matter, and, finally, d) is not a moon.
3. All other objects orbiting the Sun, except moons, will be referred to collectively as small bodies in the Solar System. This category includes nearly all asteroids, most of the objects in the Kuiper-Edgeworth Belt and the Oort Cloud, as well as other minor bodies.

In a first step, the International Astronomical Union classified the following bodies as dwarf planets: Pluto, which was formerly regarded as a planet; Ceres, an asteroid, and Eris (2003 UB_{313}), an object in the Kuiper Belt. The 'observation list' kept by the IAU shows other candidates for dwarf planet status, including objects in the Kuiper Belt as well as large asteroids. The list is bound to grow further as fresh discoveries are made and known objects examined more closely. By now, Makemake (2005 FY_9) and Haumea (2003 EL_{61}) haven been classified as dwarf planets, too.

Image on the left: Artist's impression of the dwarf planet Eris and its moon Dysnomia. *(© NASA, ESA, and A. Schaller (for STScI))*

List of candidates (selection)

Object	Moons	Diameter
Orcus	-	1000 ± 200 km
Sedna	-	1500 – 1800 km
2002 TX_{300}	-	< 700 km
2002 AW_{197}	-	800 ± 100 km
Quaoar	-	~ 1200 km
Ixion	-	500 – 1000 km
Varuna	-	700 ± 150 km
Vesta	-	578 x 560 x 458 km
Pallas	-	570 x 525 x 500 km
2007 OR_{10}	-	875 – 1400 km

Ceres

Now classified as a dwarf planet, the asteroid Ceres was discovered by Giuseppe Piazzi on 1 January 1801 and named after Ceres, the Roman goddess of agriculture and cattle farming. Measuring about 975 kilometers in diameter, Ceres is not only the largest but also the most massive object in the asteroid belt, accounting for on third of the belt's total mass. Ceres has been re-classified before in the course of its history: initially categorized as a planet at the time of its discovery, it was numbered among the asteroids for more than 150 years because it resembles the other bodies in the asteroid belt.

Pluto

There has always been controversy about Pluto's status as a planet. On the one hand, it is very much smaller than the four large gas planets in the outer Solar System; on the other, its orbit is steeply inclined to the ecliptic. The general assembly of the International Astronomical Union put an end to this debate in August 2006 when it adopted a definition of the term planet under which Pluto as well as two other objects were classified as dwarf planets. Smaller, colder, and farther away from the Sun than all the large planets, there is yet another feature that characterizes Pluto: it belongs to a group of possibly 100,000 objects measuring more than 100 kilometers in diameter which circle around the Sun beyond Neptune's orbit in a disc-shaped zone called the Kuiper-Edgeworth Belt. This is the region in which Pluto and its satellites orbit the Sun. This remote realm is populated by thousands of infinitesimal icy worlds which formed in the early days of the Solar System.

Any larger telescope will reveal Pluto as a faint dot of light of the 15th magnitude, and you need to know its position very well to avoid confusing it with a star. Pluto was discovered in 1930 by Clyde Tombaugh after a decade-long search prompted by his awareness of disturbances in the orbits of Uranus and Neptune which indicated the presence of another planet. However, today we know that Pluto, being the smallest of all planetary bodies, does not have enough mass to disturb the orbit of Neptune – its tiny variations are due to other causes.

Pluto‘s rather eccentric orbit takes it around the Sun in nearly 248 years. Because of the relatively high eccentricity of its orbit, Pluto occasionally approaches the Sun closer than Neptune, which it did most recently between 1979 and 1998. Nevertheless, the two planets will never collide because Pluto‘s orbit is inclined 17 degrees to the ecliptic. Its mean distance to the Sun is 39 astronomical units, ten astronomical units greater than that of Neptune.

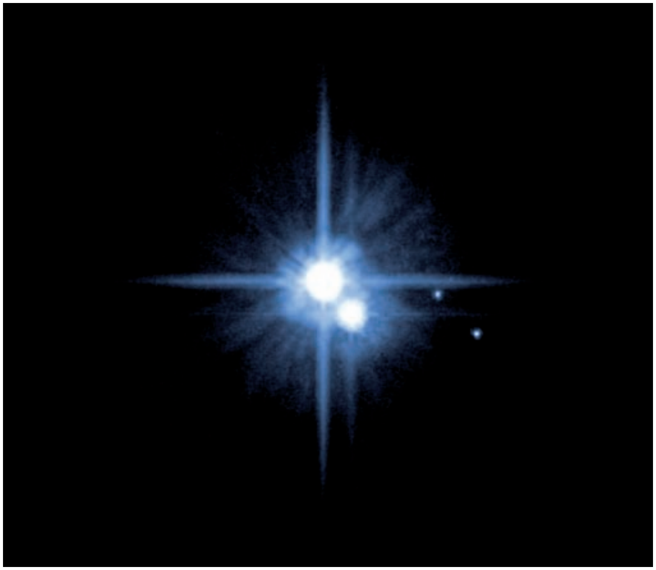
Recent measurements indicate that Pluto‘s diameter ranges around 2,390 kilometers. We do not know much about its surface. It is supposed to be covered by a mixture of frozen water, methane, and ammonia and surrounded by a thin atmosphere of methane, nitrogen, and heavier gases such as argon. The estimated surface temperature on the equator of the planet is 50 Kelvin (-223 degrees Celsius).

Facts

Ceres	Mean distance from the Sun (AU)	2.77
	Orbital period (years)	4.60
	Orbital eccentricity (circular = 0)	0.08
	Orbital inclination to ecliptic	10.58°
	Diameter (km)	952
	Known moons	0
Pluto	Mean distance from the Sun (AU)	39.5
	Orbital period (years)	247.92
	Orbital eccentricity (circular = 0)	0.2488
	Orbital inclination to ecliptic	17.6°
	Diameter (km)	2390
	Known moons	3
Eris	Mean distance from the Sun (AU)	67.7
	Orbital period (years)	557
	Orbital eccentricity (circular = 0)	0.441
	Orbital inclination to ecliptic	44.179°
	Diameter (km)	2400 ± 100
	Known moons	1
Makemake	Mean distance from the Sun (AU)	45.6
	Orbital period (years)	310
	Orbital eccentricity (circular = 0)	0.156
	Orbital inclination to ecliptic	28.998°
	Diameter (km)	1600 ± 300
	Known moons	0
Haumea	Mean distance from the Sun (AU)	43.342
	Orbital period (years)	285.3
	Orbital eccentricity (circular = 0)	0.189
	Orbital inclination to ecliptic	28.194°
	Diameter (km)	2200-1100
	Known moons	2

Observing Pluto through the 1.5-meter reflector of the US Naval Observatory, James Christy discovered a small bulge at the edge of Pluto‘s little disc in 1978 – the moon Charon. Recent measurements indicate that Charon has a diameter of 1,200 kilometers and orbits Pluto in 6.4 days at a mean distance of 19,600 kilometers. The rotation of the two bodies is locked, meaning that they always show the same face to each other. At 1 to 10, the moon-to-planet mass ratio is the highest found in the Solar System, so that Pluto and Charon might as well be regarded as twin planets. The system‘s center of mass lies 1,200 kilometers above Pluto‘s surface. Charon‘s discovery enabled researchers to determine the inclination of Pluto‘s spin axis more reliably. Because Pluto and Charon rotate synchronously around a common center of mass, Charon‘s orbital plane must coincide with the planet‘s equatorial plane. Consequently, Pluto‘s spin axis should be inclined 122 degrees away from its orbital plane. The only other planets with a similarly unusual orientation of their spin axis are Venus at 177° (inversion) and Uranus at 98° (skewness).

The theory that Pluto might be a ‘runaway‘ moon of Neptune has become more questionable since Charon was discovered. It is conceivable, however, that remnants of the primordial solar nebula contracted at a great distance from the Sun a long time ago, forming small moon-sized planets. After all, other small trans-Neptunian objects measuring between 100



and more than 1,000 kilometers in diameter have been discovered in the Kuiper-Edgeworth Belt since 1992.

In May 2005, it was discovered that Pluto has two small moons, Nix and Hydra. The fact that they move on the same orbital plane as Charon indicates that they were not trapped but originated together with Charon, which was probably formed by a gigantic collision between two Pluto-sized objects four billion years ago. In 2011 and 2012, two more moons, S/2011 (134340) 1 and S/2012 (134340) 1, were spotted on images taken by the Hubble space telescope and confirmed in later photographs. Estimated to measure 10 to 34 kilometers in size, they are the smallest moons of Pluto.

Image: Pluto and three of its moons, Charon, Nix, and Hydra.
(© NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI), and the HST Pluto Companion Search Team)

Eris (2003 UB_{313})

In July 2005, Michael E. Brown of the California Institute of Technology announced that he had discovered an object in the Kuiper Belt whose diameter of 2,400 kilometers made it a little larger than Pluto. Initially designated as 2003 UB_{313}, the object was christened Eris after the Greek goddess of discord and dispute. Its moon, S/2005 (2003 UB_{313}) 1, was named after Eris' daughter Dysnomia, the demon of lawlessness.

These new observations of Eris were made with a high-performance sensor of the 30-meter telescope at the Franco-Spanish Institut de Radioastronomie Millimétrique (IRAM) on Pico Valeta (Sierra Nevada), which measured Eris' heat emission and determined that its reflectivity resembled that of Pluto. From these data, its size could be derived. Moreover, Eris is remarkable because it is currently at a distance of 96 astronomical units from the Sun, close to the aphelion of its highly elongated orbit that is inclined at an angle of 44 degrees. At perihelion, when it is closest to the Sun, it will be at a distance of 38 astronomical units and will appear approximately as bright as Pluto. Eris takes a total of 557 years to complete an orbit around the Sun.

Makemake (2005 FY_9)

A dwarf planet and 'Plutoid', Makemake was discovered in 2005. It circles around the Sun far beyond the orbit of Neptune. Having a diameter of c. 1,600 kilometers, it is about two thirds the size of Pluto. Makemake takes about 310 years to orbit the Sun at a distance of 6 to 8 billion kilometers (40-53 astronomical units).

Haumea (2003 EL_{61})

Haumea joined the class of dwarf planets in September 2008. Discovered in 2003, its shape resembles a fat oval cigar with a diameter equivalent to Pluto's. It rotates very quickly – in no more than four hours. This may be the reason for its elongated shape. Moving along a highly elliptical orbit outside that of Neptune, Haumea is accompanied by two moons, Hi'iaka and Namaka, named after two divine beings in Hawaiian mythology.

THE KUIPER BELT

For many decades after it was discovered in 1930, Pluto was regarded as the outermost planet in the Solar System, orbiting the Sun at a mean distance of 39.4 astronomical units (about six billion kilometers). Today, we are aware that there are many other ‘planets’ besides Pluto whose orbits lie beyond that of Neptune. Apparently, Pluto was merely the first to be discovered among the many members of a new class of icy objects located in the extremely cold outer reaches of the Solar System. The existence of such a belt of minor planets was first predicted by Frederick C. Leonard in 1930 and by Kenneth E. Edgeworth in 1943. It was only later, after the publication of a scientific study in 1951, that the name of Gerard P. Kuiper, a scientist from the Netherlands, was associated with the belt. After the discovery of the first object belonging to this class, 1992 QB1, the belt was christened Kuiper-Edgeworth Belt or Kuiper Belt for short, its most common designation.

