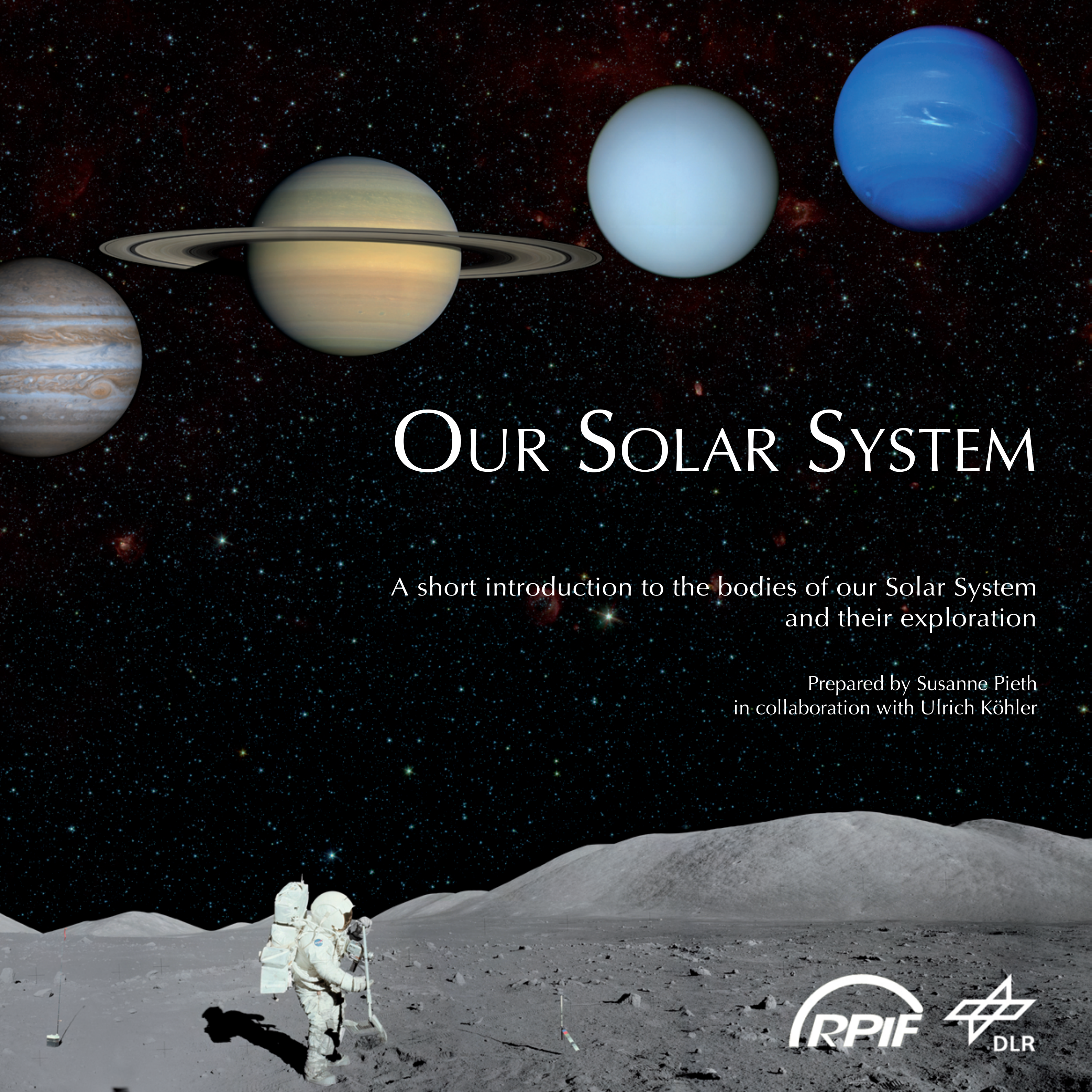

Our Solar System

A short introduction to the bodies of our Solar System and their exploration

Prepared by Susanne Pieth
in collaboration with Ulrich Köhler

RPIF DLR

German Aerospace Center
Institute of Planetary Research

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Regional Planetary Image Facility
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DLR

Contents

Preface

A journey through the Solar System

2009 was proclaimed the International Year of Astronomy to commemorate a defining moment in history. It was exactly 400 years ago that Galileo Galilei 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 has 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 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 camel through the eye of a needle.

And there are yet more anniversaries to come: 50 years ago, mankind succeeded for the first time in sending a space probe beyond the Earth's gravitational field. The first 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. Lastly, it was 40 years ago 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. And, not least, we came to appreciate that this 'blue planet' is fragile and needs to be protected.

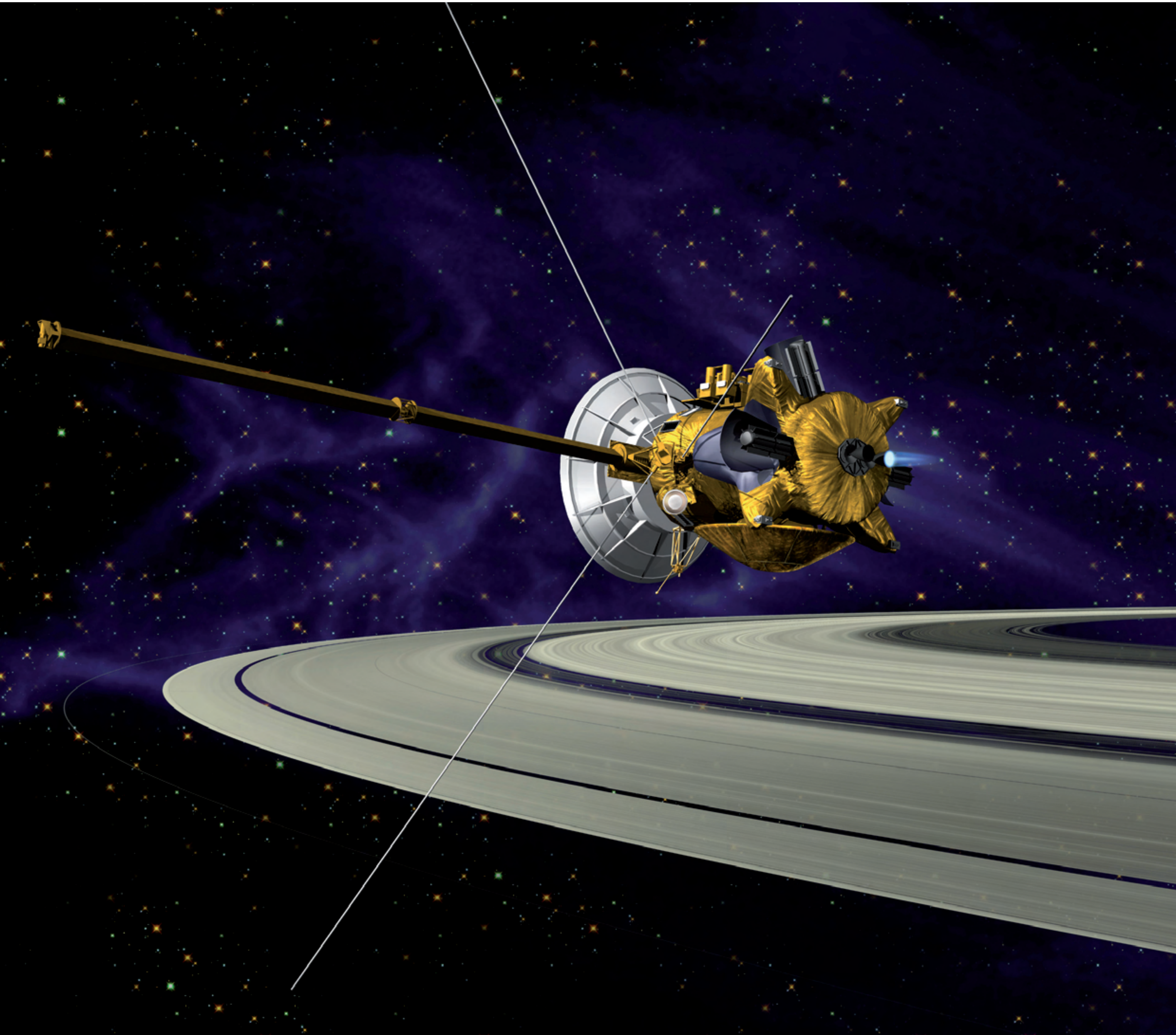
In fact, however, every riddle that is solved raises fresh questions. How did life originate on Earth? Did it come from another celestial body? Would life on Earth be possible at all without the Moon's stabilizing influence on the Earth's axis? And finally, there is the question that goes beyond the scope of science pure and simple: will we find life on another celestial body on this or the other side 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 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) fulfills this obligation 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 many NASA and ESA space probes and makes them accessible to the public. Entitled 'Our Solar System', this small publication 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.

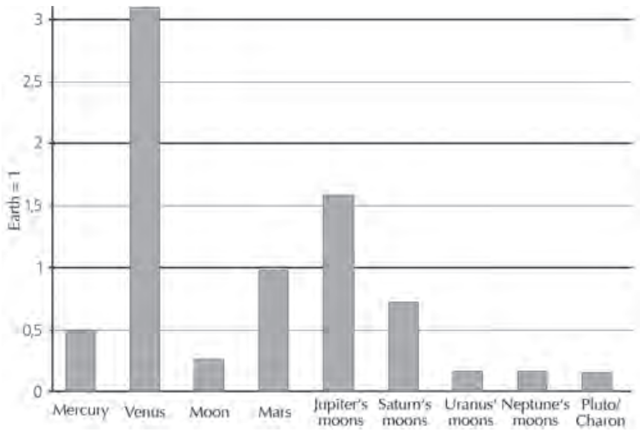


Exploring the Solar System with space probes

The launch of Sputnik 1 by the Soviet Union on 4 October 1957 marked the beginning of the space age. Shortly afterwards, the USA and the USSR – as it then was – sent more space probes beyond the Earth's gravitational field, followed later on by those of other nations. Their destinations included the Moon, other planets and their moons, asteroids and comets, and even our Sun, while yet others investigated interplanetary and cosmic dust. Although some setbacks happened, 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 and ultimately multispectral technologies) as well as imaging spectroscopy across a waveband that includes relatively short and long wavelengths. Wherever a dense atmosphere obscures our view, as in the case of Venus or the Saturnian moon Titan, surfaces may be characterized by radar.

Exploration scope

The diagram below shows how immense the scope of planetary remote sensing is even if we take into account only the rocky planets and leave aside the numerous minor bodies and the four gas giants in the outer Solar System. The volume of optical image data gathered so far does not even cover the surfaces of all planets and major moons in their entirety, even if we accept low resolutions in the kilometer range.



The solid surfaces of the planets and its moons in relation to the land surface on Earth (Earth = 1)

The sensors employed in planetary exploration operate not only in visible light but also in many other segments of the electromagnetic spectrum. However, as the latter sensors have a much lower resolution, many questions still remain unanswered and will have to be settled by future space missions.

Picture: Launch of Mars Pathfinder from Cape Canaveral on 4 December 1996 on board a Delta-II-rocket. (© NASA/JPL)

Picture left page: Artist's rendition of the spacecraft Cassini above the Saturnian rings. (© NASA/JPL)

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*
- *Manned expedition*

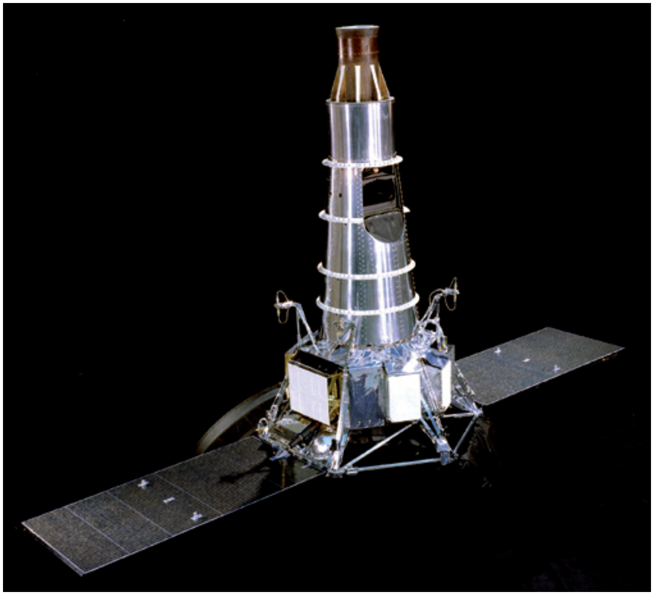
This sequence of events is not always followed strictly. Steps are often merged or skipped, as a glance at almost five decades of planetary exploration shows. The motivation may either be technical and scientific or financial and/or political.

The first four decades

On 2 January 1959, the Soviet space probe Luna 1 reached 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 manned missions, the exploration of the Moon was marked by the race for technological leadership between two competing political and societal systems, respectively. 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 that is not visible from Earth, although these were of inferior 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 manned 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 manned missions to the Moon form the salient feature 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. In both technical and scientific terms, the Apollo missions constituted a major step ahead which, however, will not be explained in detail here. During the same period, lunar



Picture: Ranger 7, launched on 28 July 1964, was the first successful mission of NASA's Ranger series to the Moon. Before its impact in Mare Nubium 4,000 images were transmitted to Earth. (© NASA) 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 under 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.

The Voyager program achieved similar eminence. After two preparatory missions by Pioneer 10 and 11 the two Voyager probes set out on their ‘Grand Tour‘ which led them to the gas planets of Jupiter, Saturn, Uranus and Neptune and their respective moons between 1977 and 1989. 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 the comet Halley, which was visited by not one but several space probes from Europe, the USSR and Japan when it last 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. It 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 astronautics.

Future missions and programs

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 return to the Moon, its further exploration and future utilization. Next to these two items, a multitude of other missions will target the minor bodies of our Solar System as well as destinations that have not been visited for some time or are completely unexplored. These destinations include Mercury, the large asteroids Ceres and Vesta and, most importantly, Pluto which lost its planetary status some time ago and represents one of the last ‘white spots‘ among the large bodies of the Solar System.

Picture: Apollo 17 astronaut Gene Cernan at the Rover in the Taurus-Littrow valley, with TV camera and antenna in the foreground. (© NASA, scan: JSC)

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 the options now available for processing large volumes of data on board the probes.

In the next few decades, it is intended to send probes to our outer neighboring planet, Mars, at intervals of about two years. The first long-range objective is to gather samples and return them to Earth, followed by a manned landing on the Red Planet at some later date. Next to the USA, whose Mars Surveyor program consists of orbiters, landers, rovers and, at some later date, the return of samples by a mission that may be conducted jointly with Europe, other nations are participating with instruments and/or probes of their own. Europe‘s contribution is Mars Express, a highly successful mission which has been transmitting a wealth of data and images from Mars since the end of 2003. Now that the Mars Reconnaissance orbiter has arrived in March 2006, as many as five probes are operating simultaneously at present, three in orbit and two rovers on the surface.

The European technology demonstrator SMART-1 which, having orbited the Moon since November 2004, ended its mission with an impact in the summer of 2006, is only the ‘curtain-raiser‘ of a massive campaign to explore our satellite. Spacecraft built by the USA, Japan, India, China, and possibly even Germany are scheduled to follow within the next decade. Orbiters, rovers and, later on, automated sample return missions will explore the surface and the interior of the Moon in preparation of the return of man.

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. Although beset by numerous technical problems, the Japanese probe Hayabusa, which very probably succeeded in taking samples on the asteroid Itokawa in November 2006, is now making a rather complicated journey back to Earth, whose atmosphere it will enter in June 2015. Not having encountered any problems so far, the European Rosetta mission launched early in 2004 is on its way to the comet Churyumov-Gerasimenko whose orbit it will join in mid-2014 to deposit the Philae lander on its core a few months later.

Having arrived in the summer of 2004 as one of the last large-scale missions to explore the Saturnian system, Cassini-Huygens has been another focus in planetary research ever since. 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 though Titan‘s atmosphere and landed on its surface in January 2005.

Further targets have been identified, and some probes are already on their way: the exploration of Mercury by the American Messenger probe launched in August 2004 (orbital entry: 2011), the planned European-Japanese mission BepiColombo (launch: 2012/13), the exploration of the asteroids Ceres and Vesta by Dawn (launch: 2007, arrival: 2011/2015) and the New Horizons mission which, launched in January 2006, will fly by Pluto in 2015. The Venus Express probe has been orbiting the planet since April 2006.

Comparative planetology in the Solar System

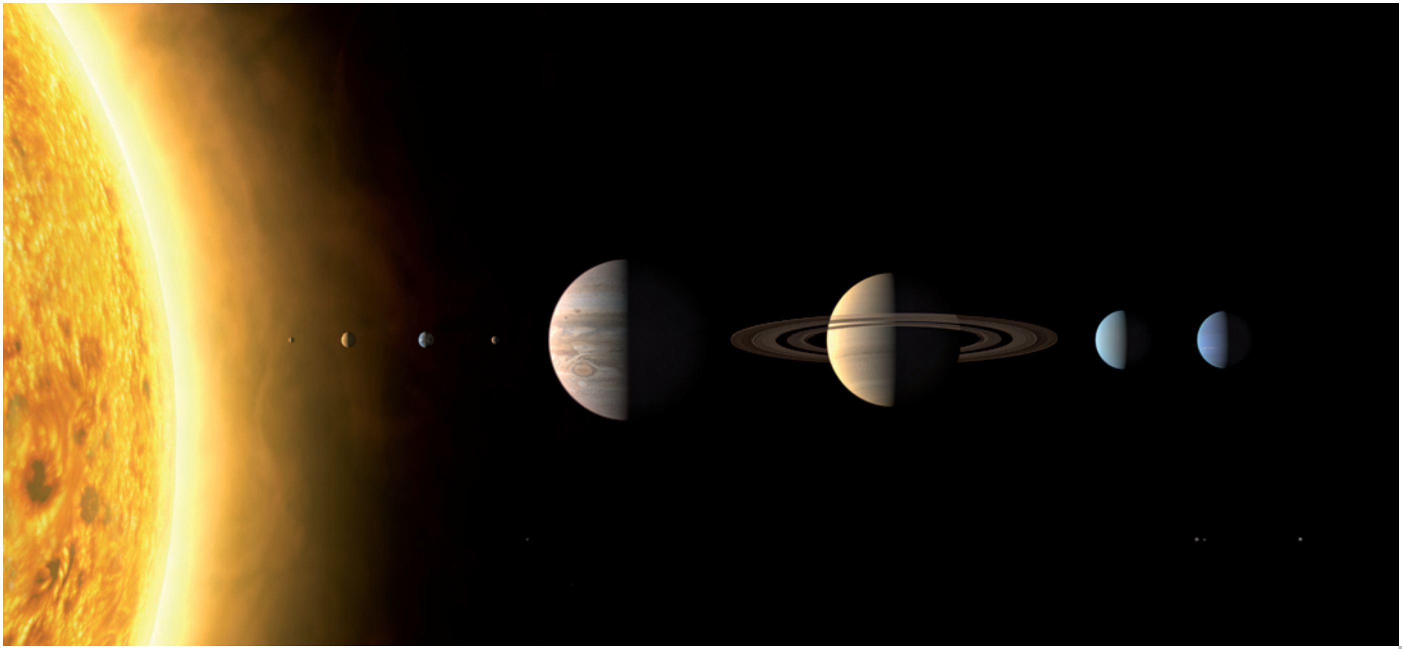
The Solar System in which we live is only one of many in our universe. Earth alone exempted, there is no planet orbiting the Sun of which we can be sure that life is possible there. Life on Earth took millions of years to develop in all its diversity, but it has only been some 50 years since man found the courage to step into space, using robotic probes first and manned spacecraft later to explore the planets and their moons – including Earth, whose study from near-Earth orbits opened up new avenues for research.

Even in ancient times, astronomers were observing pinpoints of light that appeared to move among the stars. They called these objects planets, which means 'wanderers'. Later on, they gave them the names from the Roman pantheon that we still use today: 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 god of agriculture.