The name given to objects in the Kuiper Belt, Kuiper-Belt Objects or KBOs, is controversial, which is why many scientists prefer to call them Trans-Neptunian Objects or TNOs. TNOs probably are small bodies or fragments left over from the formation of the planets. Present-day theory says that they are among the first objects that condensed from the disc of gas and dust which surrounded the newly-born Sun about 4.5 billion years ago. Collisions between such primitive minor bodies gradually led to the formation of planets. For this reason, TNOs may be regarded as samples of the material from which the planets were originally built, samples that have survived to this day with their original composition intact.

Astronomical observations show that many young stars are surrounded by discs of gas and dust. Presumably, other stars also acquire planets by processes similar to those that led to the formation of planets in our own Solar System. Being almost unchanged relics from the early history of our Solar System, TNOs are very important for planetary research because by studying them we can make significant scientific discoveries about that universal phenomenon, the formation of planets.

Image: Artist‘s impression of the Quaoar object in the Kuiper Belt.
(© NASA and G. Bacon (STScI))

Another reason why scientists are so interested in TNOs is the idea that short-period comets might come from the Kuiper Belt. The orbits of TNOs may change under the influence of Neptune and the other outer planets. This is how TNOs occasionally find their way into the inner Solar System. When such an object is gradually warmed as it approaches the Sun, part of its icy material evaporates, forming a coma and generally a tail as well. Thus, a TNO is transformed into a comet.

The Kuiper Belt should not be confused with the Oort Cloud, a gigantic reservoir of comets that surrounds the Solar System like a spherical shell and is supposed to contain billions of icy bodies. This is probably where long-period comets originally come from. The Oort Cloud begins far outside the Kuiper Belt and extends to a distance of one or two light years from the Sun. In contrast to the Kuiper Belt, however, its existence has not yet been established by direct observation.

Today, it is believed that Pluto itself is a TNO. If it ever got close to the Sun, it would probably turn into a giant comet. However, Pluto's orbit is extremely stable because it is locked in a 3:2 resonance with the orbit of Neptune. Similar dynamic conditions apply to hundreds of other TNOs with diameters of 100 kilometers and more that have been christened 'Plutinos'. Discoveries made in recent years document that there are objects which move around the Sun at distances amounting to hundreds of astronomical units (1 AU corresponds to about 150 million kilometers).

The largest specimen found so far is Sedna, a small planet that was discovered in 2003. However, because of the great distance of about 78 AUs it keeps from the Sun it is extremely difficult to observe, and the estimate that it measures about 1,500 kilometers in diameter is very uncertain. Nevertheless, it is regarded as certain that Sedna is not much smaller than Pluto, which measures about 2,400 kilometers in diameter.

Sedna's origin is a conundrum. The object may have originated in the zone of the large planets, from which it was ejected by their powerful gravitational force. Another theory suggests that Sedna's orbit was disturbed by neighboring stars in the early history of the

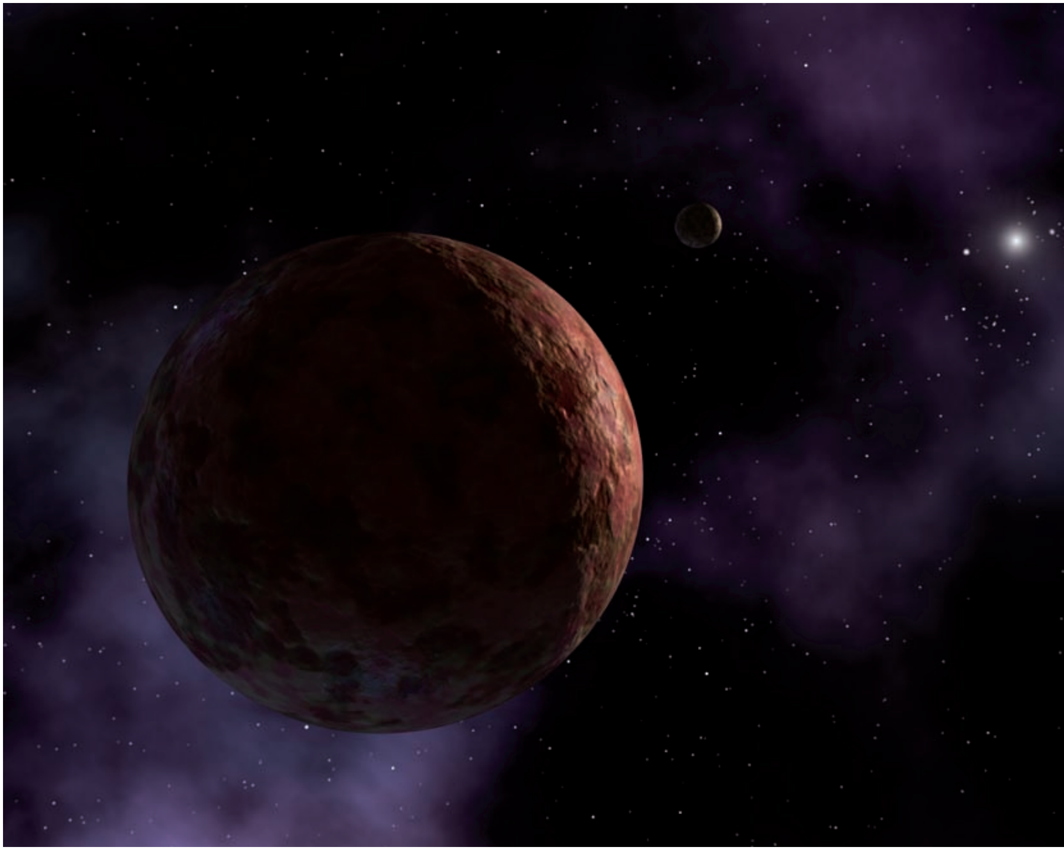


Image: The Kuiper-Belt Object Sedna in an artist's impression showing the Sun as a bright star. *(© NASA/JPL-Caltech)*

Solar System, and that this is why Sedna today is in a kind of 'no-man's land' between the Kuiper Belt and the Oort Cloud. Other planetary researchers even speculate that Sedna may have originated outside our Solar System.

In 2005, the announcement that another object called Eris had been discovered caused particular attention. From a distance of 97 AUs, it was just about possible for the Hubble space telescope to measure the diameter of the body directly. The result, 2,400 kilometers, means that Eris and Pluto are about the same size, which raised a tricky question: if Pluto is one of the planets, why cannot Eris be called the tenth planet of the Solar System? The problem is that it is highly probable that there are more such objects waiting for their discovery beyond the orbit of Neptune, and some of them might even be larger than Pluto or Eris.

In 2006, after an intense and controversial debate, the International Astronomical Union cleared the matter up by promulgating a new definition of the term 'planet' and introducing a new category of objects in the Solar System – the 'dwarf planets'. Today, Pluto and Eris – the mythological goddess of discord and dispute – as well as two other, smaller TNOs belong to the family of dwarf planets, as does Ceres, the largest object in the main asteroid belt between Mars and Jupiter. At present, the status of a number of other TNOs as well as of Pallas and Vesta in the main belt is being reviewed. There are many objects that might be classified as dwarf planets in the years to come. So, Eris is the chief cause of Pluto's losing its status as the ninth and outermost planet: in 2006, the number of 'classical' planets in our Solar System shrank to eight.

As the sensitivity of the telescopes and instruments available to astronomers these days is increasing continually, we may be certain that many more of these enigmatic inhabitants of the 'outskirts' of the Solar System will be discovered.

Image: Artist's impression of a Kuiper-Belt Object.
© NASA, ESA, and G. Bacon (STScI)

PLANETARY EVOLUTION AND LIFE

Ever since man has been consciously observing his environment, directing his gaze at the night sky, the depths of the Solar System, the planets, and the host of stars, he has been asking himself whether life might exist outside the terrestrial globe, on another heavenly body somewhere in the vastness of space. In view of the inconceivably large number of stars that exist in the universe, it would be more than astonishing if life had evolved on Earth alone. Still, a glance at our Solar System shows that our 'blue planet' differs markedly even from its neighbors. Space probes have already photographed and explored all the eight planets and their moons, but although we have made enormous progress in science, we realize again and again that Earth is extraordinary in that it obviously offers the best possible conditions for the development of life.

How does a planetary body like our Earth originate, and what are the conditions for an evolution that creates life on it? Could it be that life itself creates the best possible conditions for its development? Planetary researchers have been asking themselves these questions for quite some time. The answers can be found only by an interdisciplinary approach, a challenge to all disciplines of science. Led by DLR and sponsored by the Helmholtz Society, the 'planetary evolution and life' research alliance has been devoting itself to the subject since 2008.

Amazingly, there is no generally accepted scientific definition of life. If we follow Ilya Prigogine, an eminent thermodynamicist who regards life as the highest possible form of matter organization, we may well ask ourselves whether life is not a natural consequence of the development of planets offering certain conditions which we do not yet know in detail. How do such planets evolve, and what are the conditions for their life-promoting development? Can there be planets that harbor life in other Solar Systems, and what is the influence of life on the evolution of such planets? Does life itself create conditions for its own optimum development once the planet's biomass has grown beyond a certain threshold?

These questions are not easy to answer even for Earth, because it is one of the distinguishing features of our planet that its surface is continuously transformed by erosion and tectonics. Earth has changed incessantly in the four and a half billion years of its existence, and for that reason its early history lies rather in the dark. This does not apply to Mars and the Moon, whose surfaces have been modified to a much lesser extent.

On the other hand, it is supposed with some justification that the process of plate tectonics which is responsible for the unremitting geological changes on Earth might be an important prerequisite for the evolution of life. The terrestrial surface consists of seven large crustal plates which rub against each other, producing fresh crust and/or drawing crust into the interior along their edges. One essential characteristic of plate tectonics is the drift of continents

Image: Accretion phase in the planetary system of Epsilon Eridani, artistic rendition. *(© NASA/JPL-Caltech)*

Image above: Imaginative artistic rendition of planets in the universe that are potentially habitable. *(© NASA/JPL-Caltech/R. Hurt (SSC-Caltech))*

Image on the right: Representation of the habitable zone in our Solar System, not to scale. *(© DLR)*

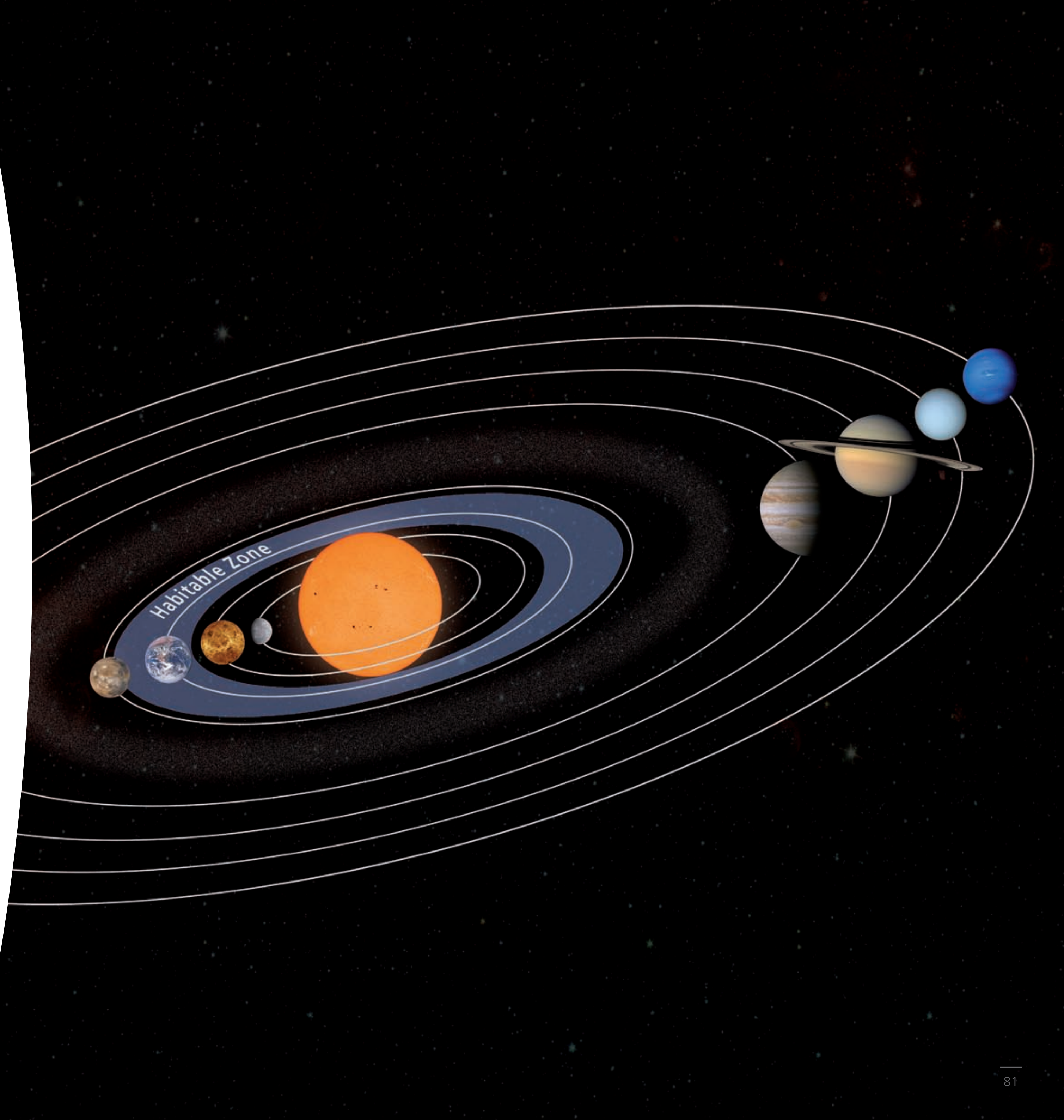
across the plastic Earth's mantle, a fact that has been known only for a hundred years and was not accepted as such for a long time. It is likely that the land masses, ocean basins, and shelves created by this process actually enabled the vast biodiversity that we find on Earth today. Volcanism and earthquakes along the edges of the plates are consequences of plate tectonics by which man is physically affected.

Plate tectonics also controls the exchange of carbon dioxide and water between the atmosphere and the planetary interior which, in turn, regulates the proportion of greenhouse gases contained in the atmosphere and creates stable temperature conditions. The constant renewal of crustal rock provides a supply of mineral nutrients that are indispensable for life. Furthermore, plate tectonics effectively cools the Earth's interior, thus safeguarding the continued existence of the Earth's magnetic field which protects the planet from cosmic radiation and the particles of the solar wind that are hostile to life. Besides, it contributes towards the stability of the atmosphere. On Mars, for example, this protective magnetic field does not exist, at least not today.

Changes in the environment that are caused by processes originating in the interior of a planet are overlaid by the effects of the impact of bodies from outer space. These effects may have been destructive, but they also may have been constructive inasmuch as they assisted in the birth of life and influenced its evolution.

It is inescapable that we should first focus on Earth's neighboring planets in our search for life on other heavenly bodies. Although Venus is almost the same size as Earth, Mars, our smaller and more distant neighbor, appears to resemble the Earth rather more as far as its climate and climatic development are concerned. The conditions prevailing on Mars today, at least in some ecological niches, might be bearable for certain terrestrial microorganisms that are able to survive in extreme environments. At the same time, the results of numerous missions show that the climate of Mars may have been warmer and more humid in its early days. Yet a mere glance at our neighboring planets clearly shows that the Earth is in a privileged position, for it circles around the Sun within a zone in which water is stable on a body the size of Earth that is capable of retaining an atmosphere, where water does not exist merely in the form of ice, as on frigid Mars, or water vapor, as on torrid Venus. This zone that is hospitable to life because water remains stable in it is called the 'habitable zone'. Stable water is an indispensable prerequisite for the existence of life.

Because water must have existed on Mars, at least in the past, the international exploration initiative of space nations and agencies has set itself the task of searching for extra-terrestrial life on the Red Planet. Should the search be crowned with success, the enormous significance of the event would radiate beyond planetary research and even beyond science itself. Such a find would complete the Copernican and Darwinian revolutions and place our


Habitable Zone

terrestrial existence in a wider context. Not only would Earth no longer be the center of the universe, it would also cease to be the only center of our cultural universe.
The quest for a second Earth at great astronomical distances from our planetary system is even more far-reaching than the search for life on Mars. After all, we cannot rule out that living organisms might have been exchanged between the bodies of the inner Solar System when impacts of massive asteroids ejected material containing organisms, sending it on a trip through space that ended in another collision with Earth, so that life could spread there. Should we find life in the outer Solar System, on the Saturnian moon Titan, for example, or the Jovian moon Europa, or even farther away on the planets of other stars, we would indeed be justified in calling this a second genesis. But how would we discover life in other planetary systems? What is the cosmic fingerprint of a planet that harbors life? Is there an unmistakable signature, a 'smoking gun'?

It is true that the search for, or rather the question about life elsewhere in the universe is as old as mankind itself. Yet sound research into this subject became possible only after space probes gave us a chance to leave our home planet and travel to the bodies of our planetary system, a process which entailed the development of a completely new branch of science called astrobiology.

Answering the question about the existence of life in the universe is one of the most thrilling challenges in the history of science.

ADDENDUM

OVERVIEW ABOUT THE MISSIONS IN THE SOLAR SYSTEM

Missions to the Sun

Pioneer 5	11 Mar 1960	Solar research, solar orbit, end of mission: 26 Jun 1960
Pioneer 6	16 Dec 1965	Solar research from Earth orbit, end of mission: Dec 2004, still telemetry contact
Pioneer 7	17 Aug 1966	Solar research from Earth orbit, end of mission: Jan 2004, still telemetry contact
Pioneer 8	13 Dec 1967	Solar research from Earth orbit, end of mission: June 2002, still telemetry contact
Pioneer 9	08 Nov 1968	Solar orbit, probe failed on 3 Mar 1987
Skylab	26 May 1973	America's first manned space station (171 days), 150,000 images of the Sun with the Apollo Telescope Mount (ATM)
Explorer 49	10 Jun 1973	Solar physics probe, lunar orbit
Helios 1	10 Dec 1974	American-German mission, solar orbit, closest approach: 47 million km
Helios 2	16 Jan 1976	American-German solar probe, closest approach: 43 million km
Solar Maximum Mission (SMM)	14 Feb 1980	Coordinated monitoring of solar activity especially solar eruptions during a period of maximum solar activity, re-entry: 2 Dec 1989
Hinotori	21 Feb 1981	Japanese mission for monitoring of solar eruptions during a period of maximum solar activity
Ulysses	06 Oct 1990	American-European mission, study of the Sun poles, end of mission: 2008
Yohkoh	31 Aug 1991	Japanese-American-British mission, study of the high energy radiation during solar eruptions
SAMPEX	03 Jul 1992	American mission, monitoring of high energy particles of the Sun
Koronas-I	02 Mar 1994	Russian mission, study of the Sun in ultra-violet light and X-ray
SOHO	12 Dec 1995	'Solar and Heliospheric Observatory', European solar probe, study of the inner structure and the physical processes which forms the solar corona
ACE	25 Aug 1997	American mission, measurements of the solar wind between Sun and Earth to allow 'storm warnings' with 1 hour lead time
TRACE	02 Apr 1998	'Transition Region and Coronal Explorer', American mission, study of the solar eruptions and the photosphere
Genesis	08 Aug 2001	Collection of a sample of solar wind and its return to Earth after two years
RHESSI	05 Feb 2002	'Reuven-Ramaty High Energy Solar Spectroscopic Imager', study of the particle acceleration and energy release during solar eruptions
SORCE	25 Jan 2003	'Solar Radiation & Climate Experiment', precise measurements of solar radiation in different wavelengths from X-ray to near infrared from Earth orbit
STEREO	18 Sep 2006	Consists of two probes, study of the structure and the evolution of solar storms on its way through space
Hinode (Solar-B)	23 Sep 2006	Japanese mission, study of the interactions between magnetic field and corona
SDO	11 Feb 2010	'Solar Dynamics Observatory', exploration of the solar atmosphere in different wavelengths, solar activity and space weather, measurements of solar interior, plasma of solar corona and radiation

Missions to Mercury

Mariner 10	03 Nov 1973	First mission to two planets, Venus flyby and three Mercury flybys, more than 10,000 images, 57 % of Mercury covered, closest approach: 694 km
MESSENGER	03 Aug 2004	'Mercury Surface, Space ENvironment, GEochemistry and Ranging', study of the planet from orbit: chemical composition of the surface, geology, magnetic field, core, poles, exosphere and magnetosphere, orbit entry on 18 March 2011 after three flybys

Missions to Venus

Venera 1	12 Feb 1961	Closest approach: 99,800 km, radio contact lost at 7 million km distance
Mariner 2	26 Aug 1962	Closest approach: 34,750 km, different studies of planetary physics
Zond 1	22 April 1964	Loss of radio contact, Venus flyby at 100,000 km distance, solar orbit
Venera 2	12 Nov 1965	Closest approach: 23,950 km, because of radio interference no data transmission possible, solar orbit
Venera 3	16 Nov 1965	Atmosphere entry, communication system failed at an altitude of 32 km, impact on the planet
Venera 4	12 Jun 1967	Atmosphere entry, landing on the night side, transmission of atmosphere and surface data for 96 minutes
Mariner 5	14 Jun 1967	Closest approach: 3,990 km, no imaging system, study of the magnetic field and temperatures
Venera 5	05 Jan 1969	Atmosphere entry
Venera 6	10 Jan 1969	Atmosphere entry
Venera 7	17 Aug 1970	Landing, transmission of temperature data for 23 minutes
Venera 8	27 Mar 1972	Landing, transmission of data from the surface for 50 minutes
Mariner 10	03 Nov 1973	Closest approach: 5,310 km during flyby on its way to Mercury, first images from Venus
Venera 9	08 Jun 1975	Landing and Orbiter, first images from the surface
Venera 10	14 Jun 1975	Landing and Orbiter, images from the surface
Pioneer Venus 1	20 May 1978	Orbiter, images from the atmosphere and radar mapping of the surface
Pioneer Venus 2	08 Aug 1978	Multiprobe spacecraft (five atmospheric probes), transmission of data from the surface for 76 minutes from one of the probes
Venera 11 Venera 12	08 Sep 1978 14 Sep 1978	Landings, transmission of data from the surface for 95 and 110 minutes, respectively
Venera 13 Venera 14	29 Oct 1981 01 Nov 1981	Landings, first panoramic images through several filters, examination of soil samples
Venera 15 Venera 16	09 Jul 1983 11 Jun 1983	Orbiters, Mapping of Venus with Synthetic Aperture Radar, Venera 15: radar images form the far side, Venera 16: stripe of 9,000 x 150 km at the north pole, resolution: 1-2 km
Vega 1 Vega 2	15 Dec 1984 21 Dec 1984	Flyby on their way to comet Halley, release of a lander and balloon for studies of the central cloud cover
Magellan	04 May 1989	Orbiter, radar mapping of 95 percent of the surface with Synthetic Aperture Radar, maximum resolution: 75 m per pixel
Galileo	18 Oct 1989	Images from Venus during flyby on its way to Jupiter
Cassini	15 Oct 1997	Venus flyby on its way to the Saturnian system
MESSENGER	03 Aug 2004	Images from Venus during flyby on its way to Mercury
Venus Express	09 Nov 2005	Orbit entry on 11 April 2006, study of the complex dynamics and chemistry of the planet and the interaction between atmosphere and surface
Akatsuki (Planet-C)	20 May 2010	Japanese mission to study the dynamics of the Venusian atmosphere from orbit, orbit entry failed and satellite flew by, next possibility to enter orbit in 2016