Our Solar System incorporates a multitude of different bodies ranging from agglomerations of dust and frozen water 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 orbits are all more or less on a plane that is aligned on the equator of the Sun's rotation. The plane of the Earth's orbit around the Sun is called the ecliptic. Relative to this plane, the planets' axes deviate only a few degrees from the vertical. Two exceptions are Uranus and Pluto, whose axes are extremely tilted so that these celestial bodies literally 'roll' on their orbit around the Sun. Pluto, a dwarf planet, is so far away from the Sun that it takes 248 years to complete an orbit. The innermost planet,

Picture: Our Solar System, Sun and planets in right proportions, distances are not in relation. (© IAU, Martin Kornmesser)



Mercury, takes only 88 days to do the same. Many minor bodies travel on elliptical orbits. Thus, comets follow elliptical to hyperbolic trajectories that take them far beyond the orbit of Jupiter and back near the Sun. Comet Halley, for example, enters the inner Solar System at intervals of about 78 years. Whenever Earth travels through a part of its orbit that has been passed by a comet before, showers of meteors can be seen in its atmosphere, a spectacular example illustrating the mechanics of orbits in the Solar System.

There is a marked trend for the mass and composition of planets to change with their distance from the Sun. Of comparatively low mass, the terrestrial planets (Mercury, Venus, Earth, Moon* and Mars) in the inner Solar System consist mainly of silicate rock and metals. Conversely, the large planets of the outer Solar System (Jupiter, Saturn, Uranus and Neptune) have a much greater mass and mainly consist of gases (mostly hydrogen and helium). They all have moons that largely consist of ice. Some substances (such as water, methane, ammonia and nitrogen) condense at low temperatures, while others (hydrogen and helium) will remain gaseous under almost all conditions that occur in nature. However, even the gas planets have cores composed of silicate rock and metal.

All in all, the planets of our Solar System have 151 moons, not including any as-yet unconfirmed discoveries. These moons vary very greatly in size, ranging from small fragments to bodies larger than Earth. Many moons were only discovered by space probes. Only one of them has an atmosphere (the Saturnian moon Titan), others again have a magnetic field (the Jovian moons Ganymede and Europa). The Jovian moon Io is the geologically most active body in the entire Solar System, as evidenced by its extreme volcanism. It is supposed that the ice crust on the Jovian moon Europa hides an ocean, and pictures of Ganymede, another Jovian moon, show that its icy crust is moving. Yet others like the Saturnian moon Phoebe or the two Martian moons Phobos and Deimos may be asteroids that were captured by their parent planet‘s gravity.

All current theories about the origin of our Solar System are based on the generally accepted idea first proposed by Immanuel Kant and Pierre Laplace, which says that the Sun and its planets developed almost simultaneously from a protostellar nebula 4.6 billion years ago. The nebula, in turn, was created when a cloud of interstellar dust collapsed. Today‘s configuration of the Solar System and its motion are due to the gravitational attraction between the clouds‘ constituent particles, the torque generated by the collapse, and other forces. What we have so far observed of the composition of the planets leads us to assume that they developed mainly by the accretion of solid particles. The four inner terrestrial planets were produced directly by accretion processes that initially involved particles of silicate and metallic dust and operated in a region where temperatures did not permit ice particles to survive for long. In the outer system, on the other hand, lighter elements condensed into ice from which the solid bodies emerged that today constitute the partially solid ice- and metal-rich cores of the outer planets. Moreover, Jupiter and Saturn formed the atmospheres we observe today by capturing large volumes of the original interstellar gas with their massive cores.

However, current theories also maintain that the development of the Solar System is neither unique nor particularly noteworthy. Stars that are just being born show similar conditions. By now, we know more than 300 solar systems that have planets, and other planetary systems innumerable are bound to be discovered as observation methods improve.

* *In comparative planetology, the Moon forms part of the Earth-Moon system and is regarded as a terrestrial planet because of its size and composition.*

Picture, left page: Artist’s rendition of our Solar System, sizes and distances are not in correct relation. (© NASA/JPL)

The Sun

The Sun was and is the source of energy that powers numerous physical, chemical and biological processes in its system. In astronomical terms, it is an average star of the G2 V spectral type that began to shine five billion years ago at the center of a dense cloud of gas and dust. With a radius of almost 700,000 kilometers and a mass of nearly two times 10^{33} grams, the Sun's mean density amounts to 1.41 g/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 shapes the orbits of all planets, asteroids and comets in the Solar System. During a solar eclipse, we can even observe that the Sun does indeed bend space in its environment in the way predicted by Albert Einstein in 1916. However, the Sun's chemical composition is just as important as its mass. It is composed of 73 percent hydrogen, 25 percent helium and two percent heavier elements, as can be demonstrated very well in a spectroscope. 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. Its most conspicuous features are dark spots which migrate from one edge of the Sun to the other within two weeks. This led observers to conclude very early on 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 velocities that vary with heliographic latitude: a revolution takes 25 days at the equator and more than 30 days at the poles of the Sun. At about two kilometers per hour, the Sun rotates rather slowly compared to other stars.

The sunspots themselves seems to be dark because they are up to 1,500 Kelvin colder than the surrounding photosphere, which is as hot as 6,000 Kelvin. They appear black against their hotter background. In 1843, Heinrich Schwabe successfully demonstrated that sunspot numbers regularly fluctuate within a period of eleven years. It is thought that this eleven-year sunspot cycle might be overlaid by even longer periods which are occasionally associated with climate changes on Earth, like the so-called 'little ice age' 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 'zones of disturbance' that appear on the outside as darker, colder spots.

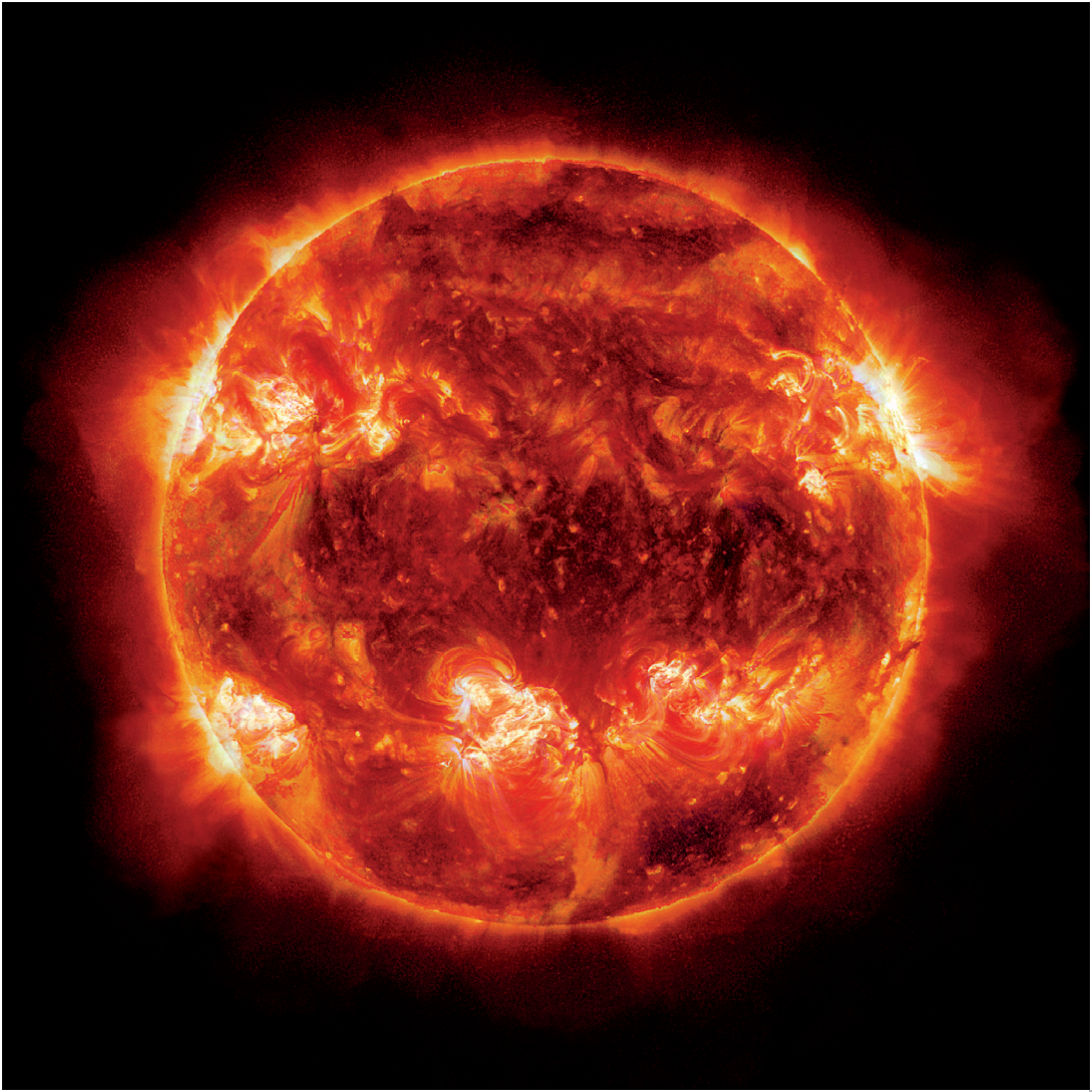
In physical terms, the sphere of the Sun may be subdivided into three zones: within the innermost 20 percent of its radius, energy is generated by nuclear fusion, a process in which four hydrogen nuclei merge to form one helium nucleus. The process releases binding energy, i.e. the amount of energy that 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 gives us about four million tons per second! To facilitate nuclear fusion in the first place, the center of the Sun must have a temperature of about 15 million Kelvin and a pressure of more than 20,000 Pascal. In the space between 20 and 70 to 80 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 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.

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 varies its shape so as to accommodate the changing fusion processes in its interior. It will do the same, for example, when it passes through the Red Giant stage in

Facts

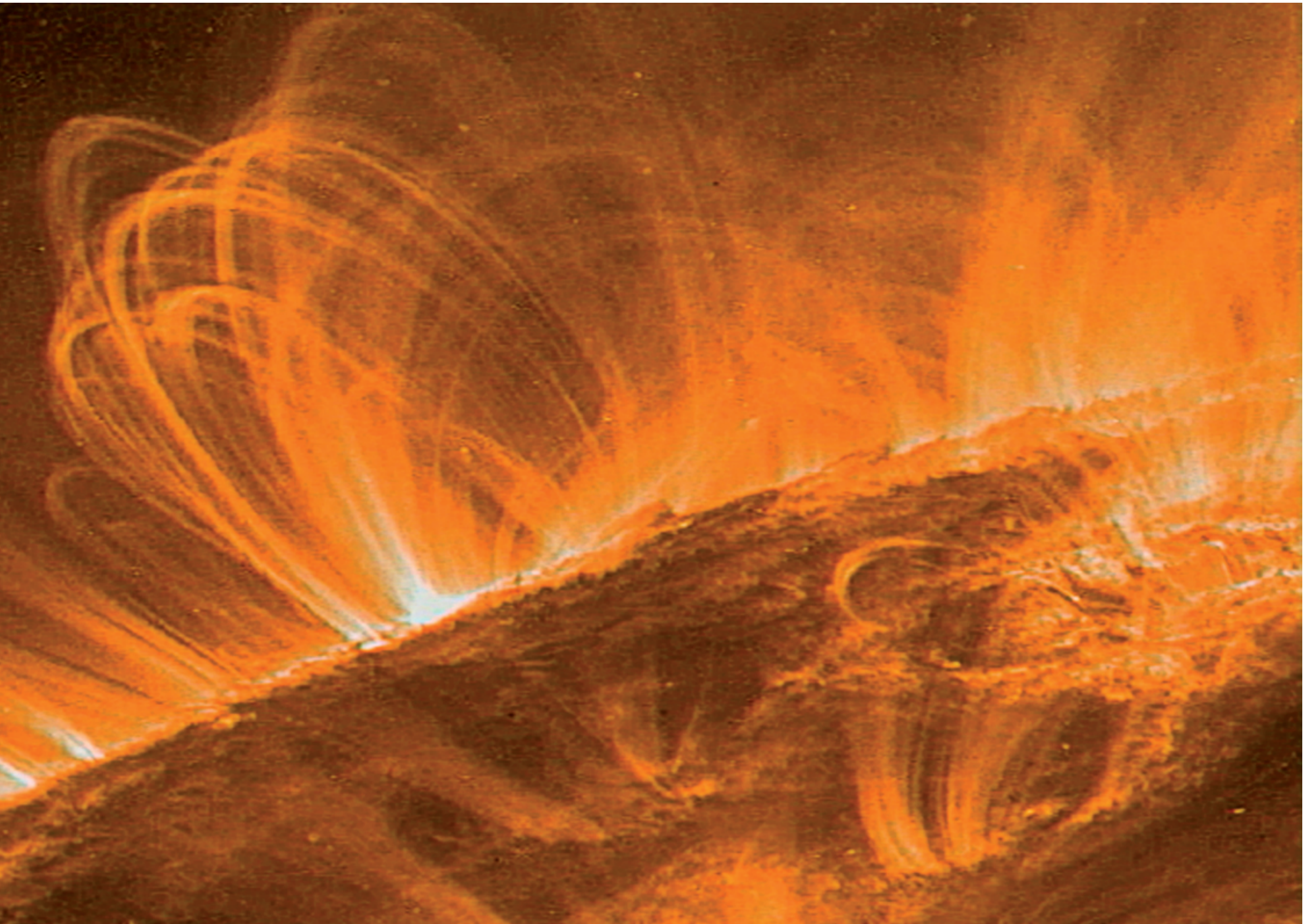
Mass	*1.989 x 10^{30} kg*
Radius	*695,500 km*
Density	*1.409 g/cm^3*
Rotation period	*26.8 - 36 days*

Picture, right page: Global view of the Sun in ultraviolet light. (© NASA/TRACE)



about five billion years. At the end of its total lifespan of about ten billion years, the Sun will shrink into a white dwarf the size of Earth.

Picture: Protuberances, hot gases along magnetic field lines, rising up from the corona, taken in ultraviolet light. (© NASA/GSFC)



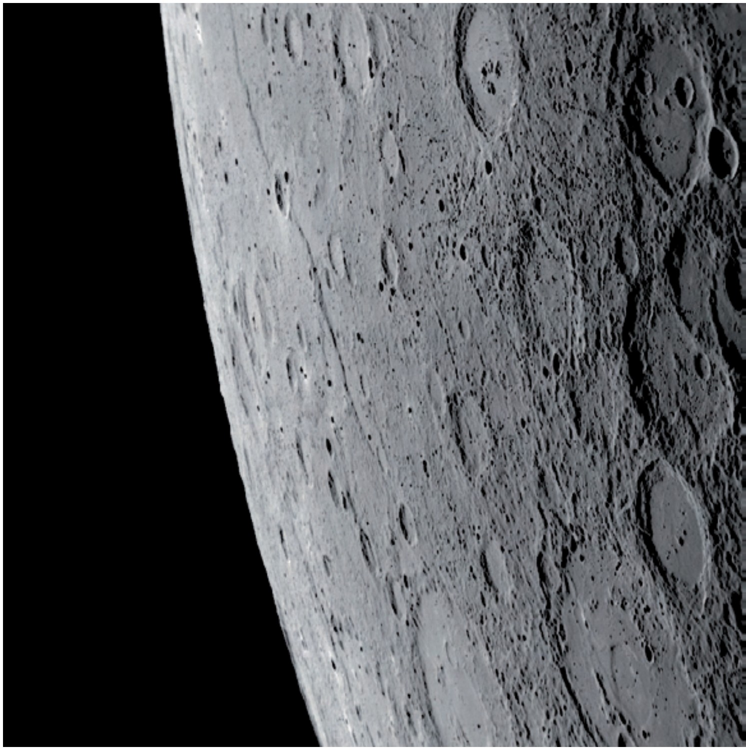
Mercury

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 then only if the ecliptic is very steeply inclined to the horizon. Within 217 years, observers on Earth may watch Mercury passing as a black dot before the bright disk of the Sun on twenty occasions in November and on nine occasions 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 centigrade.

The smallest planet in the Solar System, Mercury is smaller even than the Jovian moon Ganymed and the Saturnian moon Titan. Nevertheless, its mean density is comparable to that of Earth, which leads scientists to assume that Mercury must have a relatively extensive and heavy core of iron and nickel. Measurements show that the strength of Mercury's magnetic field is about one percent of Earth's.

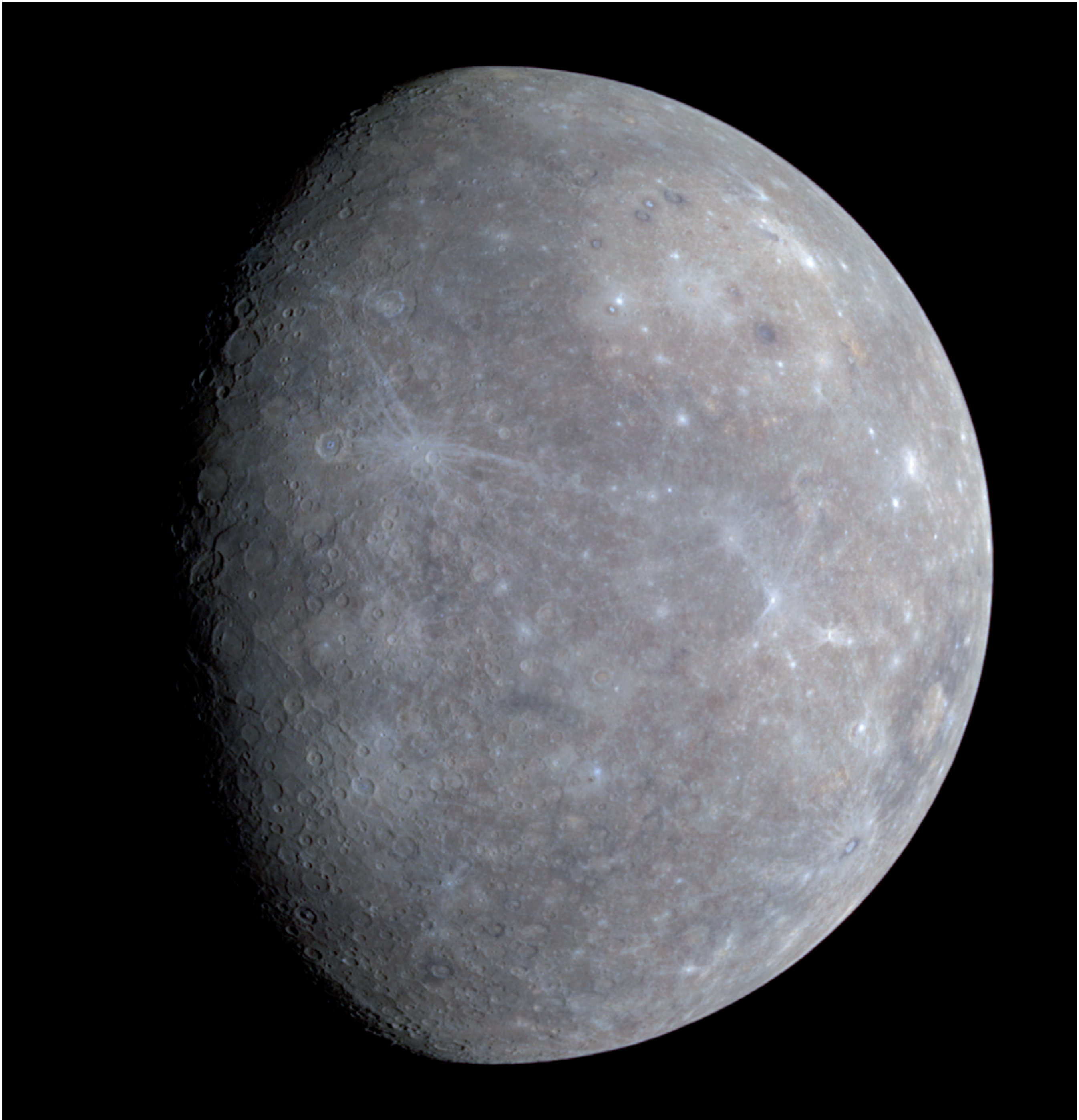


Like the Moon, Mercury's surface is riddled with impact craters of all sizes, the most impressive surface structure being the Caloris basin with a diameter of 1,300 kilometers. In this case, the body that struck the planet appears to have landed with so much force that the effects of the shock waves focused in the interior are apparent on the opposite side of the planet. Roughly speaking, Mercury's interior resembles a little that of Earth and its sur-

Facts

Mass	*3.302 x 10^{23} kg*
Radius	*2,439.7 km*
Density	*5.427 g/cm^3*
Rotation period	*58.65 Tage*
Orbital period	*88 Tage*
Mean Distance from the Sun	*57.91 x 10^6 km*