Missions to Earth

NIMBUS: Series of American weather satellites, which became an important Earth observation program by further developments of the sensors, NIMBUS 7: TOMS (Total Ozone Mapping Spectrometer)

NIMBUS 1	28 Aug 1964	NIMBUS 4	08 Apr 1970
NIMBUS 2	15 May 1966	NIMBUS 5	11 Dec 1972
NIMBUS B	18 May 1968	NIMBUS 6	12 Jun 1975
NIMBUS 3	14 Apr 1969	NIMBUS 7	24 Oct 1978

METEOR: Russian polar weather satellites, three generations, daily report for more than two thirds of Earth about clouds, ice coverage, atmospheric radiation; Visible and IR Scanning Radiometer, Meteor 1: Series of 31 satellites, from 26 March 1969 to 10 June 1981, 3-4 launches per year, Meteor 2: series of 21 satellites, first launch on 11 July 1975, last launch in 1993; Meteor 3: series of 6 satellites, Meteor 3-05 additional TOMS (Total Ozone Mapping Spectrometer), Meteor 3-06 additional Scarab and PRARE

Landsat: Series of American Earth observation satellites, Landsat 1-3 improved and enlarged versions of NIMBUS, RBV (Return Beam Vidicon), MSS (Multi-Spectral Scanner), Landsat 4-6: TM (Thematic Mapper), MSS; Landsat 6: Failure

Landsat 1	23 Jul 1972	Landsat 5	01 Mar 1984
Landsat 2	22 Jan 1975	Landsat 6	05 Oct 1993
Landsat 3	05 Mar 1978	Landsat 7	15 Apr 1999
Landsat 4	16 Jul 1982		

SMS: 'Synchronous Meteorological Satellites', American weather satellites, predecessor of GOES, VISSR (Visible Infrared Spin-Scan Radiometer)

SMS 1	17 May 1974	SMS 2	06 Feb 1975

GOES: 'Geostationary Operational Environmental System', series of American weather satellites, VAS (Visible Infrared Spin-Scan Radiometric Atmospheric Sounder)

GOES 1	16 Oct 1975	GOES 9	23 May 1995
GOES 2	16 Jun 1977	GOES 10	25 Apr 1997
GOES 3	16 Jun 1978	GOES 11	03 May 2000
GOES 4	09 Oct 1980	GOES 12	03 Jul 2001
GOES 5	22 May 1981	GOES 13	26 May 2006
GOES 6	28 Apr 1983	GOES 14	27 Jun 2009
GOES 7	26 Feb 1987	GOES 15	4 Mar 2010
GOES 8	13 Apr 1994		

GMS: 'Geostationary Meteorological Satellite',Japanese weather satellite, geostationary orbit, VISSR (Singe Imaging Visible and IR Spin Scan Radiometer), resolution; 1,25 km visible, 5 km IR

GMS-1	14 Jul 1977	GMS-4	06 Sep 1989
GMS-2	10 Aug 1981	GMS-5	18 Mar 1995
GMS-3	03 Aug 1984		

Meteosat: Series of European weather satellites, geostationary orbit, Imaging Radiometer in visible and infrared light, with Meteosat 8 Second Generation (MSG) starts: Spinning Enhanced Visible and Infrared Spectrometer (SEVIRI) and Geostationary Earth Radiation Budget (GERB)

Meteosat 1	23 Nov 1977	MOP 3/Meteosat 6	20 Nov 1993
Meteosat 2	19 Jun 1981	Meteosat 7	02 Sept 1997
Meteosat 3/P2	15 Jun 1988	Meteosat 8 (MSG-1)	28 Aug 2002
MOP 1/Meteosat 4	06 Mar 1989	Meteosat 9 (MSG-2)	22 Dec 2005
MOP 2/Meteosat 5	02 Mar 1991		

Resurs-F: Russian series of short missions with film camera systems, three Kate-200, two KFA-1000 (F1) and MK-4 (F2) film cameras, 16 launches at all, five per year, first launch in 1979

INSAT: 'Indian National Satellite System', geostationary platform for communication purposes and for Earth observation, VHRR (two-channel Very High Resolution Radiometer); INSAT 1A was abandoned, INSAT 1C Failure in power supply, INSAT 2 additional Data Relay Transponder for data collection platforms

INSAT 1A	10 Apr 1982	INSAT 3A	10 Apr 2003
INSAT 1B	30 Aug 1983	INSAT 3B	22 Mar 2000
INSAT 1C	21 Jun 1988	INSAT 3C	24 Jan 2001
INSAT 1D	12 Jun 1990	INSAT 3E	28 Sep 2003
INSAT 2A	09 Jul 1992	INSAT 4A	22 Dec 2005
INSAT 2B	22 Jul 1993	INSAT 4B	12 Mar 2007
INSAT 2C	07 Dec 1997	INSAT 4C	10 Jul 2006
INSAT 2D	04 Jun 1997	INSAT 4CR	02 Sep 2007
INSAT 2E	03 Apr 1999		

NOAA: Series of American weather satellites, additional observation of atmosphere temperatures and humidity, ocean surface temperatures, snow/ice coverage, ozone concentration; nearly polar Sun-synchronous orbit, AVHRR (Advanced Very High Resolution Radiometer), TOVS (Tiros Operational Vertical Sounder), SEM (Space Environment Monitor)

NOAA-8	28 Mar 1983	NOAA-14	30 Dec 1994
NOAA-9	12 Dec 1984	NOAA-15	13 May 1998
NOAA-10	17 Sep 1986	NOAA-16	21 Sep 2000
NOAA-11	22 Sep 1988	NOAA-17	24 Jun 2002
NOAA-12	14 May 1991	NOAA-18	20 May 2005
NOAA-13	09 Aug 1993	NOAA-19	7 Feb 2009

SPOT: 'Systeme Probataire d'Observation de la Terre', Series of French polar orbiting Earth observation satellites, two HRV (High-Resolution Visible Imagers) each, Resolution: 20 m multispectral, 10 m panchromatic, SPOT 2: additional DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), SPOT 3 additional POAM (Polar Ozone and Aerosol Measurement Instrument)

SPOT 1	22 Feb 1986	SPOT 4	24 Mar 1998
SPOT 2	22 Jan 1990	SPOT 5	04 May 2002
SPOT 3	26 Sep 1993		

MOS: 'Marine Observation Satellite', Japanese Satellite for observation of atmospheric water vapor, ocean movements, ocean surface temperatures, ice movements and coverage, chlorophyll concentration, sun-synchronous orbit, MESSR (Multi-Spectrum Electronic and Self-Scanning Radiometer), resolution: 50 m; VTIR (Visible and thermal Infrared Radiometer), resolution: 0.9 km IR, 2.7 km thermal; MSR (Microwave Scanning Radiometer), resolution: 23 km (31 GHz), 32 km (23.8 GHz)

MOS 1A	18 Feb 1987	MOS 1B	7 Feb 1990

IRS: 'Indian Remote Sensing Satellite', Sun-synchronous orbit, three LISS (Linear Imaging Self-Scanning) pushbroom CCD units, resolution: 72.5 m LISS 1; 36.25 m LISS 2; 23 m LISS 3; 5 m LISS 4, IRS P1: Failure

IRS 1A	17 Mar 1988	IRS P6 (Resourcesat)	17 Oct 2003
IRS 1B	29 Aug 1991	IRS P5 (Cartosat-1)	05 May 2005
IRS 1E (IRS P1)	20 Sep 1993	Cartosat-2	10 Jan 2007
IRS P2	15 Oct 1994	IMS-1	24 Apr 2008
IRS 1C	28 Dec 1995	Cartosat-2A	28 Apr 2008
IRS P3	21 Mar 1996	RISAT-2	20 Apr 2009
IRS1 D	29 Sep 1997	Oceansat-2	23 Sep 2009
IRS P4 (Oceansat-1)	26 May 1999	Cartosat-2B	12 Jun 2010
TES	22 Oct 2001	Resourcesat-2	20 Apr 2011

Resurs-0: Russian series, multispectral digital equivalent to Landsat, Multiple Multispectral Package from visible to near infrared light: MSU-SK conical scanner, MSU-E pushbroom CCD imager, resolution: 45 m visible, 170 m IR, 600 m thermal infrared

Resurs-01 3-14	20 Apr 1988

OKEAN-O: Russian satellite system for observation of ice and oceans with radar, RLS-BO synthetic aperture radar, MSU-S (visible/near-IR scanning radiometer), MSU-M (multispectral visible/near-IR scanning radiometer), RM-08 (8 mm-wavelength scanning radiometer)

OKEAN 1	05 Jul 1988	OKEAN O1-7	11 Oct 1994
OKEAN 2	28 Feb 1990	OKEAN-O	17 Jul 1999
OKEAN 3	04 Jun 1991		

Feng Yun: 'Wind and Clouds', Chinese series of polar orbiting meteorological satellites, VHRSR (Very High Resolution Scanning Radiometer)

FY-1A	06 Sep 1988	FY-2C	19 Oct 2004
FY-1B	03 Sep 1990	FY-2D	12 Aug 2006
FY-2A	10 Jun 1997	FY-3A	27 May 2007
FY-1C	10 Jun 1999	FY-2E	23 Dec 2008
FY-2B	25 Jun 2000	FY-3B	4 Nov 2010
FY-1D	15 May 2002		

Galileo: mission to planet Jupiter, images of the Earth during two flybys on its way to Jupiter

Galileo	18 Oct 1989

Almaz: 'Diamond', new class of Russian Earth observation satellites, 3.1 GHz Synthetic Aperture Radar, resolution: 15-30 m

Almaz 1	31 Mar 1991

ERS: 'European Remote Sensing Satellite', global coverage of oceans, coastal areas, polar caps, observation of wave lengths and heights, wind speeds and directions, ice parameters, temperature of the cloud cover, cloud coverage, water vapor concentration in the atmosphere, AMI (Active Microwave Instrument), ATSR-M (Along-Track Scanning Radiometer and Microwave Sounder), RA (Radar Altimeter), PRARE (Precise Range and Range Rate Experiment); ERS-2: GOME (Global Ozone Monitoring Experiment)