Picture: View to the limb of Mercury. Prominent towards the horizon is a long cliff face extending for more than 400 kilometers. This scarp is a result of contraction due to the planet's cooling. (© NASA/JHUAPL/Carnegie Institution of Washington)



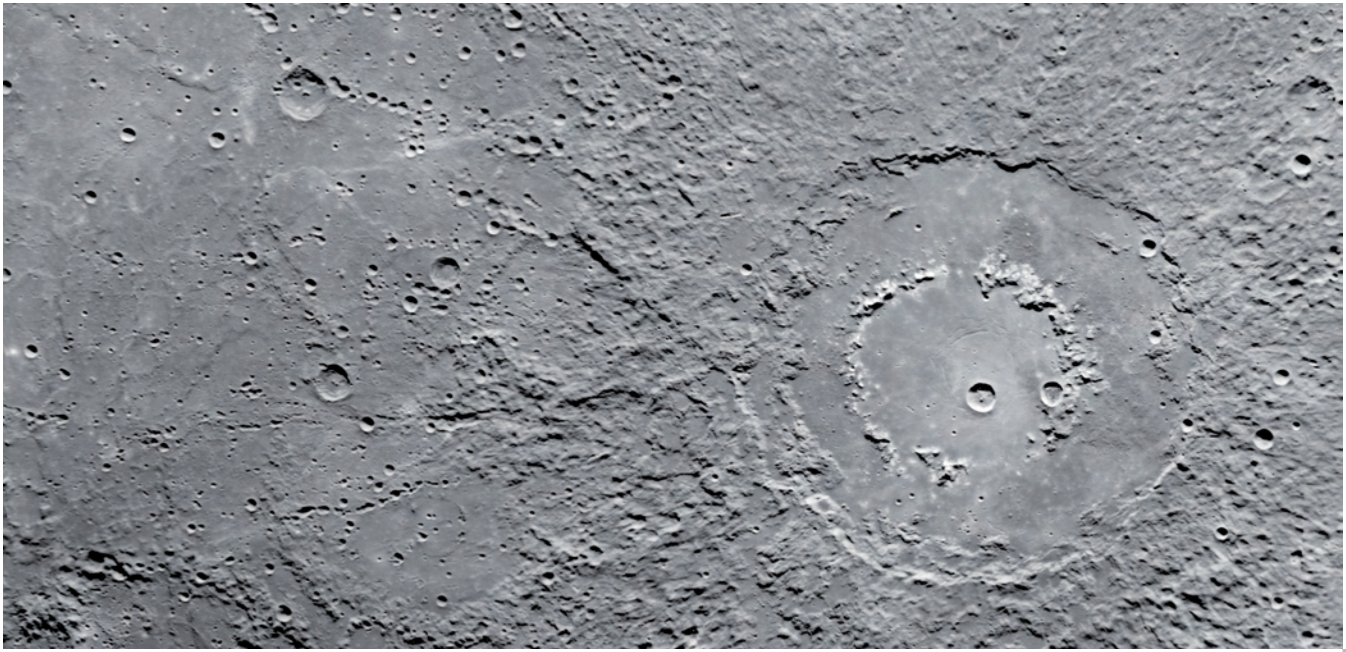
face that of the Moon. Unlike the Moon, however, Mercury shows marked scarps which suggest that its core shrank during the cooling phase.

There is much that we still do not understand about the composition of Mercury's surface and its inner structure. Being so close to the Sun, Mercury is difficult to observe from Earth with telescopes and equally difficult to reach with space probes: in any approach to Mercury, the immense attraction of our central star must be taken into account as well as its enormously intense radiation. At the moment, the Messenger space probe is following a complicated path which, having already led it past Mercury on two occasions, is supposed to end in an orbit around Mercury in 2011. At least, 25 percent of Mercury's surface that had not been mapped before could be photographed during the flybys. The new images show many features which indicate that volcanism must have once been active on Mercury.

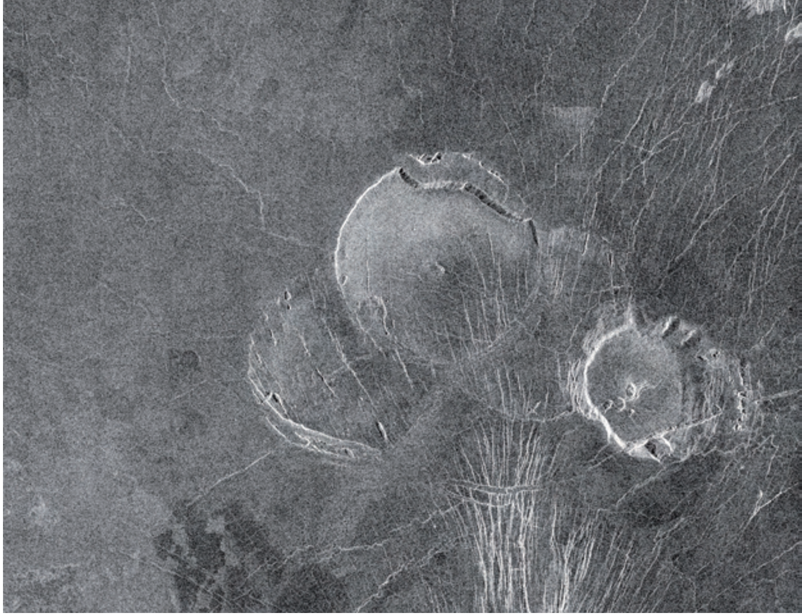
Like the Moon, Mercury is unable to retain an atmosphere, and yet Mariner 10's spectrometer revealed a paper-thin gaseous shell composed of hydrogen, helium and oxygen and containing traces of sodium and potassium. However, the total mass of these volatile elements amounts to no more than a thousand kilograms. It is likely that a large proportion of these particles was provided directly by the Sun and only a little by outgassings from the planet's interior. Moreover, ice may be hiding in some deep craters located at the poles of the planet that are permanently cold because they never receive any solar radiation; radar observations made from Earth indicate as much.

Picture: Large double-ring basin with 260 kilometers in diameter whose interior is filled with smooth material probably of volcanic origin. (© NASA/JHUAPL/Carnegie Institution of Washington)

Picture left page: Global view of Mercury in natural colors, taken by MESSENGER. The large circular light-colored area in the upper right of the image is the interior of the Caloris basin. (© 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. After the Sun and the Moon, it is the brightest celestial body, for it reflects 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/or after sunset. With a 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. The most recent passage of Venus took place on 8 June 2004; the next transit will happen on 6 June 2012.

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 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. Venus shows phases like the Moon, but 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 enormous plains that 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 10 percent is Venusian highlands that 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. 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.

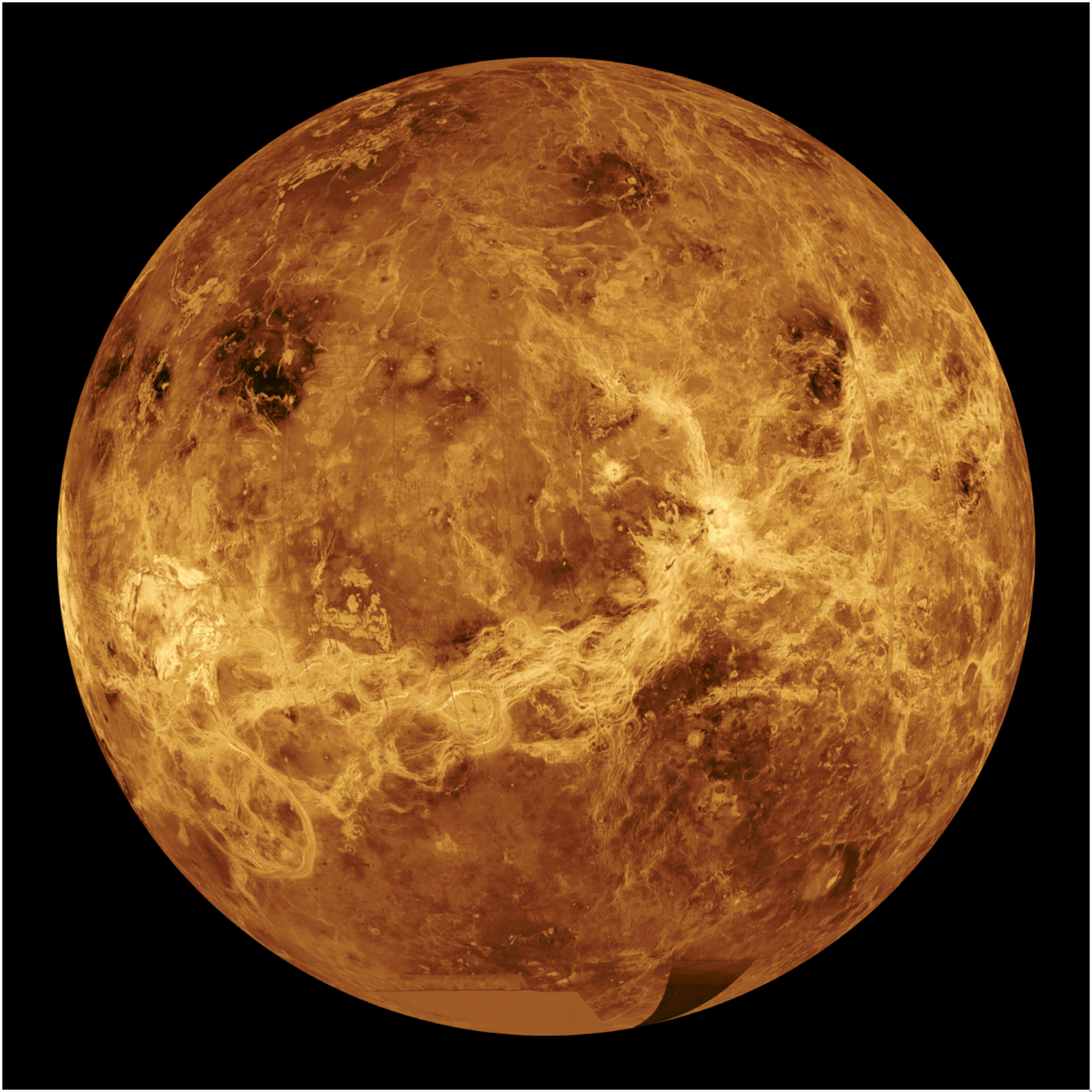
All in all, more than 1,000 volcanos and many bizarre-looking formations of volcano-tectonic origin have been detected on Venus. However, impact craters have been found as well, although their number is far lower than on Mars, for example. From this observation, we may properly conclude that the Venusian surface is not very old. Roughly between 600 and 500 million years

Facts

Mass	*4.869 x 10^{24} kg*
Radius	*6,051.9 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*

Picture: Three unusual volcanoes in the plains of Guinevere Planitia. (© NASA/JPL)

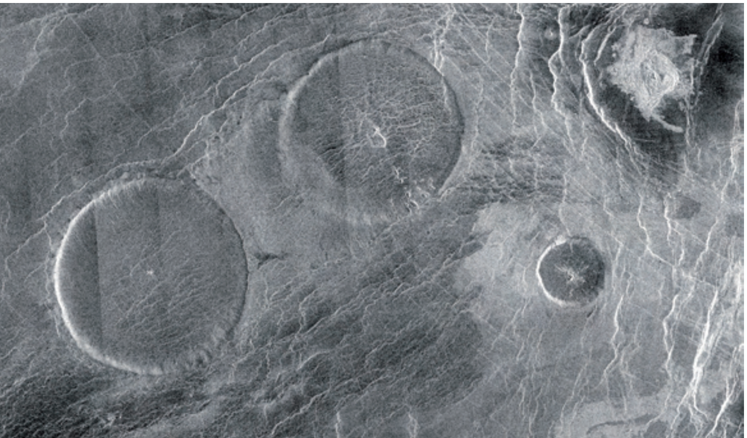
Picture right page: Computer-simulated global view on the basis of Magellan radar data. (© NASA/JPL)



ago, a global disaster reshaped the landscape of Venus from the ground up; it is likely that innumerable volcanos distributed around the entire planet erupted at that time. The reasons for this 'renewal process' are not yet fully understood.

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, for we do now know precisely whether or not continental plates 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.

Compared to Earth, the mass of the Venusian atmosphere is around 90 times greater. At ground level, the mean surface temperature is 477 degrees centigrade and the atmospheric pressure is 93 bar. 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 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 centigrade.



Three thick cloud layers float at altitudes between approx. 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.

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.

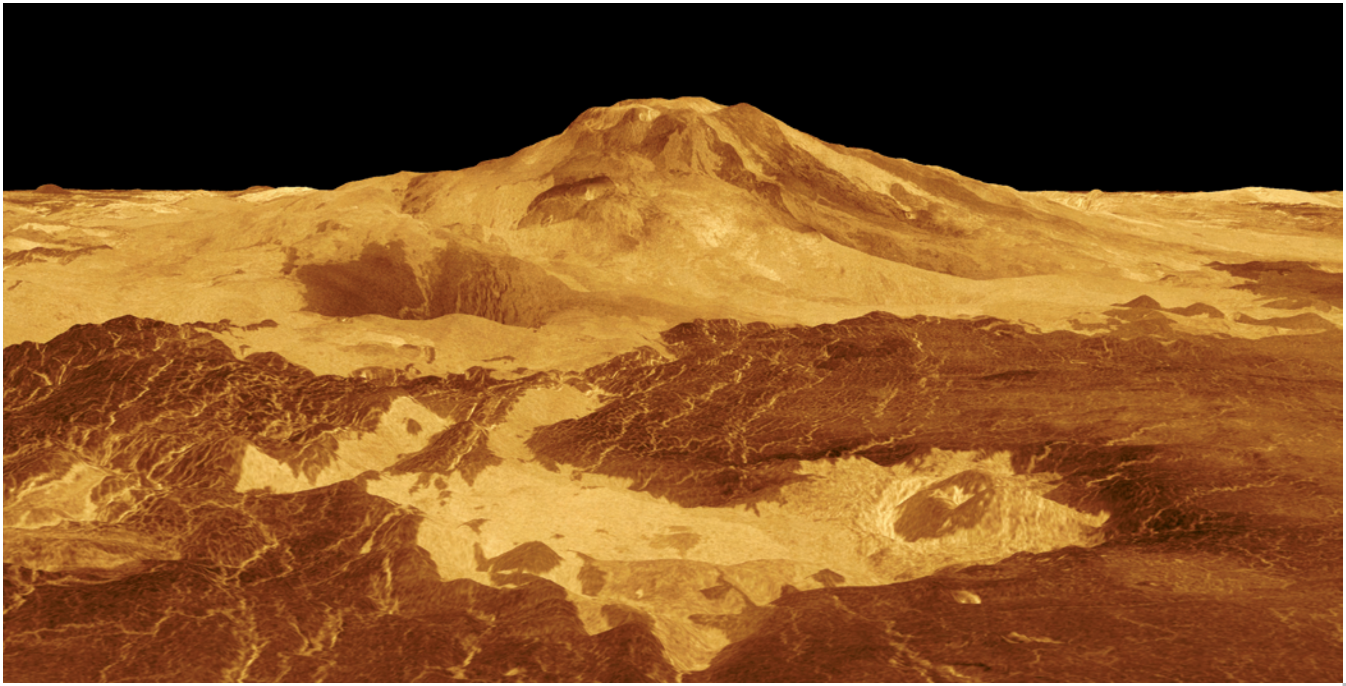
Having hardly changed at all in more than four and a half billion years, the composition of the Venusian atmosphere reflects an early stage of planetary development. It contains 96.5 percent carbon dioxide (CO_2) and no more than 3.5 percent nitrogen (N_2). Other substances that can be found at various 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 greenhouse effect on Venus: although 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. As the example of Venus clearly shows, the long-range consequences for Earth's biomass would be devastating if we had a similarly efficient greenhouse effect.

Picture: Volcanic domes in the Eistla region, 65 kilometers in diameter with broad, flat summit regions less then one kilometer in height. (© NASA/JPL)

Although they are 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 Earth 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 but also to release carbon fixed in underwater deposits from the parent rock 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.

Picture: Perspective view of Maat Mons rising up to almost five kilometers above the surrounding terrain. (© NASA/JPL)



Earth

Earth is the largest and heaviest of the 'inner' planets of the Solar System, which are also called terrestrial or Earthlike because of their similarity to our home planet. The Earth accounts for more than 50 percent of their total mass. Compared to the other Earthlike bodies, developments on Earth have been highly differentiated: in the course of more than four billion years, the Earth produced more mineral and rock variants than any of its planetary neighbors. More importantly, it is unique because it offers all those physical and chemical prerequisites that are needed to ensure the long-term existence of diverse highly-organized life forms that are capable of development.

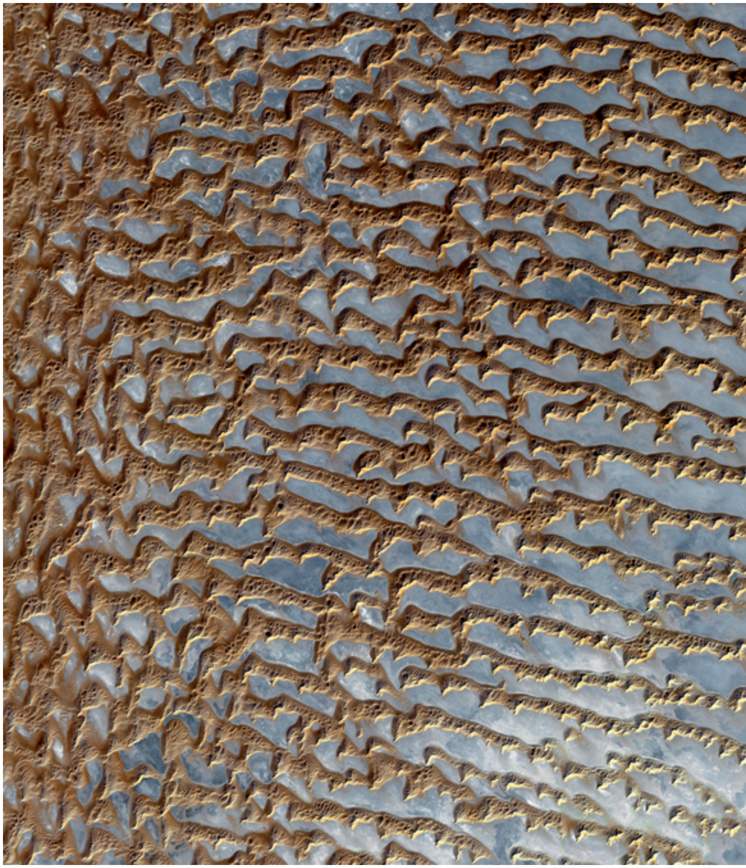
The Earth orbits the Sun in 365.24 days at an average distance of 149.6 million kilometers – the 'astronomical unit' – and a mean velocity of 29.8 kilometers per second. The plane of the Earth's orbit is called the ecliptic. The inclination of the Earth's axis away from the vertical on the ecliptic is the reason why we have seasons. The 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 surrounded by a mantle that is well above 3,000 kilometers thick. It is the liquid part of the core that causes 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 centigrade and a pressure of several million bars prevail. 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 'float' isostatically on these plates like icebergs in the sea.