ERS-1	17 Jul 1991	ERS-2	21 Apr 1995

JERS: 'Japan Earth Resources Satellite', Earth observation satellite, sun-synchronous orbit, SAR (Synthetic Aperture Radar, L-Band), resolution: 18 m; OPS: Optical Sensor in visible and near IR), resolution: 18 m

JERS 1	01 Feb 1992

TOPEX/POSEIDON (Jason 1): Combined American-French mission, Topex (NASA/JPL): 'The Ocean Topography Experiment' and Poseidon (CNES): long term observation of global ocean circulation and surface topography, Radar Altimeter, Microwave Radiometer

Topex/Poseidon	16 Aug 1992	Jason-1	07 Dec 2001

SIR-C/X-SAR: 'Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar', part of Mission to Planet Earth, resolution: 10-12 m, operated on shuttle flights

OrbView: Series of commercial satellites, weather monitoring (OrbView 1), multispectral Earth observation (OrbView 2) and high resolution imaging (Orbview 3)

OrbView 1	03 Apr 1995	OrbView 3	26 Jun 2003
OrbView 2	01 Aug 1997	OrbView 4 (Failure)	21 Sep 2001

Radarsat: Canadian radar satellite, C-Band Synthetic Aperture Radar, resolution up to 8 m, different SAR modi

Radarsat 1	04 Nov 1995

Kidsat: operation of cameras and other instruments on Space Shuttle or satellites, controlled by students as part of classes

STS-76	23 Mar 1996	STS-86	26 Sep 1997
STS-81	12 Jan 1997		

Cluster: American-European mission for exploration of the magnetosphere with four identical satellites, measurements of charged particles, electric and magnetic fields and observation of the interaction between solar clouds of high-energetic particles, Earth's atmosphre and the magnetic field. First four satellites got lost during first flight of Ariane 4.

Cluster FM1 – FM4	4 Jun 1996	Cluster FM7, FM8	9 Aug 2000
Cluster FM5, FM6	16 Jul 2000		

TRMM: 'Tropical Rainfall Measuring Mission', American-Japanese mission for study the tropical rainfalls with Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and Infrared Scanner (VIRS), Clouds and the Earth's Radiant Energy System (CERES) and Lightning Imaging Sencor (LIS)

TRMM	27 Nov 1997

Formosat: Taiwanese satellite, first high-resolution satellite with daily coverage, resolution: 2 m panchromatic, 8 m multispectral

Formosat-1	16 Jan 1999	Formosat-2	20 May 2004

IKONOS: first commercial satellite for high resolution imaging, panchromatic sensor with 1 m resolution and multispectral sensor with 4 m resolution which can be combined

IKONOS	24 Sep 1999

Terra: part of the Earth Observing System (EOS), monitoring of climate and environmental changes, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) for high resolution images in 14 wavelengths, CERES (Clouds and Earth's Radiant Energy System) for study of the Earth's and cloud's radiation budget, MISR (Multi-Angle Imaging Spectro-Radiometer) for observation using 9 angles and 4 wavelengths, MODIS (Moderate Resolution Imaging Spectroradiometer) for observations in 36 spectral ranges, MOPITT (Measurements of Pollution In the Troposphere) for study of distribution, transport, origin and discharge of carbon monoxide and methane in the atmosphere

Terra (EOS AM-1)	18 Dec 1999

Kompsat: South Corean satellites, high-resolution panchromatic and multispectral image data

Kompsat-1	21 Dec 1999	Kompsat-2	28 Jul 2006

SRTM: 'Shuttle Radar Topography Mission', combination of the SIR-C/X-SAR instrument with additional C-Band radar mounted on a 60 m long beam for stereo data

SRTM (STS-99)	11 Feb 2000

CHAMP: 'Challenging Mini-Satellite Payload', German mission, observation of the structure and dynamics from solid core over mantle to crust and the interactions between oceans and atmosphere, precise monitoring of ocean circulation and global ocean heights, changes in the global water budget, interaction of weather and climate, global sounding of vertical layers in the neutral and ion gas layers, study of the interaction between Earth's weather and 'space weather'

CHAMP	15 Jul 2000

Earth Observing-1: technology mission for tests and validation purposes of new instruments

EO-1	21 Nov 2000

Odin: Swedish satellite, observation of changes in the ozone layer and search for water and oxygen in interstellar space

Odin	20. Febr. 2001

Quickbird: commercial satellite for Earth observation, resolution: 0.6 m per pixel nadir channel, 2.44 m color channels

Quickbird	18 Oct 2001

BIRD: 'Bispectral InfraRed Detection', DLR mini satellite for fire remote sensing, allows measurements of dimensions and temperature of fires, observation and monitoring of volcanoes from space

BIRD	22 Oct 2001

TES: 'Technology Experiment Satellite',mission to test new technologies in construction, monitoring and controlling satellites, panchromatic camera

TES	22 Oct 2001

Proba: 'Project for On-Board Autonomy', ESA technology demonstrator, Compact High Resolution Imaging Spectrometer (CHRIS) for hyperspectral images with resolutions up to 17 m in 63 spectral bands; High Resolution Camera (HRC) with resolutions up to 5 m monochrome

Proba-1	22 Oct 2001	Proba-2	2 Nov 2009

TIMED: 'Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics', American mission, study of the dynamics in the mesophere and lower troposphere with Global Ultraviolet Imager (GUVI), Sounding of the Atmosphere using Broadband Emission Radiometry (SABER), Solar Extreme Ultraviolet Experiment (SEE) and TIMED Doppler Interferometer (TIDI)

TIMED 7 Dec 2001

ENVISAT: successor of ERS-1 and ERS-2, Advanded Synthetic Aperture Radar (ASAR), Medium Resolution Imaging Spectrometer (MERIS), Michelson Interferometer for Passive Atmospheric Sounding (MIPAS), Global Ozone Monitoring by Occultation of Stars (GOMOS), Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), Advanced Along-Track Scanning Radiometer (AATSR), Radar Altimeter 2 (RA-2), Microwave Radiometer (MWR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Laser Retro-Reflector (LRR)

ENVISAT 01 Mar 2002

GRACE: double satellite system, compilation of a global high resolution model of the gravitational field over five years, conclusion to cataclysmic magma in Earth's interior, melting glaciers or changing ocean currents; supply of global distributed profiles of GPS limb-sounding procedures, conclusions to so-called TEC in the ionosphere and temperature distribution and water vapor amount in the atmosphere

GRACE 17 Mar 2002

Aqua: Observation of the complex water cycle of Earth

Aqua 04 May 2002

ICESat: 'Ice, Cloud and Elevation Satellite', American mission, measurement of the ice crust, height profiles of clouds and aerosols, height of vegetation, and sea ice thickness with Geoscience Laser Altimeter System (GLAS)

ICESat 12 Jan 2003

Aura: Observation of the composition, chemistry and dynamics of Earth's atmosphere, observation of ozone, air quality and climate

Aura 15 Jul 2004

Cartosat: satellite mainly for cartographic purposes, two panchromatic cameras for stereo imaging, resolution: 2.5 m

Cartosat 1 05 May 2005 Cartosat 2A 28 Apr 2008
Cartosat 2 10 Jan 2007

CryoSat: European mission, measurements of the cryosphere with radaraltimeter (SIRAL), radio receiver DORIS and laser retroreflector, CryoSat-1 failed to reach orbit

CryoSat-1 8 Oct 2005 CryoSat-2 8 Apr 2010

ALOS: 'Advanced Land Observing Satellit', Japanese satellite: Phased Array type-L band Snythetic Aperture Radar (PALSAR), Microwave Radar and Panchromatic Remote Sensing of Stereo Mapping (PRISM), Advanced Visible and Near Infrared Radiometer type-2 (AVNIR-2)

ALOS 24 Jan 2006

COSMIC/FORMOSAT-3: Taiwanese-American mission, observation of the atmosphere, ionosphere, climate and weather

COSMIC 24 Apr 2006

Cloudsat: experimental satellite for observation of clouds and rainfall with radar

Cloudsat 28 Apr 2006

CALIPSO: Observation of the role of clouds and atmospheric aerosols on the regulation of weather, climate and the dynamic environment

CALIPSO 28 Apr 2006

THEMIS: 'Time History of Events and Macroscale Interactions during Substorms', American mission with five identical satellites to study substorms in the magnetosphere, Instrumente: Electric Field Instrument (EFI), Search Coil Magnetometer (SCM), Flux Gate Magnetometer (FGM), Electrostatic Analyzer (ESA) and Solid State Telescope (SST)

THEMIS 1-5 17 Feb 2007

AIM: 'Aeronomy of Ice in the Mesosphere', observation of polar mesospheric clouds, their origin, differences and their thermal, chemical, and dynamic environment

AIM 25 Apr 2007

Terra SAR-X: first Earth observation satellite, which provides continuously SAR data in the X-band, three different modi with resolutions from 1 to 16 m, high frequent X-band sensor

Terra SAR-X 15 Jun 2007

IMS: 'Indian Mini-Satellite, multispectral and hyperspectral cameras

IMS 1 28 Apr 2008

OSTM/Jason-2: 'Ocean Surface Topography Mission', next generation long term observation of the global ocean circulation and surface topography, European-American mission, Poseidon-3 Radar Altimeter, Advanced Microwave Radiometer

Jason-2 20 Jun 2008

GeoEye: commercial American satellite, panchromatic and multispectral image data with resolutions up to 0.41 m per pixel

GeoEye 1 6 Sep 2008

GOCE: 'Gravity and Steady-State Ocean Circulation Explorer', European Mission for measurements of the Earth's gravitational field and the variability of the sea level

GOCE	17 Mar 2009

SMOS: 'Soil Moisture and Ocean Salinity', European mission, measurements of the near-surface salt content of the oceans with L-Band-Microwave-Radiometer

SMOS	2 Nov 2009

TanDEM-X: 'TerraSAR-X-Add-on for Digital Elevation Measurements', German radar satellite, stereographic mapping of the Earth together with TerraSAR-X with SAR in the X-band

TanDEM-X	21 Jun 2010

Aquarius: American-Argentine mission, study of the near-surface salt content with microwave radiometer (L-band), scatterometer and cameras

Aquarius	10 Jun 2011

This listing of Earth Missions is only a selection.