From his studies of continental coastlines, crystalline sediments and rare fossils, Alfred Wegener (1880-1930) concluded that continents move in certain

Facts

Mass	*5.976 x 10^{24} kg*
Average radius	*6,378.1 km*
Density	*5.515 g/cm^3*
Rotation period	*23.93 h*
Orbital period	*365.24 days*
Mean distance from the Sun	*1.496 x 10^8 km*



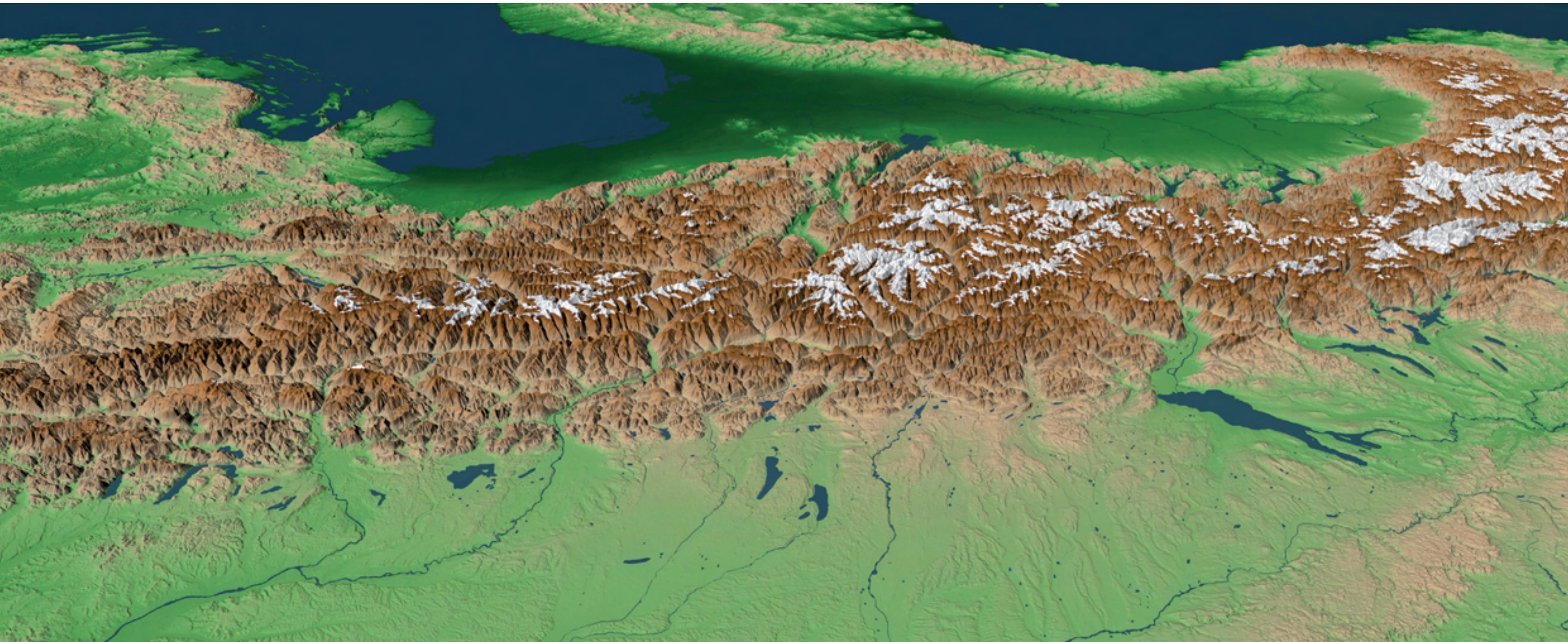
Picture: Desert Rub' al Khali, Arabian Peninsula, one of the largest sand deserts on Earth. (© NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team)

Picture left page: Global view of the Earth with Central America, taken by Apollo 16 on its way to the Moon. (© NASA) 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 glide on it elastically, powered by convection currents in the upper mantle. Where crustal plates drift apart, rifts – most of them submarine – open up in which magma rises (e.g. along the mid-Atlantic ridge); where they move together or drift past one another, so-called subduction zones form along which the rock of the crust dives into the Earth's interior, as it does in the Mariana trench. When two continents collide head-on, high mountain ranges may fold up (e.g. the Alps). Thus, the Earth's crust changes and renews itself incessantly, which is why the major part of it is now less than 100 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 helpless in the face of erosion by wind and water.

Nearly 71 percent of the Earth's surface is covered by oceans. These masses of water are able to store large volumes of (heat) energy which they release again to the air and the land after a certain delay. Not only wind but also water contributes greatly to the erosion of the surface. In its earlier age, the face of the Earth was shaped by meteorite bombardments which then were several orders of magnitude heavier than they are today. For some time now, a debate has been going on about whether a large proportion of the water masses in the oceans might have been provided by comets striking the Earth. Another force capable of reshaping terrestrial landscapes faster than fauna and flora can follow would be the greenhouse effect if it were enhanced by a further increase in the water vapor and CO_2 content in the atmosphere. In this case, remote sensing from space can provide valuable data from which climate trends and long-range forecasts may be derived.

Earth is massive enough to retain an atmosphere permanently. At present, Earth's 'lower' atmosphere (the troposphere) consists of 78 percent nitrogen (N_2), 21 percent oxygen (O_2) and

Picture: Perspective view of the Alps and their foothills, which were upfolded by the African continent. (© DLR)



one percent 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 10 kilometers, the troposphere is the zone in which our weather is made. Above the troposphere we have the stratosphere (up to 50 kilometers), the mesosphere (up to 80 kilometers) and the thermosphere which, comprising the ionosphere and the suprasphere, reaches approx. 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, it is being attenuated by harmful anthropogenic influences, especially above the cold polar zones.

Picture: Sunset over the Pacific Ocean, taken from the International Space Station. (© NASA)

The Moon

The Moon is the smallest among the Earthlike or terrestrial bodies of the inner Solar System. Its surface can be subdivided into two distinct zones: more than 80 percent is highland and somewhat less than 20 percent consists of so-called maria. Having a high albedo, the highland reflects a greater proportion of the incoming sunlight than the dark surfaces of the maria whose albedo is markedly lower. Moreover, the highlands are dotted with a much greater number of impact craters, prompting the conclusion that these surface units are of greater age.

Maria are to be found mainly on the Earth-facing side of the Moon. Younger than the highlands, they are the indirect result of the impact of giant meteorites whose craters were later filled by volcanic rock. That the number of large impact basins filled with basaltic lava is greater on the front than on the back of the Moon is due to the fact that the Moon's crust is much thicker on the side that faces away from Earth, making it difficult for magma to emerge from the mantle.

Geological developments on the Moon ceased at a relatively early date. The satellite was probably born when a planetary body about the size of Mars collided with the Earth about 4.4 to 4.5 billion years ago at a time when the Earth was still young but already differentiated into crust, mantle and core. Under the influence of gravity, the masses that were blown into space by the impact gathered around the Earth in a disk of dust and rock particles from which the Moon formed by condensation. On the new satellite of Earth, an early crust consisting of anorthositic, i.e.

Facts

Mass	*7.3483 x 10^{22} kg*
Radius	*1,737.4 km*
Density	*3.341 g/cm^3*
Rotation period	*27.32 days*
Orbital period	*27.32 days*
Mean distance from Earth	*384,000 km*

Picture: Panorama of the Apollo 17 landing site with astronaut Harrison „Jack“ Schmitt during examination of „Tracy's Rock“. (© NASA/JSC)

feldspar-rich silicate soon developed on a still-molten ocean of magma which subsequently differentiated, forming a mantle and possibly even a metallic core.

In the period that followed, the face of the Moon was scarred by frequent and very severe meteorite and asteroid impacts. The heaviest of these impacts penetrated the crust deeply enough to allow basaltic (i.e. iron and magnesium-rich silicatic) lavas to rise to the surface. Within a few hundred million years, giant impact craters filled with basalt which appears darker than the highland rocks because it is poorer in silicate. Observers on Earth thought that the dark areas were in fact water-filled seas, which explains why we are still designating impact basins as 'seas' (maria in Latin), such as the Mare Imbrium, the Mare Serenitatis and the Oceanus Procellarum.

To all intents and purposes, this development ended about three billion years ago, and magma reached the surface of the Moon only sporadically afterwards. Since then, the Moon has

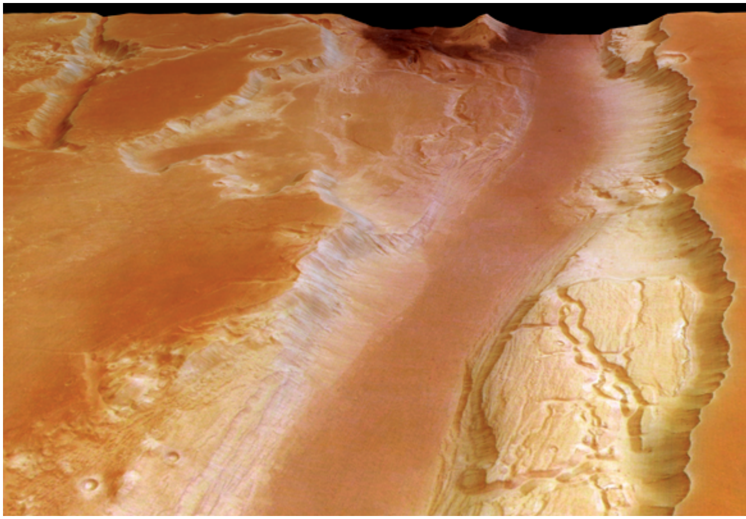
Picture: View of the Moon with numerous craters, taken by Apollo 8; in the foreground Goclenius crater with 72 kilometers in diameter named after the German Physician Rudolf Gockel. (© NASA)

been almost entirely inactive geologically, unable to retain an atmosphere of volatile gas molecules because of its low gravity and devoid of water in any major quantity. However, data transmitted by the Lunar Prospector probe that circled the Moon from 1997 to 1999 led scientists to suspect that not-inconsiderable quantities of water ice, probably of cometary origin, might be hidden in the ground at the bottom of deep, permanently shaded craters at the north and south poles.

To this day, the Moon remains the only terrestrial body that was investigated not only by a multitude of probes but also by human beings. Between 1969 and 1972, the Apollo missions brought twelve astronauts to the Moon who carried some 382 kilograms of diverse rock samples back with them to Earth. Thanks to their generally great age (more than three billion years) and a highly detailed investigation of their chemistry, the Moon samples permit us to look back into the early age of the Solar System and the evolutionary history of the Earth-Moon System. They contribute greatly towards improving our understanding of the evolution of the Solar System.

Recently, the Moon has once again become one of the most important objects of planetary research. Studying the structures of the Moon's surface and its interior may help us solve the riddle of our satellite's origin. This, in turn, would enable us to verify the history of the Earth-Moon system and answer many open questions about the early age of the Solar System and the development of planets. At the same time, it would provide a basis for improving our understanding of the Earth when it was young and its later development. The Moon may have played a crucial part in the evolution of life on Earth because its gravity has been stabilizing the Earth's axis for billions of years. Even a return of astronauts to the Moon is being debated and might be implemented about 2020.

Picture: View of the North Pole and the near side of the Moon, approximately in natural colors, taken by Galileo. (© NASA/JPL/USGS)



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 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.

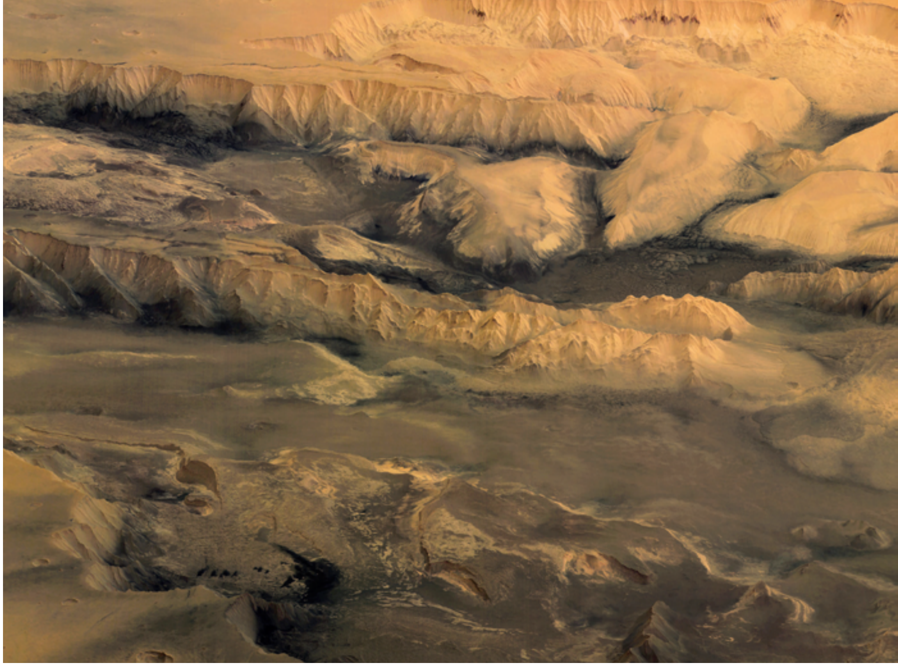
Observations of Mars may be traced back to the advanced civilizations of antiquity. It was probably because of its reddish blood-like color that the planet was given the name of the god of war, Ares or Mars. Early in the 17th century Johannes Kepler formulated his three laws, which describe the movements of the planets, on the basis of Mars position measurements made by the Danish astronomer Tycho Brahe which, although few in number, were highly precise for their time. Whenever Mars was in opposition in the last few centuries, 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. In 1877, Schiaparelli fell for an optical illusion when he thought he saw trenches and grooves on Mars which he called 'canali'. 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 optical illusion for what it was, they led many to believe in an intelligent civilization on our planetary neighbor. Six probes have landed on the planet by now, and although their analyses rule out any form of life on Mars so far, the planet remains the most important destination for international astronautics in its search for existing or extinct life on another celestial body of the Solar System.

Facts

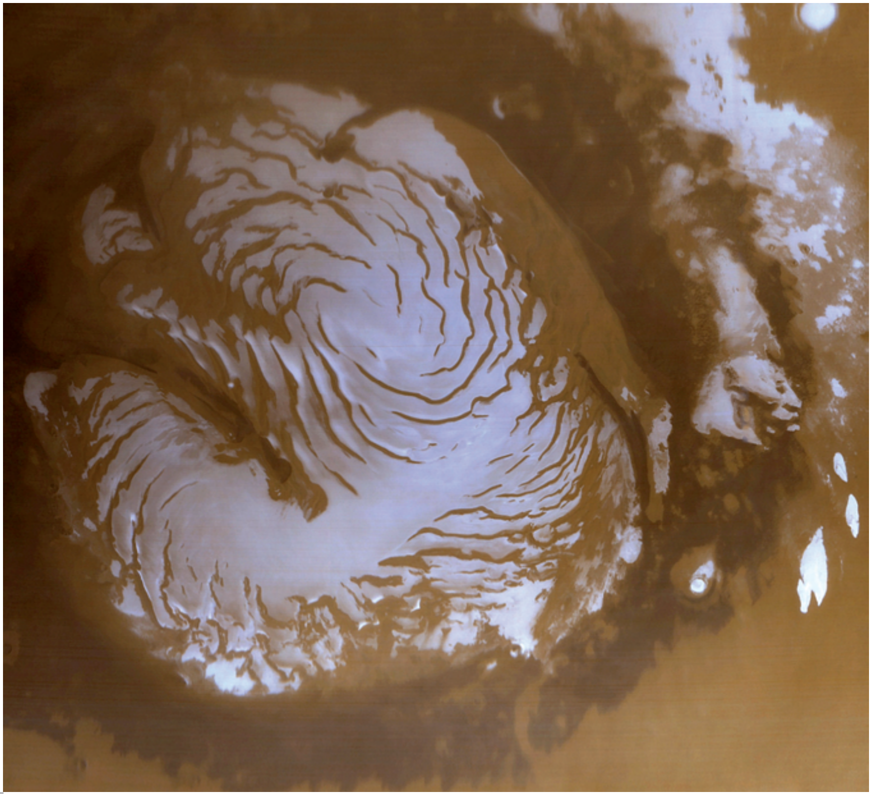
Mars	*Mass*	*6.4185 x 10^{23} kg*
	Radius	*3,397 km*
	Density	*3.94 g/cm^3*
	Rotation period	*24.62 h*
	Orbital period	*687 days*
	Mean distance from the Sun	*227.9 x 10^6 km*
Phobos	*Mass*	*1.063 x 10^{16} kg*
	Size	*26.8 x 22.4 x 18.4 km*
	Density	*2.0 g/cm^3*
	Orbital period	*0.3189 days*
	Mean distance from Mars center	*9.378 x 10^3 km*
Deimos	*Mass*	*2.38 x 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 x 10^3 km*

Thanks to Mariner 9, Viking 1/2 and, most of all, to recent orbital missions like Mars Express, Mars Global Surveyor 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 a highland area in the south that features numerous impact craters. Together with its three smaller neighbors Arsia Mons, Ascraeus

Picture: Perspective view of the southern branch of the Kasei Valles and Sacra Mensa, based on data from Mars Express. (© ESA/DLR/FU Berlin, G. Neukum)



Mons and Pavonis Mons, Olympus Mons, a shield volcano measuring 24 kilometers in height and 600 kilometers in diameter, forms a highly conspicuous landmark close to the equator, on top of a large rise, 4,000 km in diameter – the Tharsis region. Another outstanding feature is the enormous canyon system of Valles Marineris which is 5,000 kilometers long and up to 200 kilometers wide. The deepest trenches are up to 11 kilometers deep. In the catchment area of the Valles system, a landscape featuring numerous dried-up riverbeds and minor canyons stands out, indicating that water or the ice of glaciers might have been active on Mars in earlier times. Finally, the southern hemisphere harbors two impact craters, Hellas and Argyre. Depending on the seasons, the poles are covered by a thick layer of water and carbon dioxide ice, respectively. Close to the equator, daytime temperatures may rise to +30 degrees centigrade in summer, whereas nighttime temperatures at the poles may drop as low as -140 degrees centigrade in winter. On the equator, the average daytime temperature ranges below the freezing point.