Missions to the Moon

Pioneer 0	17 Aug 1958	Failure, explosion of the first stage
Pioneer 1	11 Oct 1958	Failure, could not reach escape velocity
Pioneer 3	06 Dec 1958	Failure, could not reach escape velocity
Luna 1	02 Jan 1959	Closest approach: 5,000 to 6,000 km, after this solar orbit
Pioneer 4	03 Mar 1959	Flyby of the Moon at a great distance
Luna 2	12 Sep 1959	Impact, first probe, which impacted on the Moon
Luna 3	04 Oct 1959	400 images from the far side of the Moon for the first time
Ranger 3	04 Oct 1959	Failure, missed lunar orbit
Ranger 4	23 Apr 1962	Impact, loss of radio communication on launch day
Ranger 5	18 Oct 1962	Malfunction during injection on Moon trajectory, missed the Moon by 725 km
Luna 4	02 Apr 1963	Planned as a lander, missed the Moon
Ranger 6	30 Jan 1964 to 02 Feb 1964	Impact on the edge of Mare Tranquillitatis, no images were transmitted
Ranger 7	28 Jul 1964 to 31 Jul 1964	Impact in Mare Nubium, 4,316 images during approach
Ranger 8	17 Feb 1965 to 20 Feb 1965	Impact in Mare Tranquillitatis, more than 7,000 images during approach
Ranger 9	21 Mar 1965 to 24 Mar 1965	Impact in Alphonsus crater, more than 5,800 images with better sharpness due to additional stabilization of the camera in flight axis
Luna 5	09 May 1965	Closest approach: 8,500 km; due to interferences the probe got from Earth orbit into a solar orbit
Luna 6	08 Jun 1965	Lander, missed the Moon, solar orbit
Luna 7	04 Oct 1965 to 07 Oct 1965	System tests for landing, impact in Oceanus Procellarum
Luna 8	03 Dec 1965 to 06 Dec 1965	System tests for landing, impact in Oceanus Procellarum
Luna 9	31 Jan 1965	First soft landing on the Moon on 3 Feb 1965, panoramic images of the surface
Luna 10	31 Mar 1966	First artificial satellite of the Moon
Surveyor 1	30 May 1966	Landing after direct injection into a lunar impact trajectory, 10,338 images, 1,000 using red, green, and blue filters at a time on the first lunar day, 812 images on the second lunar day
Lunar Orbiter 1	10 Aug 1966	Lunar orbit, photographic coverage of c. 5.18 million km^2, transmission of 229 images
Luna 11	24 Aug 1966	Lunar orbit, battery failed on 1 Oct 1966
Surveyor 2	20 Sep 1966	After path correction out of control, impact south of Copernicus crater
Luna 12	22 Oct 1966	Lunar orbit, data transmission ended on 19 Jan 1968
Lunar Orbiter 2	06 Nov 1966	Lunar orbit, 817 images with wide angle/narrow angle optics were transmitted
Luna 13	21 Dec 1966	Landing near Seleucus crater, close-up views of the surface
Lunar Orbiter 3	05 Feb 1967	Lunar Orbit, due to failure in the image transport system only 626 images transmitted
Surveyor 3	17 Apr 1967	Landing in the eastern part of Oceanus Procellarum, 6,315 images

Lunar Orbiter 4	04 May 1967	Lunar orbit, 546 images, coverage: 99% of near side, 75% of far side
Surveyor 4	14 Jul 1967 to 17 Jul 1967	Probe failed and impacted on the Moon
Explorer 35	19 Jul 1967	Lunar orbit
Lunar Orbiter 5	01 Aug 1967	Lunar orbit, 844 images, particularly of 36 choosen areas (Apollo landing sites)
Surveyor 5	08 Sep 1967	Landing in Mare Tranquillitatis, 18,006 images and soils analyses
Surveyor 6	07 Nov 1967	Landing in Sinus Medii, 14,500 images and approx. 55 soil analyses; 15,000 images from a new position (stereoscopic coverage)
Surveyor 7	07 Jan 1968	Landing 25 km of the northern rim of Tycho crater; 5,000 images, for the first time using a polarizing filter; soil analyses
Luna 14	07 Apr 1968	Lunar orbit, collection of data of interaction between Earth and Moon and of the lunar gravitational field
Zond 5	14 Sep 1968	Tests of the return of a space probe after Moon flight, flight around the Moon and back to Earth, closest approach: 1,950 km, first successful Soviet circumlunar Earth-return mission
Zond 6	10 Nov 1968	First aerodynamic return, closest approach: 2,420 km, two image series of the far side at a distance of 10,000 km, resolution: about 200 m per pixel
Apollo 8	21 Dec 1968 to 27 Dec 1968	First manned spaceflight, photographic exploration of the planned Apollo landing site and other areas
Apollo 10	18 May 1969 to 28 May 1969	Landing simulation in lunar orbit, closest approach: 15,185 m
Luna 15	13 Jul 1969	Automatic probe, tests of the most important conditions for landings from lunar orbit
Apollo 11	16 Jul 1969 to 24 Jul 1969	First manned Moon landing; landing in Mare Tranquillitatis, return of soil and rock samples
Zond 7	07 Aug 1969 to 14 Aug 1969	Closest approach: 2,000 km, three image series from different distances, aerodynamic return
Apollo 12	14 Nov 1969 to 24 Nov 1969	Second manned Moon landing in Oceanus Procellarum
Apollo 13	11 Apr 1970 to 17 Apr 1970	Attempted manned Moon landing, abortion after explosion of an oxygen tank in service module, successful return
Luna 16	12 Sep 1970	First return of soil samples with an unmanned remote controlled semi-automatic probe
Zond 8	20 Oct 1970	Closest approach: 1,120 km, return trajectory over northern hemisphere of Earth, color and black & white images from Moon and Earth
Luna 17	10 Nov 1970	Landing in Mare Imbrium, remote controlled semi-automatic lunar rover, more than 200 panoramic images, 20,000 other images, soil analyses
Apollo 14	31 Jan 1971 to 09 Feb 1971	Third manned Moon landing near Fra Mauro crater in eastern Oceanus Procellarum
Apollo 15	26 Jul 1971 to 07 Aug 1971	Fourth manned Moon landing in Rima Hadley area, first manned lunar rover
Luna 18	02 Sep 1971	Landing in Mare Foecunditatis after 54 orbits
Luna 19	28 Sep 1971	Lunar orbit, high resolution images of the lunar surface
Luna 20	14 Feb 1972	Landing at the northeastern edge of Mare Foecunditatis, return of samples
Apollo 16	16 Apr 1972 to 27 Apr 1972	Fifth manned Moon landing in Cayley plateau near Descartes crater
Apollo 17	07 Dec 1972 to 19 Dec 1972	Sixth and last manned Moon landing in Taurus-Littrow, return of 113 kg lunar samples
Explorer 49	10 Jun 1973	Radio astronomical observations of the far side of the Moon
Luna 21	08 Jan 1974	Landing in Le Monnier crater, remote controlled semi-automatic lunar rover
Luna 22	02 Jun 1974	Lunar orbit at 212 km altitude, long term observation of physical aspects of the Moon
Luna 23	28 Sep 1974	After lunar orbit landing in Mare Crisium failed
Luna 24	12 Jun 1976	Landing at the southeastern edge of Mare Crisium, restart, return of 170 g lunar samples

Galileo	18 Oct 1989	Multispectral images during two flybys on its way to Jupiter (Dec. 1990 and Dec. 1992)
Hiten	24 Jan 1990	Japanese Moon mission consisting of two small orbiters, no data transmission from lunar orbit possible
Clementine	25 Jan 1994	Lunar orbit, multispectral mapping of the whole Moon, resolution: 125-250 m per pixel
Lunar Prospector	06 Jan 1998	Polar lunar orbit, amongst others Gamma Ray Spectrometer, Alpha Particle Spectrometer
SMART-1	27 Sep 2003	European lunar orbiter, solar powered ion engine, study of the geology, morphology, topography, mineralogy, geochemistry, and exospheric environment
Kaguya (SELENE)	14 Sep 2007	Japanese lunar orbiter, global observation of the Moon regarding mineralogy, topography, geography, and gravitation
Chang'e 1	24 Oct 2007	First Chinese lunar orbiter, satellite test, 3D images, study of the distribution and amounts of elements
Chandrayaan 1	22 Oct 2008	Indian lunar orbiter, technology mission, production of global high resolution map, mineralogical mapping, study of topography with laser
Lunar Reconnaissance Orbiter (LRO)	17 Jun 2009	Lunar orbit, mapping of the surface, characterization of future landing sites regarding terrain roughness, usable resource and radiation environment, LROC (Lunar Reconnaissance Camera), LOLA (Lunar Orbiter Laser Altimeter)
Lunar Crater Observation and Sensing Satellite (LCROSS)	17 Jun 2009	Impactor, launched along with LRO, search for water ice, consists of a Shepherding Spacecraft (S-S/C) attached to the Centaur upper stage, the Centaur impacted on the lunar surface on 9 Oct 2009, which was observed by the S-S/C
Chang'e 2	01 Oct 2010	Modified backup satellite of Chang'e 1, high-resolution images of the surface, search for landing sites
GRAIL	10 Sep 2011	'Gravity Recovery and Interior Laboratory', consists of two satellites launched together, mapping the structure of the crust and lithosphere, understanding of the asymmetric thermal evolution of the Moon, determination of the structure of basins in the underground and of the mascons, Orbit entry in Dec 2011 and Jan 2012, end of mission with impacts of the satellites on the Moon on 17 Dec 2012
LADEE	07 Sep 2013	'Lunar Atmosphere and Dust Environment Exporer', study of the exosphere and dust in the vicinity of the Moon with neutral mass spectrometer, ultraviolet-visible spectrometer and lunar dust experiment. In addition technical demonstration of a laser communication terminal.

Missions to Mars

Marsnik 1 (Mars 1960A)	10 Oct 1960	First Soviet planetary probe, failure of the third stage, parking orbit not reached, highest altitude: 120 km, re-entry
Marsnik 2 (Mars 1960B)	14 Oct 1960	Second Soviet planetary probe, failure of the third stage, parking orbit not reached, highest altitude: 120 km, re-entry
Sputnik 22 (Mars 1962A)	24 Oct 1962	Failure, either the probe broke up during injection into Earth orbit or the upper stage exploded in Earth orbit
Mars 1	01 Nov 1962	Observations in near Mars space, loss of contact on 21 Mar 1963 at a distance of 106 million km, Mars orbit not reached
Sputnik 24 (Mars 1962B)	04 Nov 1962	Failure, could not leave Earth orbit
Mariner 3	05 Nov 1964	Failure of shell separation, loss of contact
Mariner 4	28 Nov 1964	Arrival at Mars on 14 Jul 1965, closest approach: 9,840 km, 22 images of the Martian surface
Zond 2	30 Nov 1964	Flyby of Mars on 6 Aug 1965, closest approach: 1,500 km, Failure of the communication system in April 1965
Zond 3	18 Jul 1965	Lunar images, flight to Mars