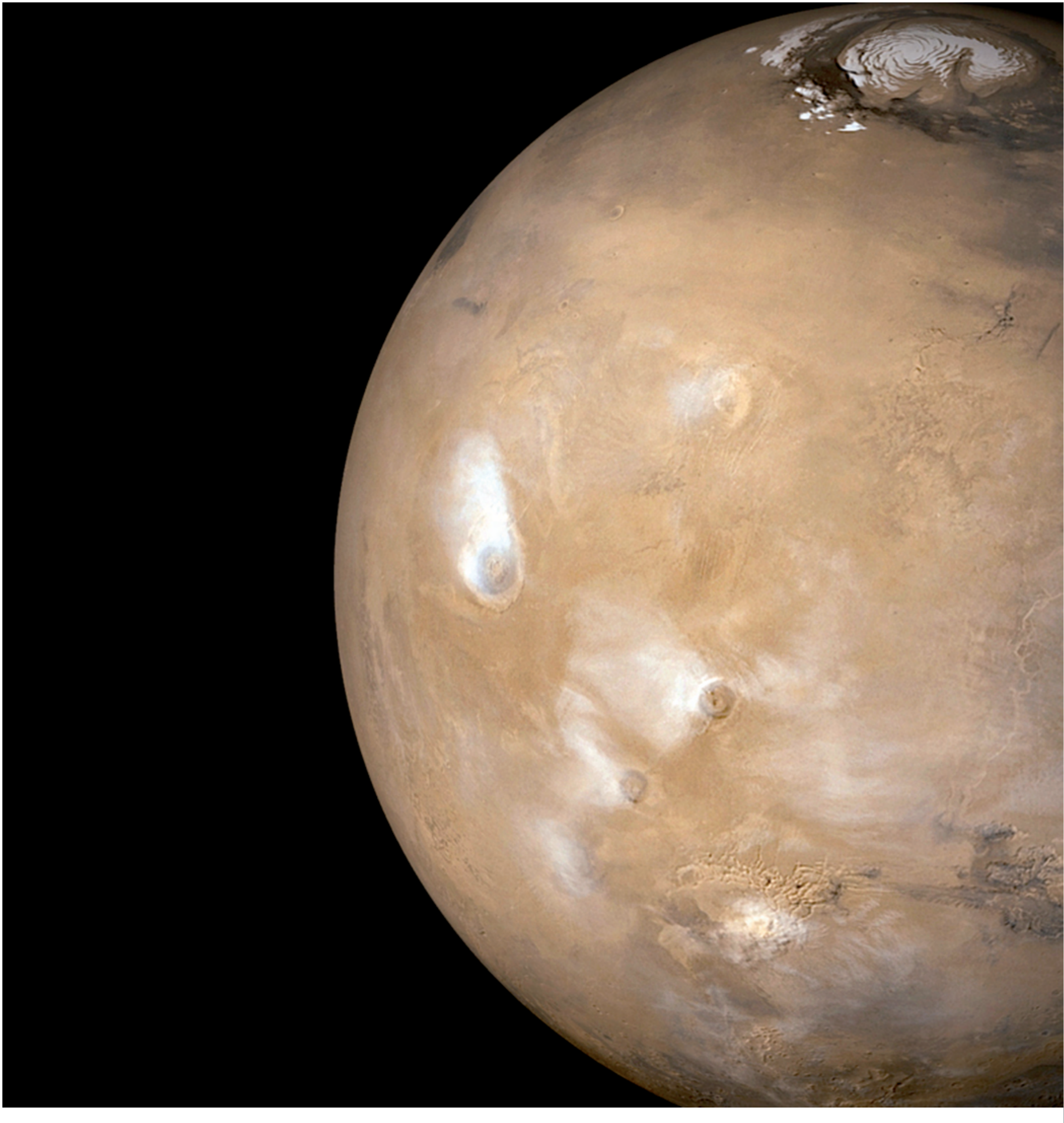


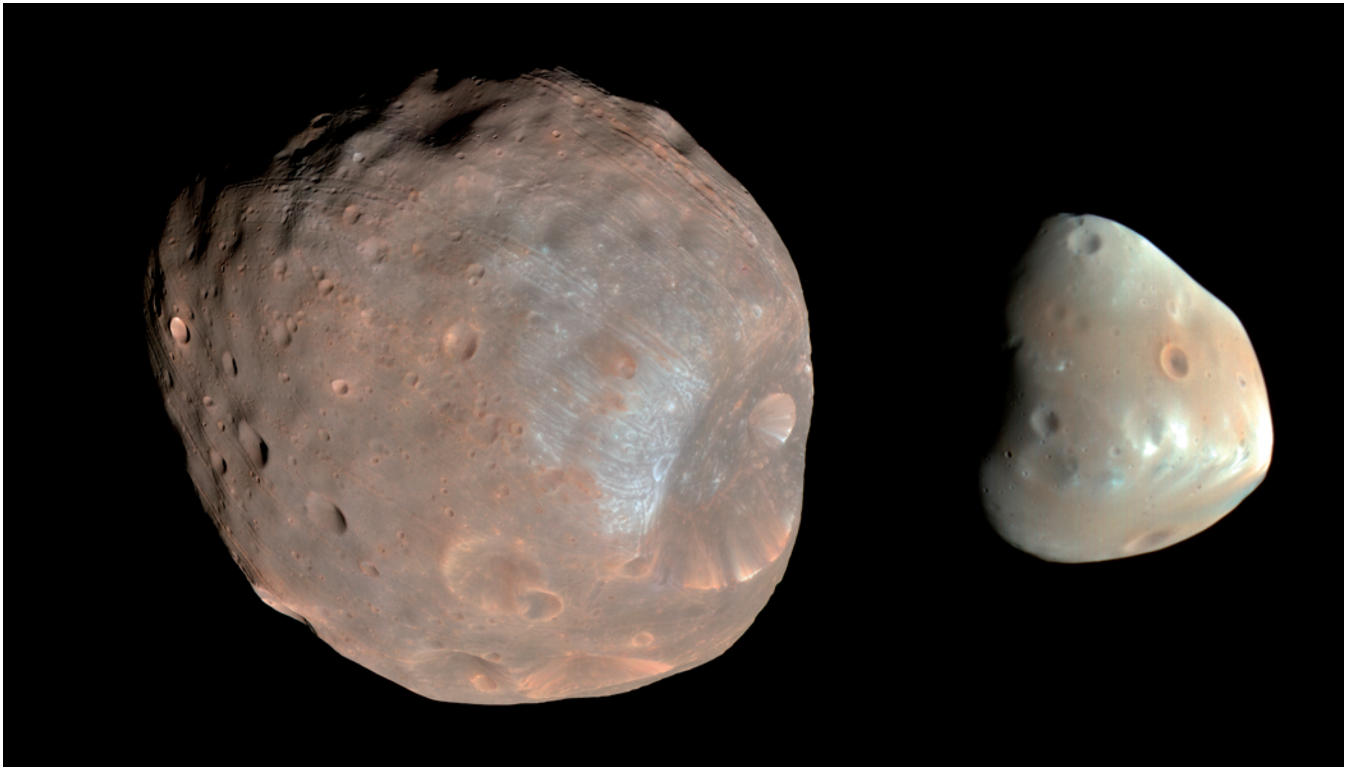
Like that of Venus, the atmosphere of Mars consists predominantly (95 percent) of carbon dioxide (CO_2), but the pressure on the surface amounts to no more than six millibar (1,013 millibar on Earth). In the Martian atmosphere, clouds of water vapor may form and tremendous storms may develop in certain seasons. Carrying sand and dust up to a height of 50 kilometers, they distribute the material over the entire planet, causing the

Picture top: View over the central part of the Valles Marineris. (© ESA/DLR/FU Berlin, G. Neukum)

Picture bottom: North polar cap in summer, taken by Mars Global Surveyor. (© NASA/JPL/MSSS)

Picture right page: Dust storm in Syria Planum south of Labyrinthus Noctis and the great volcano Olympus Mons in the center with the smaller Tharsis volcanoes on the right side. (© NASA/JPL/MSSS)





sky to take on a yellowish-brown hue and creating clearly visible dune fields. While most dust storms are regionally limited, they may grow to global dimensions every five or ten years.

The moons of Mars

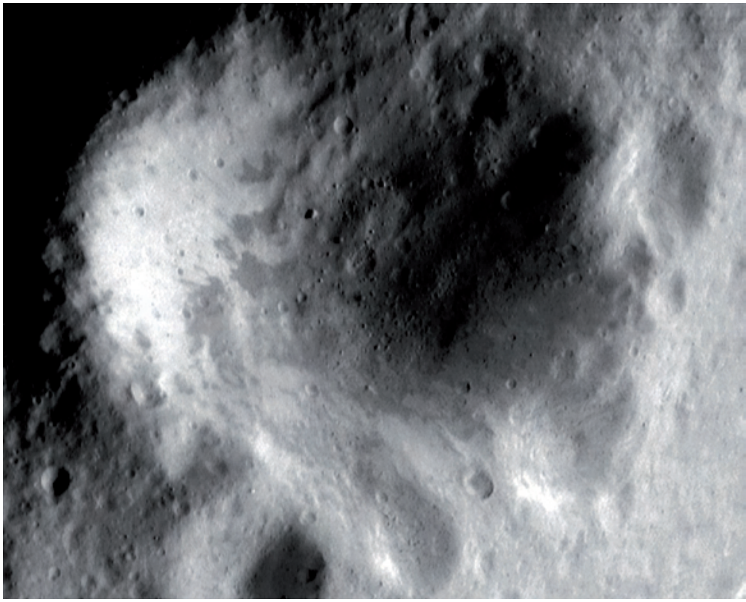
Discovered in 1877 by Asaph Hall, the two Martian moons, Phobos and Deimos, share certain characteristics. Both have a highly irregular shape and a very dark surface that reflects only about 5 percent of the sunlight. Phobos features impact craters of which Stickney and Hall are the largest, measuring twelve and five kilometers, respectively.

It is not clear how the two Martian moons originated. It may well be that Phobos and Deimos did not originally develop 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 of 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 minute 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 turn into a short-lived ring around Mars, or else it might crash on the planet. The Russian probe Phobos Grunt, which is scheduled for launching late in 2009, will land on the Martian moon and examine it in detail.

Picture: Martian moons Phobos (left) and Deimos (right). © NASA/JPL-Caltech/University of Arizona)

The Asteroids



Situated between the orbits of Mars and Jupiter, the asteroid belt contains nearly half a million registered asteroids, also known as minor planets. Their distribution around the belt is mainly controlled by the gravitational influence of the giant planet Jupiter. There are zones within the belt that are almost entirely devoid of asteroids and others in which they appear en masse. It is conceivable that the two small Martian moons, Phobos and Deimos, may once have been part of the belt; at some time or other, they approached too close to Mars and were entrapped by it. All in all, about 7,000 asteroids have been named; in actual fact, the total number of asteroids measuring more than one kilometer in diameter is probably greater by more than one order of magnitude. Some asteroids travel on highly eccentric orbits that cross those of Mars, Earth and even Mercury – the Aten, Apollo and Amor asteroids. The 7,000 Near-Earth Asteroids (NEOs) that are known today have recently become objects of closer study, the objective being to determine long in advance the probability of a collision with Earth and its consequences.

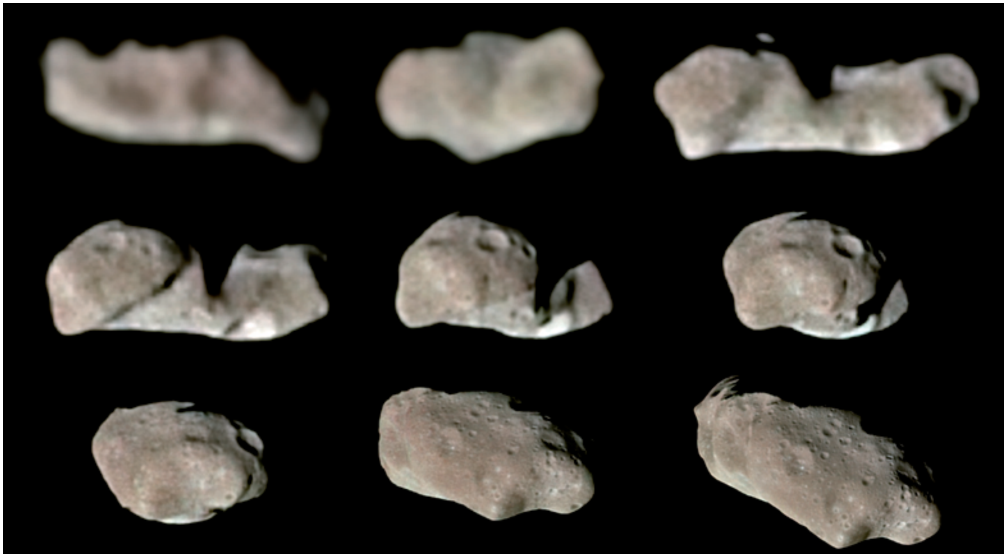
In the last century, occasionally violent controversies arose about which 'higher' philological principle should form the basis on which newly-discovered minor planets should be named. At the same time, the names given to minor planets show something of the human foibles and relations of their discoverers, and thus it is that the name of many an astronomer's wife, daughter, lover and even pet is now emblazoned in the sky.

The first asteroid was discovered on the eve of the new year 1801 by Giuseppe Piazzi (1746-1826), then the 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 restless star turned out to be a small planet which Piazzi named after the goddess of vegetation and patron saint of Sicily, Ceres. Moreover, Ceres closed a gap which, according to the so-called Titius-Bode law, existed between Mars and Jupiter where nobody had found a planet as yet. At all events, Piazzi was lucky enough to find, right off the bat, a minor planet which, with its diameter of about 1,000 kilometers, remains undisputedly the largest to this day. Today, Ceres is rated as a dwarf planet. Most asteroids measure between 20 and 100 kilometers in diameter.

In the last few years, several asteroids have been inspected on the spot by space probes. In 1991 and 1993, the space probe Galileo flew close by the two asteroids Gaspra and Ida on its

The Titius-Bode law is a simple mathematical rule, from which the distances of the planets to the Sun can be derived quite exactly – and from this rule a 'missing' planet in the region between Mars and Jupiter can be postulated. This rule was established from Johann Daniel Titius (1729-1796) and Johann Elert Bode (1747-1826) at the end of the 18th century. A similar simple series (Venus: no moon, Earth: one moon, Mars: two moons, Jupiter: four moons) led to the mention of two Martian moons in the book 'Gulliver's Travels' by Jonathan Swift already 100 years before the discovery of the Martian moons by Asaph Hall (1829-1907). The Titius-Bode law is not generally valid.

Picture: Asteroid Eros, view of Psycho Crater, with a diameter of 5.3 kilometers the largest crater on Eros. (© NASA/JHUAPL) way to Jupiter. While examining their surface from various angles, it discovered that 60-kilometer-long Ida had a satellite somewhat more than one kilometer in size, which was named Dactyl. The find confirmed something that had already been known from photometric light curves: asteroids are rotating lumps of rock, irregular in shape and pockmarked by craters, and they may even have very small moons.



Late in June 1997, the American space probe NEAR visited the asteroid Mathilde on its way to the minor planet Eros (No. 433) which it orbited for a year from February 2000 onwards. On 23 January 2000, the Saturnian probe Cassini on its flight through the asteroid belt took some photographs from a distance of about 2 million kilometers on which the asteroid Masursky, named after the lunar researcher and planetologist Harald Masursky (1923-1990) shows up as a small dot. Thus, the asteroids Gaspra, Ida, Mathilde and Eros are the only bodies in the asteroid belt of which we have high-resolution images. Moreover, radar and telescope images of some minor near-Earth planets like Toutatis and Geographos show surface structures in rough outline.

Studying the small bodies is important because many of them reflect the earliest stages in the evolutionary history of our Solar System, and because analyses of their surface, morphology and composition might tell us more about its early age

These are the reasons why the space probe Dawn was developed, which has been on the way to the asteroid belt since 2007. Propelled by an ion drive, this NASA discovery mission will reach the asteroid Vesta in August 2011. It will then enter into an orbit around the asteroid which, with its diameter of about 500 kilometers, ranks third in size and second in weight. Having completed its experiments, the probe will move on to the dwarf planet Ceres in April 2012. Dawn will be the first mission in the history of astronautics to orbit two different celestial bodies. The camera on board Dawn was developed by DLR and the Max Planck Society.

Picture: Nine different views of asteroid Ida in natural colors, taken during approach of the Galileo probe to the asteroid. (© NASA/JPL)

Picture right page: The asteroids Eros, Mathilde, Ida, and Gaspra (from left to right) are the only ones ever visited by spacecrafts. (© Individual images: NASA/JPL/JHUAPL and NASA/JPL/USGS, Montage: DLR)

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 become a sun itself. 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 since Galileo's time and the movements of the four Galilean moons that are named after their discoverer.

Jupiter takes somewhat less than twelve years to orbit the Sun, traveling at an average speed of 13 kilometers per second. Through its enormous mass, the giant planet influences the paths of all the other bodies in the Solar System. Thus, for example, Jupiter's gravitational influence causes gaps in the asteroid belt, diverts comets from their original flight path and even captures some of them, and interferes with the orbits of the other planets – an effect that must always be figured in when orbits are calculated for prolonged periods. Furthermore, we use its powerful gravitational field to accelerate space probes and change their course noticeably (Voyager, Ulysses, Cassini-Huygens). Jupiter's radius (R_J) measures 71,500 kilometers, and its rotation period falls just short of ten hours. Together with Jupiter's low mean density of 1.33 g/cm^3, this high speed is the reason why Jupiter is visibly flatter at the poles.

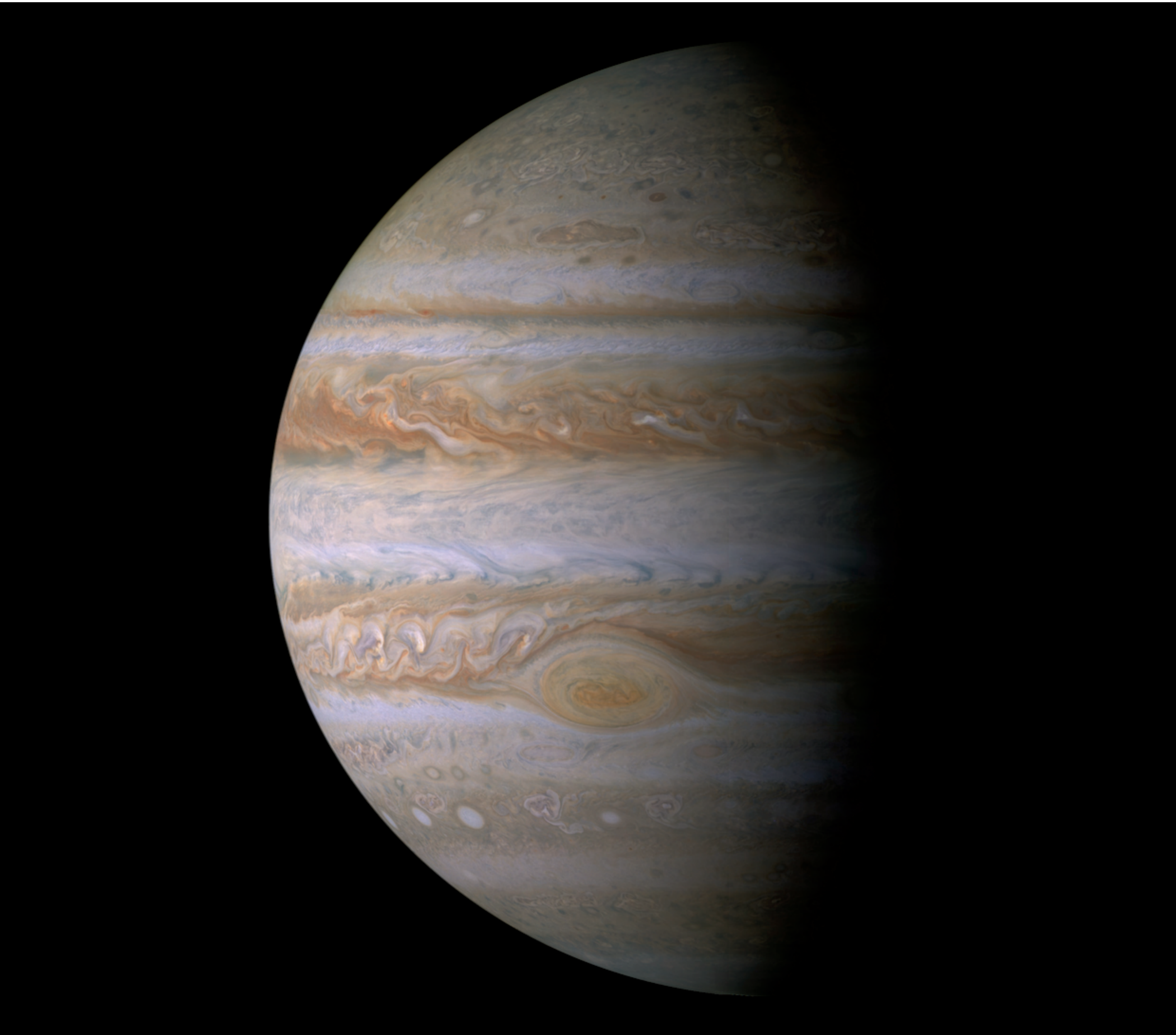
Facts

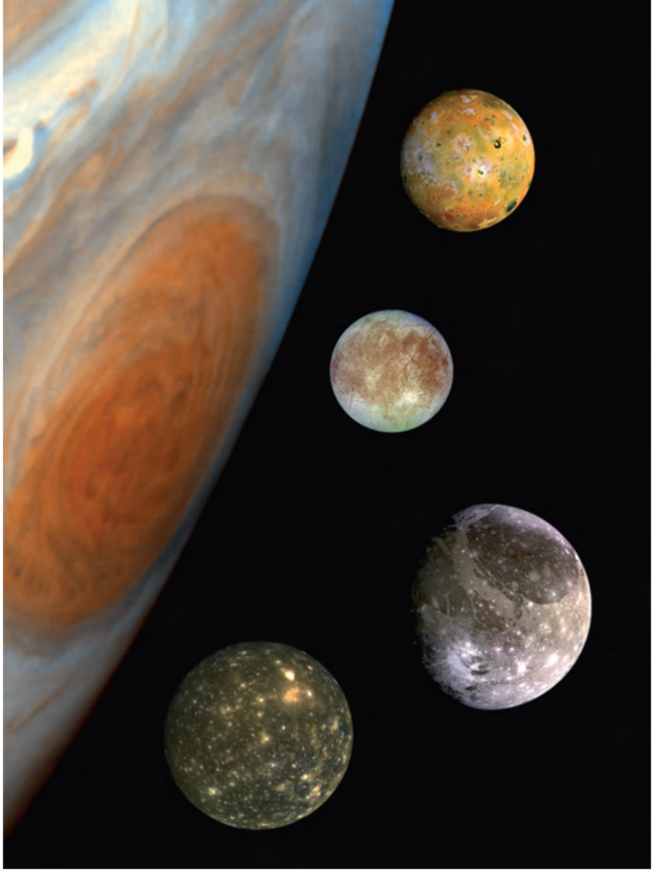
Jupiter	*Mass*	*1.8987 x 10^{27} kg*
	Radius (equatorial)	*71,492 km*
	Radius (polar)	*66,854 km*
	Density	*1.33 g/cm^3*
	Rotation period	*9.925 h*
	Orbital period	*11.86 years*
	Mean distance from the Sun	*778.4 x 10^6 km*
Io	*Mass*	*8.93 x 10^{22} kg*
	Mean radius	*1,821 km*
	Density	*3.55 g/cm^3*
	Orbital period	*1.769 days*
	Mean distance from Jupiter	*422,000 km*
Europa	*Mass*	*4.79 x 10^{22} kg*
	Radius	*1,562 km*
	Density	*3.01 g/cm^3*
	Orbital period	*3.551 days*
	Mean distance from Jupiter	*671,000 km*

Wind velocities at the equator rise to 150 meters per second (540 km/h). The conspicuous Great Red Spot (GRS) is thought to be an isolated giant cyclone that moves slower than the other atmospheric structures in the vicinity. Moving inside from its uppermost layers, the dense atmosphere consists mainly of hydrogen (H_2), ammonia (NH_3) ice crystals, ammonium hydrogen sulphide (NH_4HS), and water (H_2O) ice and droplets. Models predict that at a depth of 1.0 to 0.75 R_J the planet consists of a molecular mix of hydrogen and helium which becomes metallic because of the high pressure prevailing at 0.2 R_J. It is expected that only the innermost center of the planet (0-0.2 R_J) is occupied by a small compact planetary core ten times the size of Earth.