Mariner 6 Mariner 7	25 Feb 1969 27 Mar 1969	Dual-spacecraft mission, successful course correction, 200 television images from the surface, study of the atmosphere (structure and composition)
Mars 1969A	27 Mar 1969	Failure, explosion of the third stage
Mars 1969B	02 Apr 1969	Failure of the first stage promptly after launch
Mariner 8	08 May 1971	Failure, malfunction of the Centaur stage
Cosmos 419	10 May 1971	Reach of parking orbit around Earth, malfunction of fourth stage of block D because of a failure in timer programming
Mars 2	19 May 1971	Reached Mars orbit on 21 Nov 1971, first release of landing capsule (crash-landing), orbiter took TV images
Mars 3	28 May 1971	Reached Mars orbit on 21 Dec 1971, release of a landing capsule (soft landing), lander instruments worked for 20 seconds only
Mariner 9	30 May 1971	Reached Mars orbit on 14 Nov 1971, first artificial satellite of a planet, 6,876 images of the surface, maximum resolution: 100 m per pixel
Mars 4	21 Jul 1973	Could not reach Mars orbit due to technical failures, flyby at a distance of 2,200 km on 10 Feb 1974
Mars 5	25 Jul 1973	Reached Mars orbit on 12 Feb 1974, orbiter worked a few days only, transmission of data from atmosphere and images of a small part of the southern hemisphere
Mars 6	05 Aug 1973	Reached Mars on 12 Mar 1974, landing in Margaritifer Sinus, failure of data transmission
Mars 7	09 Aug 1973	Reached Mars on 9 Mar 1974, could not reach Mars orbit, landing capsule missed its target
Viking 1	20 Aug 1975	Orbiter and lander, reached Mars orbit on 19 July 1976, landing on 20 Jul 1976 in Chryse Planitia
Viking 2	09 Sep 1975	Orbiter and lander, reached Mars orbit on 7 Aug 1976, landing on 3 Sep 1976 in Utopia Planitia, both landers (Viking 1 and 2) transmitted panoramic images and other data, all in all 55,000 images (including the moons), coverage of the whole surface with resolutions from 100 to 200 m per pixel, regional up to 30 m, some images up to 8 m per pixel
Phobos 1	07 Jul 1988	Loss of contact because of a wrong signal, recovery of the probe not possible
Phobos 2	12 Jul 1988	Mars orbit, thermal images of a nearly 1,500 km broad strip at the equator, resolution: about 2 km per pixel, 9 images of Phobos, loss of communication on 7 Mar 1989
Mars Observer	25 Sep 1992	Loss of communication on 21 Aug 1993 three days before orbit insertion at Mars, most likely cause: explosion of the engine during re-burn (injection maneuver), several instruments including a camera system
Mars Global Surveyor	07 Nov 1996	Replacement for Mars Observer, Mars orbit insertion started on 12 Sep 1997, one year longer aerobraking to mapping orbit because of not exactly expanded solar panels
Mars-96	16 Nov 1996	Russian mission, with international participation, failure, malfunction of the fourth rocket stage, instable Earth orbit, loss of probe and fourth stage on 17 Nov 1996
Mars Pathfinder	04 Dec 1996	Landing on 4 Jul 1997 in Ares Vallis, rover Sojourner left lander on 6 Jul 1997, lander and rover worked until loss of contact on 27 Sep 1997
Nozomi (Planet B)	04 Jul 1998	Japanese Mars mission, exploration of the atmosphere, 11 scientific instruments
Mars Climate Orbiter	11 Dec 1998	Study of weather and climate, water and CO_2 budget, Mars Climate Orbiter Color Imager and Pressure Modulated Infrared Radiometer, loss of probe during orbit insertion
Mars Polar Lander	03 Jan 1999	Study of weather and climate, water and CO_2 budget, landing failed

Deep Space 2	03 Jan 1999	Part of the New Millenium Program, consisted of two micro penetrators, which should penetrate into the surface of Mars near south pole, were attached to the Mars Polar Lander, landing failed
2001 Mars Odyssey	07 Apr 2001	Detailed mineralogical observation of the surface and study of the radiation environment, also communication relay for future landing missions
Mars Express	02 Jun 2003	European mission with orbiter and lander Beagle 2, lander separation on 19 Dec 2003, landing failed, orbit insertion on 25 Dec 2003, global high resolution photo geology, mineralogical mapping, study of atmospheric composition
Spirit (Mars Exploration Rover A)	10 Jun 2003	Rover mission, landing in Gusev crater on 4 Jan 2004, rover with many scientific instruments and a daily range of 100 m, search for traces of life, study of climate and geology
Opportunity (Mars Exploration Rover B)	08 Jul 2003	Rover mission, landing in Meridiani Planum on 25 Jan 2004, rover with many scientific instruments and a daily range of 100 m, search for traces of life, study of climate and geology
Mars Reconnaissance Orbiter (MRO)	12 Aug 2005	Orbit entry: 10 Mar 2006, study of the current climate, observation of the surface using a high resolution camera und search for landing sites
Phoenix	04 Aug 2007	Small stationary lander, landing in the north polar region at 68.15° N and 125.9° W on 25 May 2008, study of the surface in high latitudes, observation of the polar climate and weather, composition of the lower atmosphere, geomorphology, and roll of water
Phobos Grunt	08 Nov 2011	Russian mission to the Martian moon Phobos, exploration of the landing site, soil sampling from the surface and return to Earth, could not reach trajectory to Mars due to a failure in propulsive unit, Earth orbit and subsequently loss of the satellite
Yinghuo-1	08 Nov 2011	Chinese satellite 'lightning bug', tandem flight with Phobos-Grunt, measurements of gravity field for one year from orbit around Mars, loss of the satellite
Mars Science Laboratory (MSL)	25 Nov 2011	Rover mission, landing in Gale crater, rover 'Curiosity' with many scientific instruments for the search for life, successful landing on 6 Aug 2012, nominal mission duration: one Martian year (687 days)

Missions to asteroids

Galileo	18 Oct 1989	Flyby at 951 Gaspra (Oct 1991) and 243 Ida (Aug 1993) on its way to Jupiter
NEAR	17 Feb 1996	Flyby at 253 Mathilde on 27 Jun 1997 on its way to asteroid 433 Eros, in orbit around Eros from Feb 2000 to Feb 2001, afterwards landing on Eros
Cassini	15 Oct 1997	Flyby at 2685 Masursky (Jan 2000) on its way to Saturn
Deep Space 1	24 Oct 1998	Test of new technologies (ion propulsion) for use in space, flyby at asteroid Braille and comet Borrelly
Hayabusa (Muses-C)	09 May 2003	Orbiter and lander with sample return from the surface of asteroid 25143 Itokawa
Rosetta	26 Feb 2004	Flyby at 2867 Šteins (2008) and 21 Lutetia (2010) on its way to comet Churyumov-Gerasimenko
Dawn	27 Sep 2007	Orbiter to 4 Vesta (arrival in July 2011 and in orbit around Vesta for one year) and 1 Ceres (arrival 2015)

Missions to Jupiter

Pioneer 10	03 Mar 1972	Flyby at Jupiter, numerous images of the equatorial region, first probe, which left the solar system
Pioneer 11	06 Apr 1973	Flyby at Jupiter, 22 color images of from the southern region
Voyager 2	20 Apr 1977	Flyby at Jupiter on 22 Jul 1979, closest approach: 643,000 km, 18,000 images of Jupiter and its moons
Voyager 1	05 Sep 1977	Flyby at Jupiter on 5 Mar 1979, closest approach: 286,000 km, 18,000 images of Jupiter and its moons
Ulysses	06 Oct 1990	American-European solar probe, flyby at Jupiter on its way to the Sun
Galileo	18 Oct 1989	First spacecraft with complex trajectory with gravitational assists, arrival at Jupiter in Dec 1995, atmospheric probe, study of Jupiter's atmosphere and magnetosphere, Galilean satellites
Cassini	15 Oct 1997	Flyby at Jupiter on its way to the Saturnian system
New Horizons	19 Jan 2007	Flyby at Jupiter on its way to the Pluto-Charon system
Juno	05 Aug 2011	Polar orbit around Jupiter, exploration of atmosphere, magnetic field, gravity field and magnetosphere, after Earth flyby in 2013 arrival at Jupiter on 5 Jul 2016

Missions to Saturn

Pioneer 11	06 Apr 1973	Flyby at Saturn, closest approach: 20,800 km
Voyager 2	20 Aug 1977	Flyby at Saturn, closest approach: 38,000 km, about 16,000 images of Saturn and its moons
Voyager 1	05 Sep 1977	Flyby at Saturn, closest approach: 124,000 km, about 16,000 images of Saturn and its moons
Cassini	15 Oct 1997	Orbiter, exploration of the Saturnian system, release of atmospheric probe 'Huygens' into Titan's atmosphere

Missions to Uranus

Voyager 2	20 Aug 1977	Flyby at Uranus in Jan 1986; closest approach: 107,000 km, images of Uranus and its moons

Missions to Neptune

Voyager 2	20 Aug 1977	Flyby at Neptune in Aug 1989, images of Neptune and its moons

Missions to dwarf planets

New Horizons	19 Jan 2006	Arrival in Pluto-Charon system 2015, afterwards flight to the Kuiper belt
Dawn	27 Sep 2007	First mission, which should go in orbit about two different bodies consecutively: 4 Vesta (arrival 2011, in Orbit around Vesta for one year) and 1 Ceres (arrival 2015)

Missions to comets

International Sun Earth Explorer 3	12 Aug 1978	Flight through plasma tail of comet Giacobini-Zinner
Vega 1	15 Dec 1984	Flyby at comet Halley on 6 Mar 1986 after Venus flyby
Vega 2	21 Dec 1984	Flyby at comet Halley on 9 Mar 1986 after Venus flyby
Sakigake	07 Jan 1985	Japanese mission, flyby at comet Halley on 1 Mar 1986
Giotto	02 Jul 1985	Flyby at comet Halley on 13 Mar 1986, images of the nucleus, flyby at comet Grigg-Skellerup on 10 Jul 1992
Suisei	18 Aug 1985	Japanese mission, flyby at comet Halley on 8 Mar 1986
Galileo	18 Oct 1989	Images from traces after impact of Shoemaker-Levy 9 fragments on Jupiter, 17-22 April 1994
Hubble Space Telescope	25 Apr 1990	Images from traces after impact of Shoemaker-Levy 9 fragments on Jupiter
NEAR	17 Feb 1996	Flyby at comet Hyakutake on its way to asteroid 433 Eros
Deep Space 1	24 Jan 1998	Test of new technologies (ion propulsion) for use in space, flyby at asteroid Braille and comet Borrelly (Sep 2001)
Stardust	07 Feb 1999	Flyby at comet P/Wild 2, samples of dust and volatile matters from the comet's coma, mapping of nucleus, sample return to Earth; mission extension as Stardust/NEXT (New Exploration of Tempel 1)
CONTOUR	03 Jul 2002	Close flybys at comets Encke and Schwassmann-Wachmann 3 and possibly comet d'Arrest
Rosetta	26 Feb 2004	Orbiter and lander, measuring and mapping of comet 67 P/Churyumov-Gerasimenko, afterwards landing on the nucleus, arrival at the comet 2014
Deep Impact	12 Jan 2005	Flyby at comet Tempel 1, release of an impactor to the nucleus, observation of the impact; mission extension as EPOXI, observation of comet Hartley 2

Missions to the Kuiper belt

New Horizons	19 Jan 2006	Arrival in Pluto-Charon system 2015, afterwards flight to the Kuiper belt

HOW CAN I ORDER IMAGE DATA?

The Regional Planetary Image Facility (RPIF)

Having read this little brochure, you may have asked yourself whether there is a source in Germany from which such material can be obtained. It is true that on the internet you can research a great deal yourself these days, but occasionally it is easier to use the services of someone who knows his way around better than you do or may even be able to relieve you of the entire research work, which is rendered difficult here and there because it requires foreign language skills.

This is where the Regional Planetary Image Facility (RPIF) comes in. The RPIF is a library for planetary image data. Its function is to file and make available all data so far gathered by space probes about planetary objects in our Solar System, remote-sensing data of Earth alone excepted.*

After the RPIF had been founded in 1985 on the basis of an agreement between DLR and NASA, the library was opened four years later. Initially domiciled with the planetary exploration department at the Institute of Optoelectronics in Oberpfaffenhofen, the RPIF has been located at the Institute of Planetary Research in Berlin-Adlershof since 1992. It is part of an international network of image libraries, coordinated by NASA. There are 17 of these facilities worldwide, of which nine are domiciled in the USA, five in Europe, and one each in Canada, Japan, and Israel. Basically, the Berlin RPIF is supposed to serve the entire German-speaking region. All image libraries maintain close contact with one another via data networks. Forming part of NASA's Planetary Data System (PDS), they offer extensive options of research in the system's databases.

The inventory

The inventory includes image and spectral data as well as the attitude and position data of the relevant probe. To complement these data, there are documents, maps, and a small selection of technical journals and literature. All data are held available in documented and catalogued form for scientific research purposes as well as for the general public. Internally, they are used for research work such as the evaluation of project-related data, for preparing space missions, and for dissertations or diploma papers.

While most of the data come from American sources, there are also data from European and Soviet/Russian missions. The table shows the current status of the inventory. Because of its database, which is almost complete as far as American missions are concerned, the RPIF is the 'preferred source' for planetary image data in Germany, providing an excellent foundation for research activities in this field.

NASA supplies the RPIF with data relating to current as well as future space flights. At present, for example, the facility receives data sent from the Saturnian system by the Cassini mission and from Mars by other current missions. To supplement the data about Mars, there are up-to-date images taken by the European Mars Express probe to which the DLR Institute of Planetary Research contributed its High Resolution Stereo Camera. Furthermore, there are data about the Moon from the Lunar Reconnaissance Orbiter, and about the Asteroid Vesta from the Dawn mission.

RPIF
Network
Regional Planetary Image Facility

*** Remote-sensing data about Earth are kept on file at DLR's Earth Observation Center (EOS) in Oberpfaffenhofen: http://www.dlr.de/eoc**

To complement the original material, there is an extensive library of maps which by now comprises more than 2,400 items, an extensive collection of digital image data and slides, and 16-millimeter films as well as videos and DVDs. Representing one of the library's key activities, this collection of digital image data and slides, all released for publication, is of particular interest to journalists and teachers as well as interested members of the public.

Public relations

For persons wishing to use the RPIF's extensive stock of material, a work area is available for inspection to researchers as well as the public. The data that are available include documents from NASA, the Jet Propulsion Laboratory (Pasadena, California), and the National Space Science Data Center (Greenbelt, Maryland). Computer-based catalogues permit selecting data on the basis of any search terms.

There is no charge for either information or data research. Images in small quantities will be supplied by the RPIF at cost. Larger quantities, particularly when destined for research, must be ordered from the National Space Science Data Center, with the support of the RPIF. Next to assisting individual users, the RPIF offers presentations on a variety of subjects for groups and school forms or as part of teacher in-service training. Lastly, the RPIF presents itself at numerous professional meetings, exhibitions, and fairs.

Overview about mission, from which data sets are available

Planet	Mission
Merkur	Mariner 10, MESSENGER
Venus	Mariner 10, Pioneer Venus, Venera 15 & 16, Galileo, Magellan, Venus Express, MESSENGER
Erde	Galileo, SIR-C/X-SAR, Topex/Poseidon, Jason-1, Clementine, Kidsat, SRTM, TERRA, Space Shuttle
Mond	Lunar Orbiter 1-5, Apollo, Galileo, Clementine, Lunar Prospector, Cassini, SMART 1, Kaguya, Lunar Reconnaissance Orbiter
Mars	Mariner 9, Viking Orbiter 1 & 2, Viking Lander 1 & 2, Mars Phobos, Mars Pathfinder, Mars Global Surveyor, 2001 Mars Odyssey, Mars Exploration Rover 1 & 2, Mars Express, Mars Reconnaissance Orbiter, Phoenix, Mars Science Laboratory
Asteroiden	Galileo, NEAR, Cassini, Deep Space 1, Rosetta, Dawn
Jupiter	Voyager 1 & 2, Galileo, Cassini, New Horizons
Saturn	Pioneer 11, Voyager 1 & 2, Cassini-Huygens
Uranus	Voyager 2
Neptun	Voyager 2
Komet Shoemaker-Levy 9	Galileo, Hubble Space Telescope, Data from several observatories
Komet Hale-Bopp	Data from several observatories
Kometen	Deep Space 1, Stardust, Hubble Space Telescope

On our internet page, http://www.dlr.de/rpif/, you will find an overview of the current stock of images, particularly those released for publication. Besides other material, such as posters, image series, and building kits, it contains a complete catalogue in PDF format.

The Institute's projects

The RPIF is committed to filing and making available to interested persons and the worldwide public data relating to space missions that have been concluded (e.g. Galileo, Mars Pathfinder, Deep Space 1), are going on at present (Mars Express, Venus Express, Cassini, Rosetta, Dawn), or are being prepared with the participation of the Institute (ExoMars, BepiColombo).

The Galileo project was the most diverse and the most complicated uncrewed space mission to explore Jupiter and its Galilean moons. Launched in 1989, the orbiter – after a journey of several years through our Solar System – has been delivering fascinating images since June 1996, showing the volcanically active moon Io and the icy moons Europa, Ganymede, and Callisto. Released by the orbiter months before it arrived at the planet, an atmospheric entry probe investigated the chemical composition of Jupiter's atmosphere. The mission ended in July 2003.

Deep Space 1, the first mission under NASA's New Millennium program, took off in October 1998. It was to examine the comet Borrelly after flying by the asteroid Braille. For validation purposes, it carried a variety of developments in space technology, including a solar electric propulsion unit. The probe was equipped with a camera and a plasma spectrometer which was used to examine the plasma environment of the probe and the surface of both the asteroid and the comet during the nominal mission.

Under the Mars Pathfinder mission, the Institute was involved in the scientific evaluation of the rover's image data. Thus, the stereoscopic images taken at the landing site of the rover were processed into photogrammetric products and the image data subjected to a multispectral analysis.

Since July 2004, the Cassini mission has been exploring the planet Saturn, its ring system, its magnetosphere, and its moons. Launched in 1997, the probe reached the planet seven years later after several swing-by manoeuvers, and by 2017 it will have completed at least 289 orbits around it. Its payload included Huygens, the atmospheric probe/lander that explored the atmosphere and surface of the Saturnian moon, Titan. Several close flybys past icy moons have already yielded spectacular results. The probe has flown twice through a gap in the ring system and applied all its remote-sensing instruments in an investigation of cloud-shrouded Titan. DLR is involved in several experiments of the Cassini mission, including in particular the spectrometer for visible light and infrared (VIMS). Moreover, DLR has a share in the cosmic dust analyzer, the ultraviolet spectrometer, and the ISS camera experiment.

The European Mars Express mission that took off on 2 June 2003 comprises an orbiter and a British-built lander module which, however, failed to touch down on the surface of Mars. After the failure of the Russian Mars 96 mission, the European space organization ESA planned this mission so that some of the spare instruments developed for Mars 96 might serve the purpose of achieving its scientific objectives. Thus, the second flight model of the high-resolution stereo camera (HRSC) originally developed by the Institute for the Russian Mars 96 mission serves to continue the significant task of completely mapping Mars in high resolution, color, and 3-D. The camera has been proving its unique capabilities since the beginning of 2004.

The launch of the European Rosetta mission was originally scheduled for January 2003 but deferred to 2 March 2004. Since that time, the probe has been on its way to the comet 67/P Churyumov-Gerasimenko. Because of its delayed take-off, it was no longer possible for the probe to explore the comet Wirtanen, as had originally been intended. Instead, Rosetta will enter an orbit around the comet Churyumov-Gerasimenko in 2014, explore the comet's nucleus for several months, and finally release the Philae lander. The Institute is involved in several of the mission's experiments, the most important among them being the VIRTIS spectrometer on the orbiter and the ROLIS camera, the MUPUS temperature sensor, and the SESAME sensor packet to investigate the properties of the ground, all of which are installed on the lander.

On 27 September 2007, the Dawn mission took off for two very different objects: the asteroid 4 Vesta and the dwarf planet 1 Ceres. Developed in co-operation with the Max Planck Institute of Solar System Research on the basis of the cameras that flew on Mars Express and Rosetta, the camera on board the probe delivers images of Vesta in seven colors and of Ceres in three colors. The payload includes another European instrument, an Italian-built spectrometer. After arriving at Vesta in July 2011, the probe examined the asteroid for more than a year. After a flight of another three years, the dwarf planet Ceres will be the object of its investigations for somewhat less than a year.

The planets inside the Earth's orbit have been moving back into the focus of research since 2005. Following the launch of NASA's MESSENGER mission to Mercury in 2004, the European Space Agency (ESA) launched Venus Express on 9 November 2005 to extend the exploration of the inner Solar System to Earth's sister planet, which is of similar size. The design of the probe is based on that of the Mars Express orbiter. In addition,

Useful WWW links

Planetary Science World Wide Web Sites
http://www.lpi.usra.edu/library/website.html

Planetary Photojournal
http://photojournal.jpl.nasa.gov

Windows to the Universe
http://www.windows.ucar.edu/

Views of the Solar System
http://www.solarviews.com/germ/homepage.htm

Nine Planets
http://www.nineplanets.org/

Nine Planets (in German)
http://www.neunplaneten.de/nineplanets/

Jet Propulsion Laboratory
http://www.jpl.nasa.gov

Archive of space missions (in German)
http://www.dlr.de/arm

certain spare instruments originally designed for Mars Express and Rosetta were adapted to the project. The share of the DLR Institute of Planetary Research includes a camera for exploring the dense atmosphere as well as contributions to the spectrometer experiment. Having entered its orbit around Venus on 11 April 2006, Venus express will go on circling around the planet until the end of 2014 at least.

Lastly, the European BepiColombo mission is intended to make a crucial contribution towards mapping and exploring Mercury, complementing the results of the current American Mercury orbiter, MESSENGER. The mission comprises two components that will be orbiting the planet separately: built by ESA, the Mercury Planetary Orbiter (MPO) is supposed to explore the surface, whereas the Mercury Magnetospheric Orbiter (MMO) built by the Japanese space agency JAXA will investigate Mercury's magnetic field and its interaction with the solar wind. The DLR Institute of Planetary Research is coordinating the development of a laser altimeter on the MPO that will survey elevation differences on the planet at high precision. The spacecraft is scheduled to take off in July 2015, reaching Mercury after a flight of six years.

Enquiries should be addressed to:

German Aerospace Center
Institute of Planetary Research
RPIF
Rutherfordstraße 2
D-12489 Berlin
Germany
Phone: +49 30 67 055 333
Fax: +49 30 67 055 372
E-Mail: rpif@dlr.de
http://www.dlr.de/RPIF/

The DLR_School_Labs and the DLR_next youth portal

Through its DLR_School_Labs, DLR informs pupils about the exploration of the Solar System and many other exciting projects from the aerospace, energy, and transport sectors – see www.DLR.de/dlrschoollab.

Young people wishing to know more about our fascinating world of research on a virtual basis can do so at www.DLR.de/next, where numerous current projects are described in texts, pictures, and videos – fun included! For DLR_next – DLR's official youth portal – also offers multi-media features such as a 'virtual journey through the Solar System'.

Links:

http://www.DLR.de/dlrschoollab
http://www.DLR.de/next