Questions about the uppermost cloud layers were answered by the probe Galileo which in December 1995 released a probe carrying six scientific experiments, the first to enter the cold atmosphere of one of the outer planets. One important finding was that the helium content of Jupiter's atmosphere is comparable to the incidence of that element in the Sun. Thus, in a manner of speaking, Jupiter is in the same fresh, undissociated 'juvenile' state in which our central star was at a very early stage in the development of the Solar System. At present, Jupiter is known to have 63 moons. It is surrounded by a system of equatorial rings no more than 30 kilometers in thickness which apparently consists of three separate rings.

Picture right page: Jupiter with its Great Dark Spot, a huge storm system. (© NASA/JPL/Space Science Institute)





The moons of Jupiter

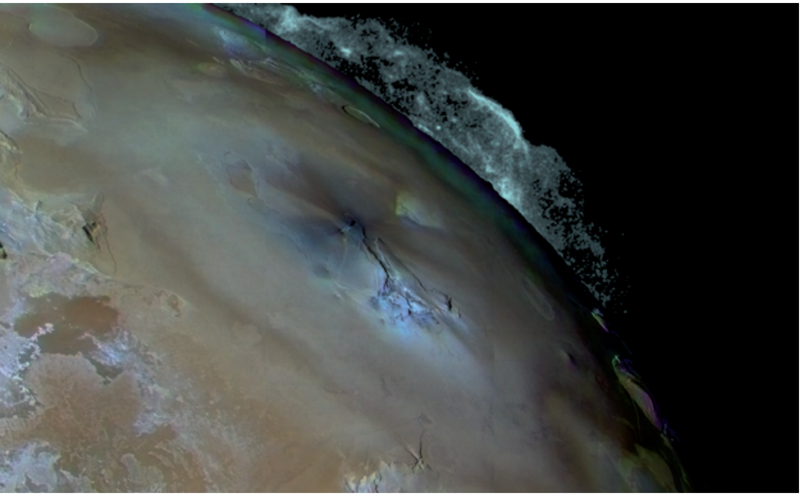
In 1610, Galileo Galilei's discovery of the Galilean moons Io, Europa, Ganymede and Callisto established the existence of satellites that orbit a larger body, confirming the theory that it is not Earth which stands at the center of the universe – or at least of the Solar System as it was then known – and that the Sun forms the center of a planetary system within which the Earth orbits it as one of several planets. Io is the innermost of the Galilean moons. It resembles the Moon both in volume and density. Io orbits Jupiter on a nearly circular path on which it meets Europa at intervals of three and a half days. Together with Jupiter's enormous attraction, this resonance causes tides which, many times more powerful than the influence of the Moon on Earth, generate heat in the interior of Io. This, in turn, causes intense volcanic activity. More than a dozen active volcanoes and more than one hundred volcanic ejection centers were registered during the Voyager flybys and the observations of Galileo. Reaching a height of up to 11,000 meters, Io's mountains are probably also of volcanic origin, as are its stratified structures which are up to 1,700 meters high. Io is a body whose surface is constantly being reshaped by volcanic activity. Erupting volcanoes eject material to a height of several hundred kilometers, from which it distributes itself over large areas on the surface. The movements of the moon caused by Jupiter's magnetic field induce powerful electric currents and ionize large parts of the volcanic ejecta, which are then lost to space.

The second of the Galilean moons, Europa is somewhat smaller than the Moon. The icy surface shows relatively few impact craters. Its upper layers consist mainly of water ice with admixtures of rock and mineral fragments and possibly salts. Europa's surface is dominated by elongated mountain ranges that are visible in nearly all medium and high-resolution images. It is highly probable that an ocean of liquid water up to 200 kilometers deep exists below the icy crust. Whether or not this hypothetical ocean exists was a question of such importance to the scientific community that the Galileo mission was extended specifically to examine Europa. If the existence of this ocean is incontrovertibly established, its volume of liquid water would be the largest to be found on any body of the Solar System. This is why Europa, after Mars, is the most promising destination in our search for potential organism habitats away from Earth.

Viewed from Jupiter, Ganymede is the third of the Galilean moons and also the largest. Measuring 5,262 kilometers in diameter, it is in fact the largest moon in the

Ganymede	*Mass*	*1.48 x 10^{23} kg*
	Radius	*2,632 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	*2,404 km*
	Density	*1.86 g/cm^3*
	Orbital period	*16.69 days*
	Mean distance from Jupiter	*1,883,000 km*

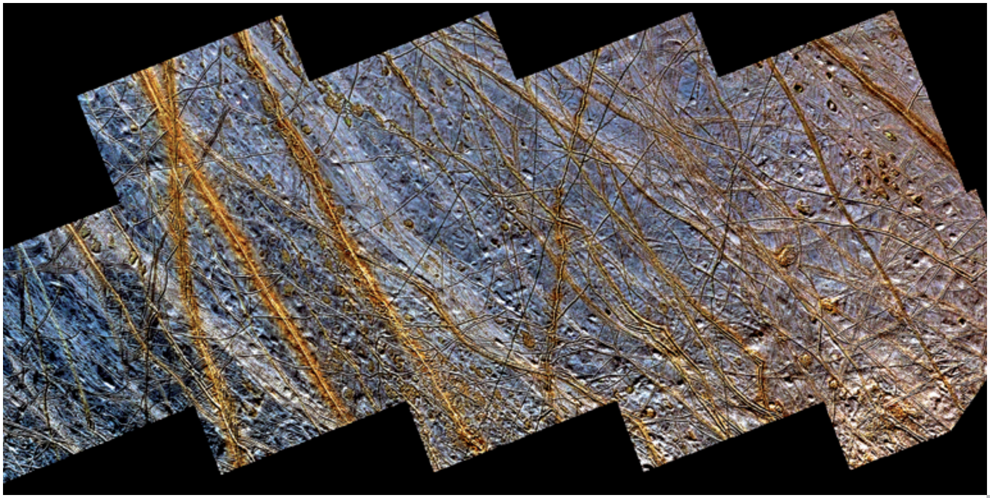
Picture: Galilean moons and Jupiter's Great Red Spot, relative in size. (© NASA/JPL/DLR)



Solar System. Ganymede's density is very low, indicating that it consists of a core of iron or iron sulphide surrounded by a mantle of water ice that accounts for more than half the moon's volume. On the surface, large areas that are old, dark and dotted with craters are intersected by bright furrowed zones that cover about 60 percent of the surface. Ganymede's interior is differentiated into core, mantle and crust, and it has a dipole magnetic field.

Callisto is the outermost of the Galilean moons. Its mean density is the lowest of all. Together with its large diameter, this suggests that Callisto contains large quantities of water ice. Its surface is dotted with craters. In addition, there are at least nine impact formations which are surrounded by a number of concentric rings called palimpsests, originally the designation given to those papyrus manuscripts of antiquity that are covered by several layers of writing. The largest palimpsest, Walhalla, consists of a central, crater-poor section measuring about 600 kilometers in diameter which is surrounded by a system of concentric rings that reach out to a distance of 1,500 kilometers. High-resolution images show a powdery layer which appears to have blanketed the smaller craters and seems to be younger than most of them. Its origin is completely in the dark. Like Ganymede, Callisto is geologically inactive today. However, measurements of its magnetic field performed by the Galileo space probe may be interpreted as indicating the existence of an – albeit shallow – ocean beneath Callisto's icy crust.

In addition to the four Galilean moons, the Jovian systems includes Metis, Adrastea, Amalthea, Thebe, Leda, Himalia, Lysithea, Elara, Ananke, Carme, Pasiphae and Sinope as well as 47 other, smaller moons, some of which were only discovered in the last few years.



Picture top: Eruption of Pele volcano on Io. The eruption plume reaches up to 300 kilometers in height. (© NASA/JPL/USGS)

Picture bottom: Typical surface structures on Europa: double ridges, dark spots and smooth icy plains. (© NASA/JPL/USGS)

Saturn

Having a radius of about 60,000 kilometers, Saturn is the second largest planet in our Solar System. It is also the remotest planet that can be seen with the naked eye. Until 1781 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 night sky. This close constellation is occasionally quoted as a plausible explanation 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 0.70 g/cm^3. The gravity that prevails at the upper edge of the cloud cover is only a little less than on Earth. Saturn rotates very quickly (in around ten hours) and has the lowest mean density of all the known planets. The consequence of this is a marked polar flattening of 1:10 that can be observed even in a low-powered telescope.

Wind velocities in the equatorial zone may reach 500 meters per second (1,800 km/h). Since 1876, a cyclone has been observed in Saturn's northern hemisphere which regularly appears at intervals of some 30 years. Named the Great White Spot in the technical literature, it suggests that the planet may have seasons. Like Jupiter, Saturn radiates more heat than it receives from the Sun.

According to the classical subdivision, Saturn's ring system comprises seven groups designated as D, C, B, A, F, G and E as their distance from the planet increases. From the flybys of the Voyager probes in 1980/81 we know that Saturn's equatorial plane, which is inclined by almost 27 degrees to the ecliptic, is really occupied by more than 1,000 individual rings whose origin, shape, dynamics and composition need to be studied further. It may be that there was once a moon in the space that is now occupied by the rings. This moon was probably struck and broken up by an asteroid. The remaining rock fragments were then ground into dust by successive asteroid impacts and mutual collisions. Spreading out over several orbits, the resultant par-

Facts

Saturn	*Mass*	*5.688 x 10^{26} kg*
	Radius (equatorial)	*60,268 km*
	Radius (polar)	*54,364 km*
	Density	*0.70 g/cm^3*
	Rotation period	*10.233 h*
	Orbital period	*29.4 years*
	Mean distance from the Sun	*1.429 x 10^9 km*
Mimas	*Mass*	*3.8 x 10^{19} kg*
	Mean radius	*196 km*
	Density	*1.17 g/cm^3*
	Orbital period	*0.942 days*
	Mean distance from Saturn	*185,520 km*
Enceladus	*Mass*	*8.4 x 10^{19} kg*
	Mean radius	*247 km*
	Density	*1.24 g/cm^3*
	Orbital period	*1.370 days*
	Mean distance from Saturn	*238,020 km*
Tethys	*Mass*	*7.55 x 10^{20} kg*
	Mean radius	*523 km*
	Density	*1.21 g/cm^3*
	Orbital period	*1.888 days*
	Mean distance from Saturn	*294,660 km*

Picture left page: Global view of Saturn's unilluminated side of the rings in natural colors from high above. (© NASA/JPL/Space Science Institute) ticles formed today's ring system. This destructive process still goes on today, but the incessant collisions also produce new small moons, so that a dynamic cycle of growth and decay is operating in the rings. Some of them have so-called 'shepherd moons' which keep their constituent elements on track. From ring to ring, particles vary between the size of a grain of dust and the size of a house; some rings mainly consist of solid elements, whereas others contain a greater proportion of volatile gas and ice particles. For the outermost ring, E, evidence has been accumulating that it is fed by ice particles ejected from the volcanically active zones of the neighboring moon Enceladus.

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 probably less than one kilometer thick, for when it appears edge-on it vanishes even when viewed through the largest terrestrial telescopes. The last occasion to observe the 'ringless' planet was in August 2009 when Earth crosses Saturn's ring plane from south to north.

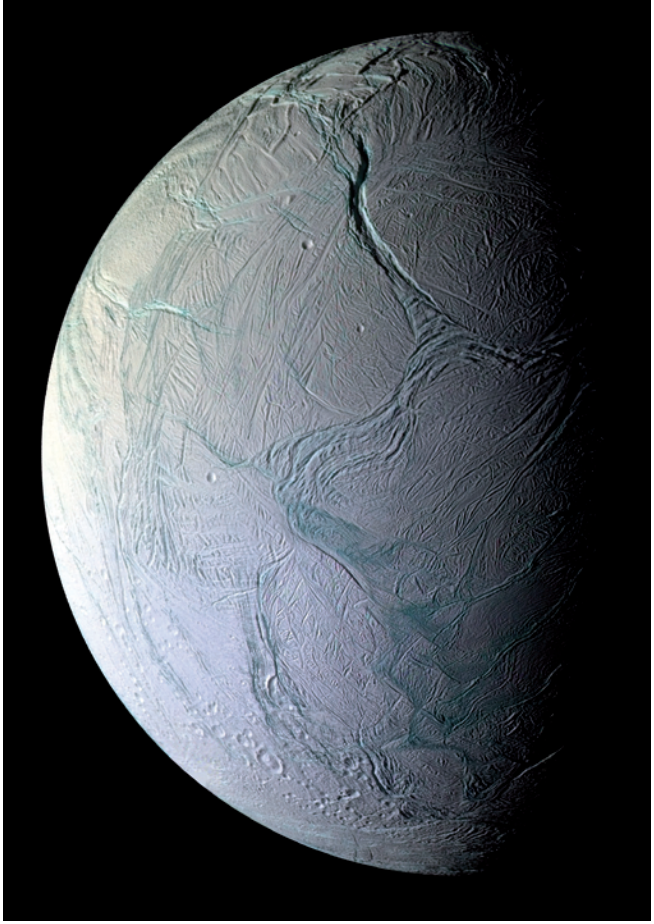
The moons of Saturn

Saturn is surrounded by 18 moons that have been known for some time: Pan, Atlas, Prometheus, Pandora, Epimetheus, Janus, Mimas, Enceladus, Tethys, Telesto, Calypso, Dione, Helene, Rhea, Titan, Hyperion, Iapetus and Phoebe. Another 42 smaller moons have been discovered so far, either by Cassini or by observers on Earth using a telescope.

Dione	*Mass*	*1.05 x 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 x 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 x 10^{23} kg*
	Radius	*2,575 km*
	Density	*1.88 g/cm^3*
	Orbital period	*15.9454 days*
	Mean distance from Saturn	*1,221,850 km*
Hyperion	*Mass*	*1.77 x 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 x 10^{21} kg*
	Radius	*730 km*
	Density	*1.21 g/cm^3*
	Orbital period	*79.33 Tage*
	Mean distance from Saturn	*3,561,300 km*

Titan, Saturn's largest moon, is the only satellite in the Solar System that possesses a dense, extensive atmosphere. Its color is reddish-orange. Titan's atmosphere consists mainly of nitrogen augmented by traces of methane, ethane, acetylene, propane, diacetylene, methyl acetylene, hydrogen, cyanide and cyanoacetylene as well as carbon dioxide and monoxide. Titan and Earth are the only bodies in the Solar System whose atmosphere consists mainly of nitrogen. Being opaque, it obscures our view of the surface. Titan was the target of the European lander probe Huygens which was dropped by its parent probe Cassini on 25 December 2004, floated for several hours in Titan's atmosphere on 14 January 2005 and finally landed on the surface of the enigmatic Saturnian moon. The Cassini-Huygens mission discovered lakes of liquid hydrocarbons (methane, ethane) on Titan's surface, where the temperature is -160 degrees centigrade.

The innermost of Saturn's large moons, Mimas, consists mostly of ice. Its surface is extensively scarred by impact craters. The larger ones among them (more than 20 kilometers) have central



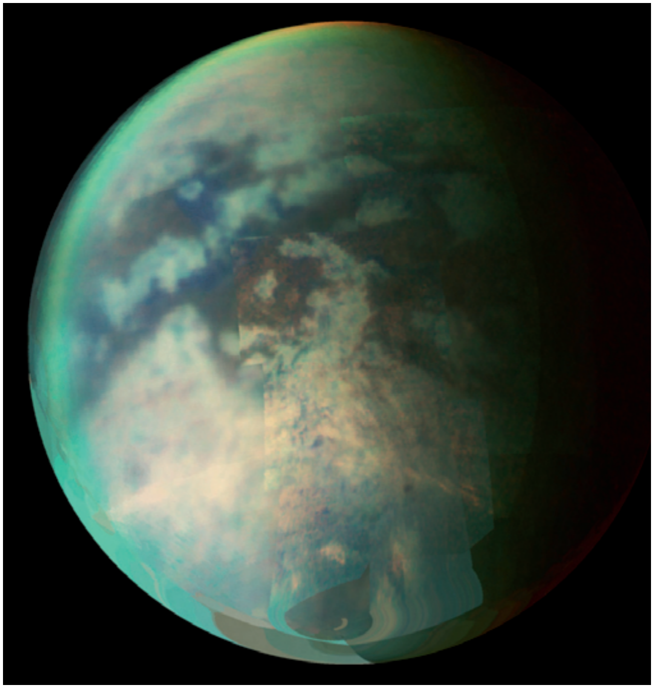
moon Io, this makes Enceladus the third body in the Solar System on which current volcanic activity has been demonstrated beyond doubt.

Measuring 1,500 kilometers in diameter, Rhea, Saturn's second largest moon, is thought to consist mostly of ice. Its two hemispheres differ distinctly: the hemisphere that leads in the direction of the moon's movement around Saturn is covered with craters and brighter than the opposite hemisphere, which shows bright filament-like structures similar to those that can be observed on the Saturnian moon Dione and elsewhere.

With a diameter of 1,436 kilometers, Iapetus is the third largest Saturnian moon after Titan and Rhea. Covered by a reddish black-brown material, the forward-facing hemisphere is darker than either the rear or the poles. This body shows the starkest brightness contrasts in the entire Solar System. The surface of Iapetus is riddled with craters. Its low density suggests that it

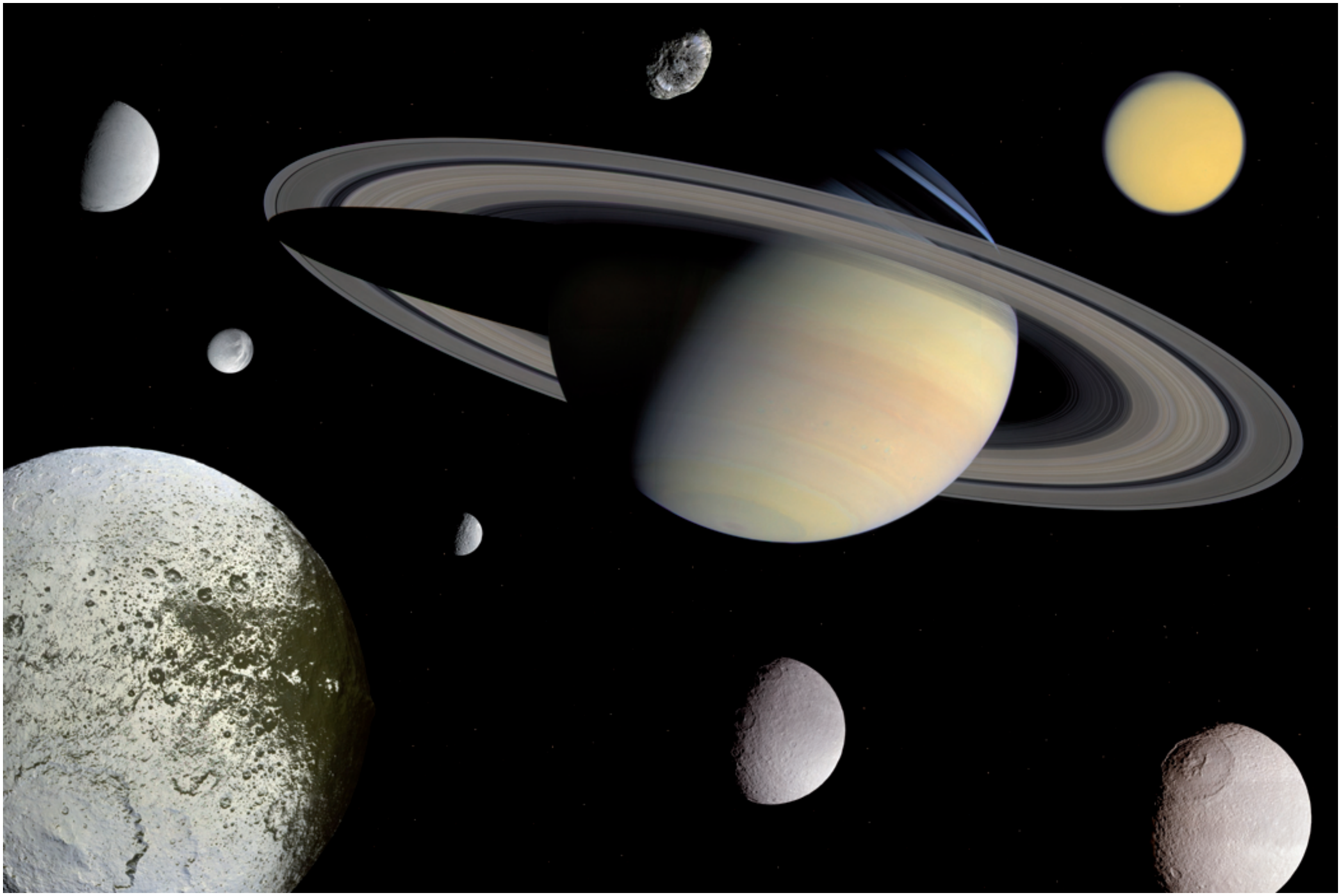
peaks, and the most conspicuous is Herschel Crater with a diameter of about 130 kilometers. It is ten kilometers deep, and its central peak is 6,000 meters high.

Enceladus is next to the innermost of Saturn's large moons. Its surface is highly differentiated, showing landscapes with worn-out old craters, smooth plains with only a few craters, and other plains furrowed by parallel fissures up to one kilometer deep. The Cassini mission discovered active ice volcanism (cryovolcanism) at the south pole of the moon; after Earth and the Jovian



Picture top: Moon Enceladus with the 1,000 meters deep Labtayt Sulci in the upper part of the image in enhanced colors. (© NASA/JPL/Space Science Institute)

Picture bottom: Moon Titan, global view with a likely old impact basin, mosaic of several images in infrared light, taken by Cassini. (© NASA/JPL/Space Science Institute)



consists primarily of ice. Along the equator, the moon is encircled by a ridge of mountains up to 20 kilometers high whose origin has not been understood so far.

Dione, the fourth of Saturn's large moons, has a density of 1.4 g/cm^3 being greater than that of any other Saturnian moon, Titan and Phoebe alone excepted. Its surface is dotted with craters 30 to 40 kilometers in size, and there are some larger craters with diameters greater than 100 kilometers. The most striking formation is Amata, a crater with a diameter of 240 kilometers which sits at the center of a system of fine bright linear structures. The southern hemisphere features wide ridges and a valley close to the south pole that is more than 500 kilometers long.

The moon that is farthest away from Saturn is Phoebe, almost 13 million kilometers out. Its characteristics suggest that Phoebe is not one of Saturn's original satellites but a minor body from the Kuiper-Edgeworth belt beyond Neptune which was forced by Saturn's gravity into an orbit around the ringed planet.

Picture: Saturn and its large moons, not relative in size. (© Individual images: NASA/JPL/Space Science Institute, montage: DLR)

Uranus

In 1781, William Herschel discovered the seventh planet of our Solar System which was named Uranus soon after. However, the planet was probably observed earlier than that because it is just bright enough to be seen with the naked eye. Five major moons circle around Uranus. In 1977, occultation observations made with an airborne telescope revealed the existence of five rings whose number has meanwhile grown to 13.

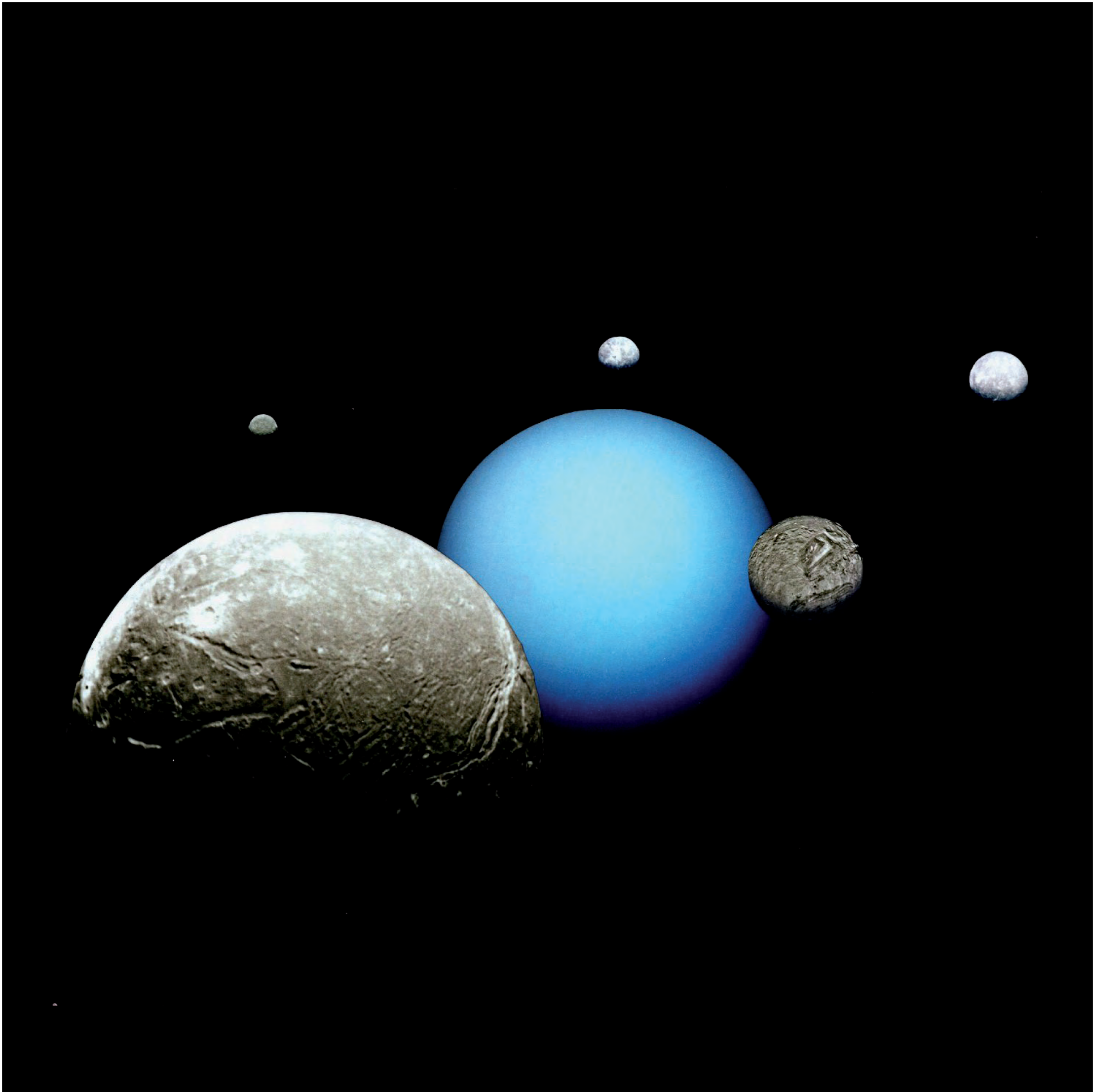
Uranus takes 84 years, the length of a long human life, to orbit the Sun. The planet is 20 astronomical units away from the Sun, twice as far as Saturn and four times as far as Jupiter. Consequently, the amount of solar energy it receives per unit of area is four and sixteen times less than the insolation received by its two inner neighboring planets, respectively. Moreover, there is no source of heat in the interior of Uranus, a feature which distinguishes it from both Jupiter and Saturn. As the planet‘s spin axis is inclined 98 degrees, running almost parallel with its orbital plane, the planet ‘rolls‘ along its orbit around the Sun, and its seasons are highly unusual compared to those of other planets: the north and south poles each receive intense solar radiation for a period of 21 years, while the equatorial zones and middle latitudes of the planet similarly receive a greater share of the Sun‘s energy for another two 21-year periods. These relatively massive inequalities in insolation should, properly speaking, cause great atmospheric dynamism at the various planetary latitudes; however, measurements made by Voyager show that this is true only for the uppermost layers of the atmosphere where preponderantly zonal cloud circulation movements were observed.

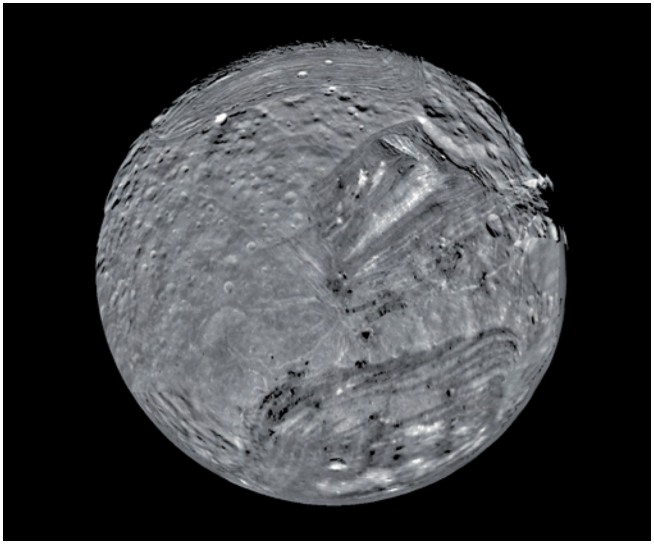
Facts

Uranus	*Mass*	*8.684 x 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 x 10^9 km*
Miranda	*Mass*	*6.6 x 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 x 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 x 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*

If we were to model the dimensions and mass of Uranus with Earth globes, we would have to fit 15 Earth masses into a sphere containing 64 times the volume of Earth. In first approximation, the inner structure of Uranus resembles that of Jupiter and Saturn. Unlike these, however, the upper layers of its atmosphere contain a noticeable admixture of methane (CH_4) which gives the planet its blue-green color. Although Uranus shows no marked cloud bands and structures, its rotation period was successfully measured at 17.3 hours during the flyby of Voyager 2 in 1986. During the same flyby, moreover, a relatively powerful magnetic field was discovered whose axis is at an angle of 60 degrees to the planet‘s spin axis.

Located without exception on the equatorial plane, Uranus‘ 13 rings are at a distance of 39,000 to 97,000 kilometers from the planet‘s center. As they reflect only a scant five





percent of the sunlight, the rings must be very dark and colorless and may contain a high proportion of carbon.

The moons of Uranus

Uranus has five large moons that have been known for some time, Miranda, Ariel, Umbriel, Oberon and Titania as well as ten other relatively small satellites, namely Cordelia, Ophelia, Bianca, Cressida, Desdemona, Juliet, Portia, Rosalind, Belinda and Puck, all discovered by Voyager. Yet more moons were found in the last few years – Caliban, Stephano, Sycorax, Prospero, Trinculo and Setebos together with the infinitesimal satellites Francisco, Margaret, Ferdinand, Perdita, Mab and Cupid. All in all, we know of 27 moons so far.

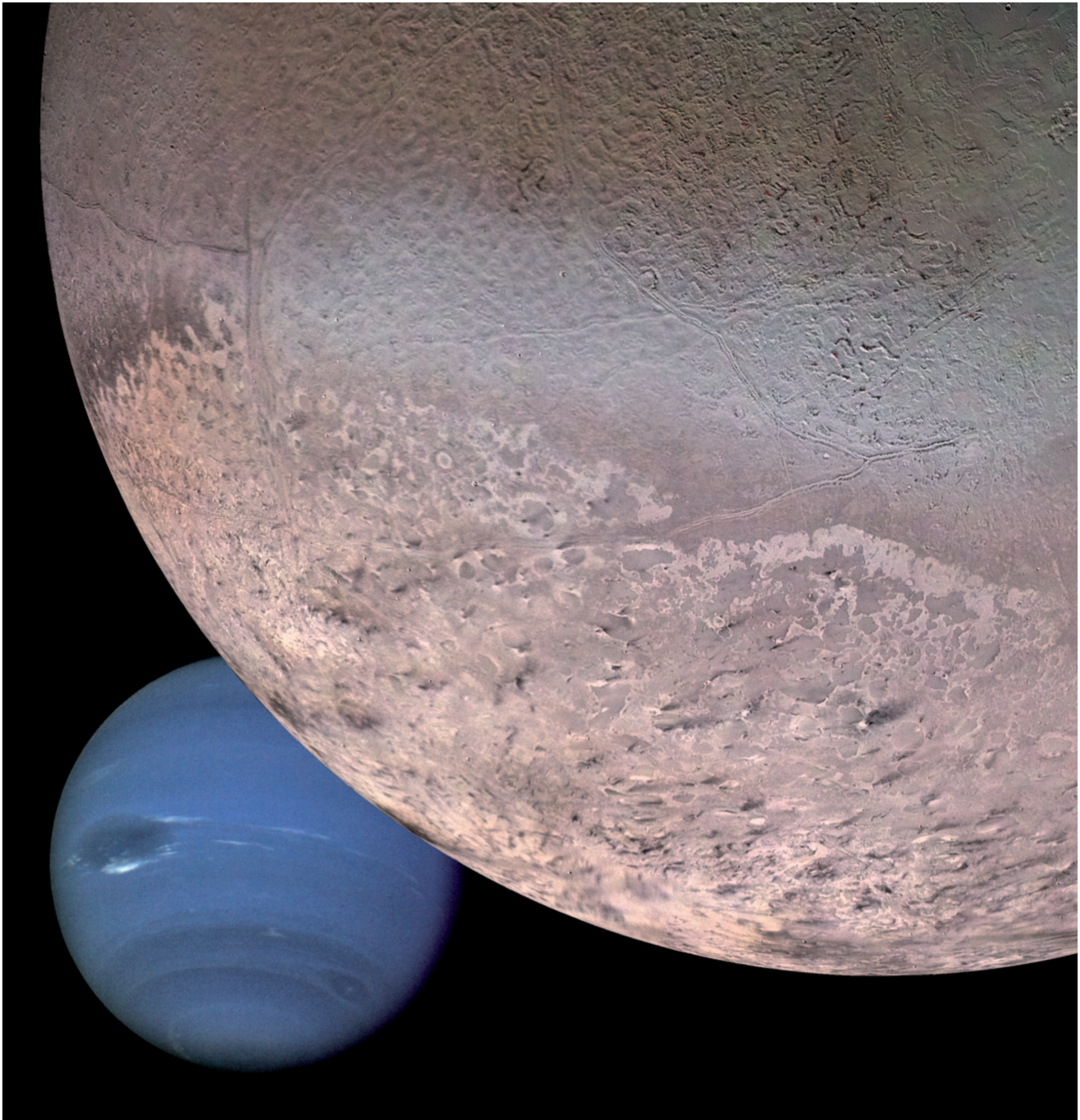
Miranda is the innermost and smallest of Uranus' known moons. The structure of its surface is astonishingly diverse, featuring craters, furrowed landscapes, embankments, scarps and large ring formations. Ariel is the second moon of Uranus. Its surface shows many craters, suggesting that it is of great age. The surface of Ariel is the brightest and, geologically speaking, youngest in the system of Uranus. Umbriel is the third largest of the Uranian moons. Its relatively dark surface shows only a few bright spots. The largest of the Uranian moons, 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 extend over hundreds of kilometers. Oberon, the outermost of the Uranian moons, resembles Titania in that its surface is covered by impact craters, some of which show dark material of unknown origin in their depths.

Picture left: View of Uranus in natural colors. (© NASA/JPL)

Picture right: Uranian moon Miranda with remarkable surface structures. (© NASA/JPL)

Picture left page: Uranus with its large moons Ariel, Miranda, Titania, Oberon, and Umbriel (from largest to smallest). (© NASA/JPL)

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*



Neptune

The outermost of the giant planets, Neptune was discovered as late as 1846 by Johann Galle and Heinrich Ludwig d'Arrest on the basis of irregularities in the orbital movement of Uranus. It is likely that the planet was seen 233 years earlier by Galileo who, however, failed to recognize it as a 'wanderer'. To a terrestrial observer, Neptune appears to remain for a very 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. As it is 30 astronomical units away from it, the solar energy it receives per unit of area is only $^{1}/_{900}$ of that received by Earth. Nevertheless, the wind velocities discovered in its atmosphere by Voyager 2 during its flyby are the highest ever measured on a planet – 560 meters per second or 2,060 kilometers per hour. The planet appears to have other sources of energy besides the Sun at its disposal, for it was found that it radiates 2.7 times more energy than it receives from the Sun.

From the images taken by the Voyager 2 probe, Neptune is familiar to us as an aesthetic bright-blue sphere featuring a large and a small dark spot as well as conspicuously bright structures and clouds in the upper atmosphere that recall cirrus clouds on Earth. The planet's equatorial diameter is 49,492 kilometers, and its interior is spacious enough to accommodate 60 terrestrial globes. Moreover, its density is somewhat greater than that of the other gas planets. One theory says that, at the time of its birth, the planet absorbed large quantities of water, methane and ammonia which then congealed into an icy core. Predominantly consisting of molecular hydrogen, the atmosphere probably contains 10 to 15 percent helium as well as traces of methane and ethane. Changing cloud patterns and widespread haze can be observed in the atmosphere. The Great Blue Spot, also known as the Great Dark Spot, is an atmospheric vortex. However, recent observations by the Hubble space telescope show that it is far from being as long-lived as its permanent counterpart, the Great Red Spot on Jupiter.

Neptune rotates around its axis in somewhat more than 16 hours. Its spin and magnetic field axes are set at an angle of 47 degrees; moreover, its magnetic field is offset by 0.4 planetary radii from the planetary center, which leads to complicated interactions with the solar wind.

When ring segments were discovered around Neptune for the first time in 1984, it was believed that Neptune had a ring system of its own. And indeed, pictures taken by Voyager 2 show two narrow, entire, sharply delimited main rings measuring 63,000 and 53,000 kilometers in radius and 10 to 15 kilometers in width. In addition to these, two or three relatively faint rings have been discovered that are wider and probably consist of minor particles with a low albedo.

The moons of Neptune

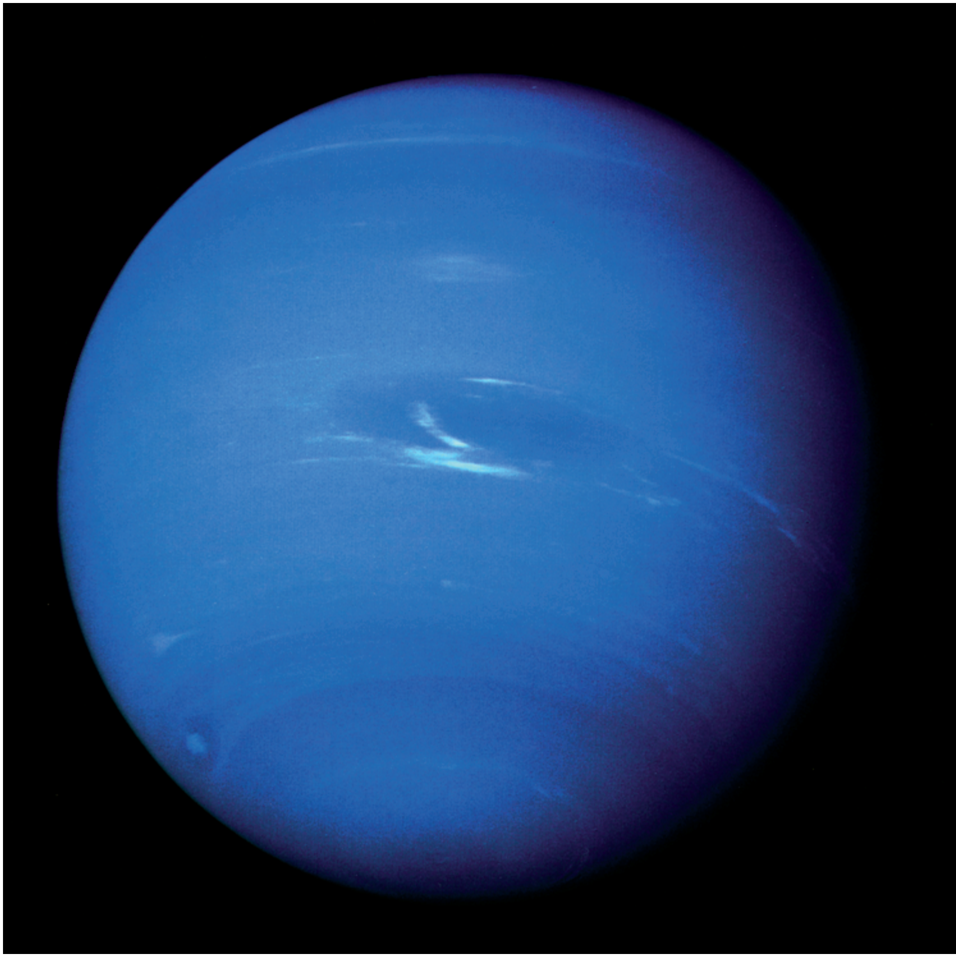
Neptune has 13 moons, of which Triton and Nereid were known before Voyager 2 passed by. Neptune's largest moon, Triton, has a very thin atmosphere of nitrogen and methane. Its surface is highly complex, with relatively few impact craters,

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	*1,352 km*
	Orbital period	*5.877 days*
	Mean distance from Neptune	*354,800 km*
Nereide	*Mass*	*2 x 10^{19} kg*
	Density	*not known*
	Radius	*170 km*
	Orbital period	*360.14 days*
	Mean distance from Neptune	*5,513,400 km*

Picture left page: Neptune with its largest moon Triton, montage. (© NASA/JPL/USGS) but there are several large basins that were probably formed by impacts. Measuring 2,760 kilometers in diameter, Triton is somewhat smaller than the Moon, yet its surface structures are surprisingly diverse. Thus, a large area surrounding the south pole appears pink, while the northern part is greenish-grey. The explanation lies in Triton's unusual seasons. Because of the length of time it takes to orbit the Sun and the extreme inclination of its axis, each pole is exposed to the sunlight for 82 years and subsequently remains in the dark for the same length of time. During the summer phases, nitrogen and methane ice evaporate, exposing the dark icy crust below. On the cold winter side, on the other hand, the precipitation of ice makes the surface appear brighter because ice reflects sunlight well.

Moreover, images show some dark jets several kilometers in height. Apparently, they shoot out of the ground, leaving oval black marks on the surface that may be as long as 150 kilometers. These jets may be geyser-like eruptions that occur when subsurface cavities 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.



Nereid is the smaller and more distant of the two moons that have been known for a long time. Its orbit is highly elliptic. Voyager 2 was unable to observe Nereid at close range. However, light-curve fluctuations have given rise to the assumption that the satellite is not spherical but oblong; alternatively, its surface may be composed of materials of different albedo.

The moons that were discovered by Voyager 2 have been named Naiad, Thalassa, Despina, Galatea, Larissa and Proteus. Further moons, namely Halimede, Psamanthe, Sao, Laomedeia and Neso were discovered only recently.

Picture: Global view of Neptune with the Great Dark Spot and a recognizable banded structure of the atmosphere. (© NASA/JPL)

The Comets

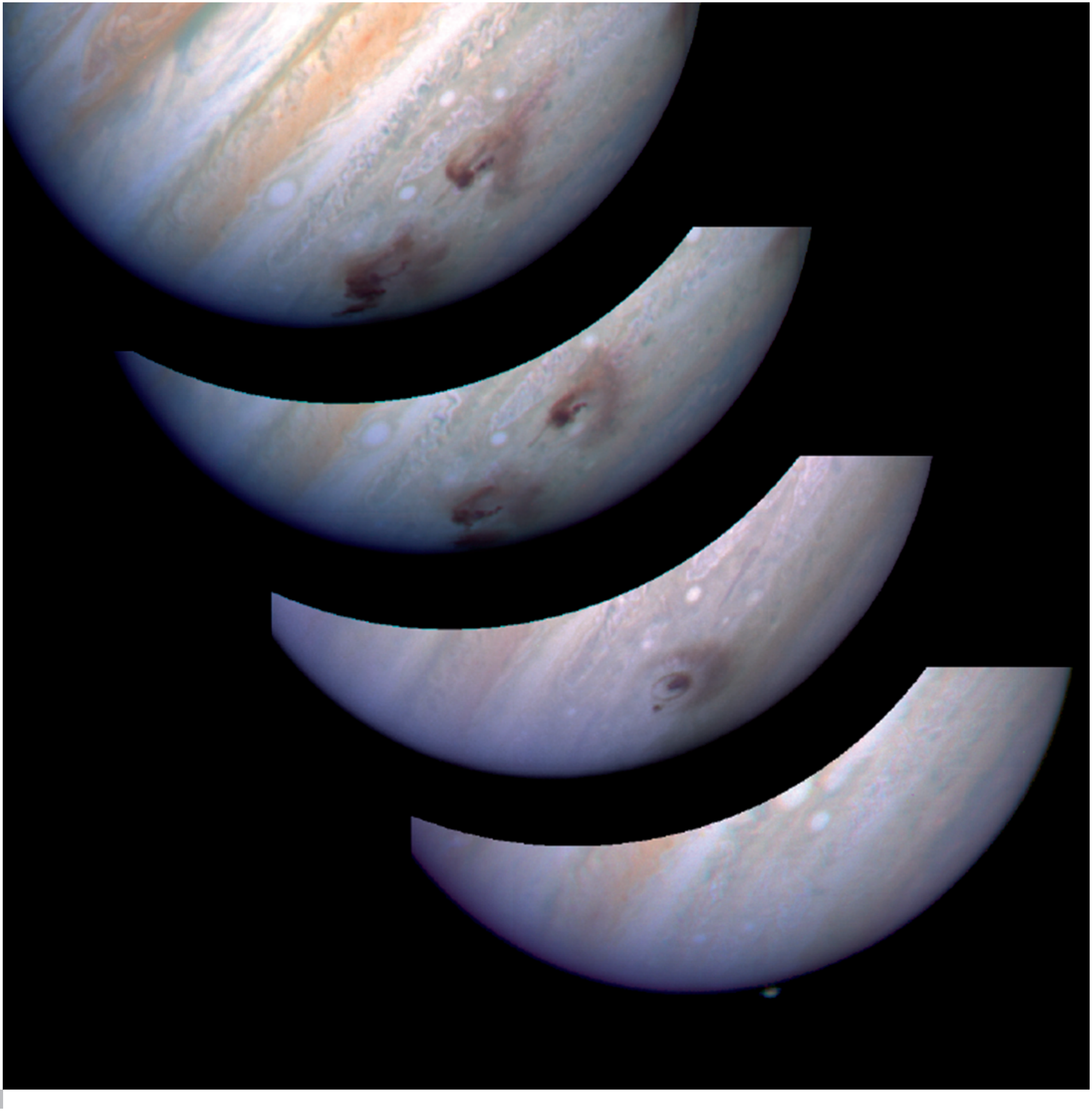
Comets have been observed since time immemorial – stars bearing tails which, appearing in the sky suddenly and unexpectedly often spread fear and terror or at least caused great amazement among the people. Only contemporary astrophysics and planetary research deprived these curious phenomena of their 'magic'. Believing them to be exhalations, Aristotle located these shining hair-like objects in the outermost layer of the terrestrial atmosphere. 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 the analytical methods for calculating orbits. Famous mathematicians like Gauß and Euler were involved in these endeavors.

Today we know that comets are small bodies measuring a few score kilometers in diameter whose original home lies on the distant outskirts of the Solar System, far away from the known realm of the planets. It is supposed that in these remote reaches, at distances varying between 40 and 10,000 astronomical units, the Sun is surrounded by an enormous spherical cloud containing billions of cometary bodies which orbit it at an extremely slow pace. Occasionally, slight gravitational disturbances in its orbit might cause one of these bodies to enter a path that brings it closer to the Sun. On the way, its originally frozen gaseous constituents will gradually thaw and flow away from its nucleus, carrying dust particles from the surface along with them. Thus, the small nucleus will be gradually surrounded by a hazy, diffuse atmosphere (coma) measuring between ten thousand and a hundred thousand kilometers in diameter from which a conspicuous 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 two 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. It is assumed with some justification that comets are small, unaltered relics from the earliest age of the Solar System.

When a comet comes close to any of the large planets, Jupiter especially, the shape and period of its orbit change measurably. In this way, many originally long-period comets have been turned into short-period comets that orbit the Sun in a few years. The consequence of this is that they 'age' more quickly as they exhaust their store of gas and dust. Indeed, planetologists and comet researchers currently ask themselves whether some of the known asteroids might not be comets that have become unable to develop any activity.

The force that holds a comet together is not strong. They break up occasionally, especially when they come too close to the Sun, and some even plunge into it. When a comet breaks up, its debris spreads out along its trajectory. When the Earth flies into such a cloud of debris, the smaller particles enter the atmo-

Picture: Comet Hale-Bopp with two tails, taken in April 1997. (© Observatory Slovenia)



sphere and burn up in it as meteors. Many well-known meteor showers may be traced back to broken-up comets or comet effluvia.

New comets are being discovered in large numbers every year. During an observation campaign conducted in October 1997, staff members of the DLR Institute of Planetary Research discovered the comet P/1997 T3 together with their colleagues at the observatory of Uppsala, Sweden. As is common practice in such cases, the discoverers were honored by naming the comet Lagerkvist-Carsenty.

Comet 1P/Halley

Its regular appearance and its distinctive tail have made Halley's Comet the most popular periodic comet. Next to Tempel 1, moreover, it is the only one of which high-resolution images exist. It has probably been observed for more than 3,000 years, certainly since 240 BC. It travels around the Sun on an orbit that is elongated, elliptic and inclined to the plane of the Earth's orbit. Its mean orbital period is 76 years. The point at which it is farthest away from the Sun, the aphelion, lies beyond the orbit of Neptune, while the perihelion, the point at which it is closest to the Sun, is situated between the orbits of Mercury and Venus. Halley last passed through its perihelion on 9 February 1986.

Comet P/Shoemaker-Levy 9

The comet P/Shoemaker-Levy 9 (SL9) was discovered in March 1993 by astronomers Carolyn and Eugene Shoemaker and David Levy at the observatory of Mount Palomar in California. It was quickly found to display three unusual characteristics: first, it did not have a single body but consisted of many 'parts' that followed one another like pearls on a string. Second, these 20 or so fragments were circling around Jupiter in a two-year orbit. And third, all parts of the comet were on a collision course with the planet. In the period between 16 and 22 July 1994, they struck the part of Jupiter's southern hemisphere that was facing away from the Earth at a speed of about 60 kilometers per second (216,000 km/h). The only measuring instruments that had a direct view of the impact sites were the remote-sensing experiments on board the Galileo probe, which was about 240 million kilometers away from its Jovian destination at the time. A few minutes after the impacts, the sites rotated into the view of telescopes on Earth. The phenomena that subsequently appeared in Jupiter's atmosphere became the subject of the great-

est globally-coordinated observation campaign so far recorded in the history of astronomy. When the measurements were evaluated, it was found that the energy released by the impacts was equivalent to 10-20 kilotons of TNT or 30-60 million atomic bombs of the Hiroshima type. The traces left behind by the impacts in Jupiter's atmosphere were larger than the diameter of Earth.

Comet C/1995 O1 Hale-Bopp

On 23 July 1995, Alan Hale of New Mexico and Thomas Bopp of Arizona independently discovered an unusually bright comet beyond the orbit of Jupiter. At the time of its discovery, it was the remotest comet ever found by amateur astronomers. Given the name Hale-Bopp, the comet has a nucleus measuring 40 kilometers in diameter. Viewed from the same distance, it would be 1,000 times brighter that Halley. When it came closest to the Sun on 1 April 1997 it was 136 million kilometers away from

Picture: Nucleus of Comet Tempel 1. (© NASA/JPL/UMD)

Picture left page: Traces of the impact of fragment C of the comet Shoemaker-Levy 9 into the atmosphere of Jupiter over a period of five days. (© R. Evans, J. Trauger, H. Hammel and the HST Comet Science Team and NASA) it. On 22 March 1997, the comet passed the Earth at a distance of 195.2 million kilometers. At the end of March 1997, its tail was between 80 and 96 million kilometers long. The comet's flyby in the spring of 1997 was observed by telescopes all over the world.

Comet 9P/Tempel 1

Tempel 1 is a short-period comet that hails from the Kuiper belt. It was discovered on 3 April 1867 by Ernst Wilhelm Leberecht Tempel, an astronomer from Saxony. As it has approached the planet Jupiter to 0.41 AU three times since 1881, its orbital period is now only about 5.5 years. Because of these repeated changes, the comet was temporarily 'lost'. Its path was finally computed in the '60s, when disturbances in its orbit caused by the planets could be taken into account. In 1968, Tempel 1 appeared in a photograph, although its rediscovery was finally confirmed only when it returned in 1972.

When it made its appearance in the summer of 2005, Tempel 1 was investigated by the Deep Impact space probe. On 3 July 2005, the probe fired a projectile the size of an ice box at the nucleus of the comet. Weighing about 370 kg, this so-called impactor struck the comet at a speed of about 37,000 kilometers per hour. The event, which was observed by the probe from a distance of around 8,600 kilometers, left behind a crater measuring some 250 meters in diameter. Around 4,500 images were taken to record the experiment. As this was science's first direct look at the interior of a cometary nucleus and, by the same token, at the matter of which our Solar System was originally composed, the event was observed by all available telescopes in space as well as on Earth.

Comet 67P/Churyumov-Gerasimenko

Comet 67P is the target of one of the most ambitious undertakings in European astronautics – the Rosetta mission to explore a comet at close range. Launched in March 2004, the probe is scheduled to reach the comet in May 2014 after a flight of more than ten years. It will begin by injecting itself into an orbit to conduct initial measurements and look for a suitable landing site. Once this is done, the Philae lander developed by DLR will detach itself from the parent craft and land on the comet. The first images of the comet's nucleus were supplied by the Hubble space telescope on 12 March 2003, showing an oval body three by five kilometers in size. It is known from light-curve analyses that the comet rotates in about twelve hours.

Picture: Rosetta lander Philae on the nucleus of comet 67P/Churyumov-Gerasimenko, artist's view. (© 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 and fresh knowledge about planetary systems. The IAU resolved that planets and other bodies in our Solar System, except satellites, be divided into three distinct categories in the following way:

1) *A planet is a celestial body that a) is in orbit around the Sun, b) has sufficient mass for its self-gravity to give it a nearly round shape, meaning that it is in hydrostatic equilibrium, and c) has cleared the neighborhood around its orbit of foreign cosmic matter.*
2) *A dwarf planet is a celestial body that a) is in orbit around the Sun, b) has sufficient mass for its self-gravity to give it a nearly round shape, meaning that it is in hydrostatic equilibrium, c) has not cleared the neighborhood around its orbit of foreign cosmic matter, and d) is not a satellite.*
3) *All other objects, except satellites, orbiting the Sun will be referred to collectively as small Solar System bodies. This category covers 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 three 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. As amended in 2009, the ‘observation report‘ maintained by the IAU lists another twelve candidates for dwarf planet status, including objects in the Kuiper belt as well as large asteroids. The list is bound to grow as further discoveries are made and known objects examined more closely. By now, Makemake (2005 FY_9) and Haumea (2003 EL_{61}) have been classified as dwarf planets.

List of Candidates

Object	*Moons*	*Diameter*
Orcus	-	*1,000 ± 200 km*
Sedna	-	*1,500 – 1,800 km*
2002 TX_{300}	-	*< 700 km*
2002 AW_{197}	-	*800 ± 100 km*
Quaoar	-	*~ 1,200 km*
Ixion	-	*500 – 1,000 km*
Varuna	-	*700 ± 150 km*
Vesta	-	*578 x 560 x 458 km*
Pallas	-	*570 x 525 x 500 km*
2007 OR_{10}	-	*875 – 1,400 km*

Ceres

Recently added to the category of dwarf planets, Ceres was discovered by Giuseppe Piazzi on 1 January 1801 and named after the Roman goddess of vegetation. Its diameter of about 975 kilometers makes Ceres not only the largest but also the most massive object in the asteroid belt, for it accounts for one third of the belt‘s total mass. Ceres has been reclassified before in the course of its history: initially categorized as a planet when it was discovered, 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. 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 are classified as dwarf planets. Smaller, colder and farther away from the Sun than all the large planets, Pluto has yet another identity as a member of a group of possibly 100,000 objects measuring more than 100 kilometers in diameter that circle around the Sun beyond Neptune‘s orbit in a disk-shaped zone called the Kuiper-Edgeworth belt. This is the region in which Pluto and its satellites orbit the Sun. This far-away 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 does not have enough mass for this, being the smallest of all planetary bodies.

Pluto's rather eccentric orbit (e = 0.25) 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 AUs 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 water, methane and ammonia ice 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 centigrade).

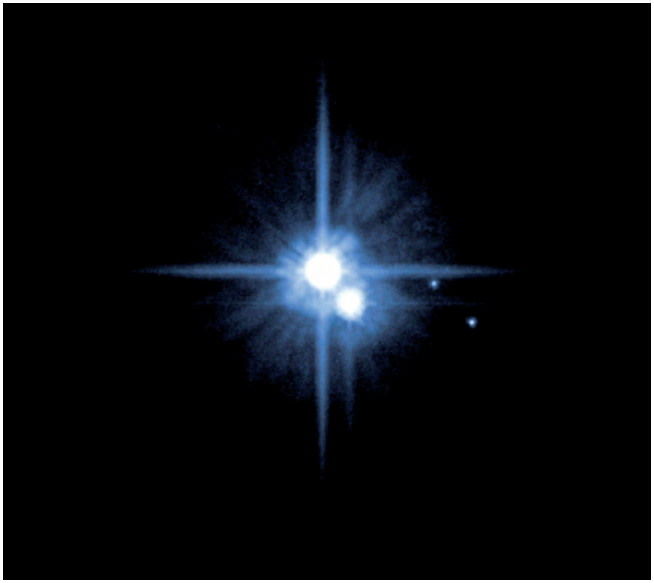
Observing Pluto through the 1.5-meter reflector of the US Naval Observatory, James Christy discovered a small bulge at the edge of Pluto's little disk in 1978 – the moon Charon. Recent measurements indicate that Charon has a diameter of 1,200 kilometers. It orbits Pluto in 6.4 days at a mean distance of 19,600 kilometers. The rotation of the two bodies is locked, meaning that they always show the same face to each other. At 1/10, the moon-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 comparable disorientation of their spin axes are Venus at 177 degrees (inversion) and Uranus at 98 degrees (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 the remnants of the primal solar nebula contracted at a great distance from the Sun a long time ago, forming small moon-sized planets. After all, more than 40

Facts

Ceres	*Mean distance from the Sun (AE*)*	*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 (AE*)*	*39.5*
	Orbital period (years)	*247.92*
	Orbital eccentricity (circular = 0)	*0.2488*
	Orbital inclination to ecliptic	*17.6°*
	Diameter (km)	*2,390*
	Known moons	*3*
Eris	*Mean distance from the Sun (AE*)*	*67.7*
	Orbital period (years)	*557*
	Orbital eccentricity (circular = 0)	*0.441*
	Orbital inclination to ecliptic	*44.179°*
	Diameter (km)	*2,400 ± 100*
	Known moons	*1*
Makemake	*Mean distance from the Sun (AE*)*	*45.6*
	Orbital period (years)	*310*
	Orbital eccentricity (circular = 0)	*0.156*
	Orbital inclination to ecliptic	*28.998°*
	Diameter (km)	*1,600 ± 300*
	Known moons	*0*
Haumea	*Mean distance from the Sun (AE*)*	*43.342*
	Orbital period (years)	*285.3*
	Orbital eccentricity (circular = 0)	*0.189*
	Orbital inclination to ecliptic	*28.194°*
	Diameter (km)	*2,200-1,100*
	Known moons	*2*

Picture left page: Artist's view of the dwarf planet Eris and its moon Dysnomia. (© NASA, ESA, and A. Schaller for STScI)



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 another 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 of two Pluto-sized objects four billion years ago.

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. Temporarily designated as 2003 UB$_{313}$, the object was named 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 highly efficient sensor of the 30-meter telescope at the French-Spanish Institut de Radioastronomie Millimétrique (IRAM) on Pico Valeta (Sierra Nevada), which measured Eris‘ heat emission and determined that its reflection was similar to 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, 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 it 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. With a diameter of about 1,600 kilometers it is about two thirds the size of Pluto. Makemake orbits the Sun in around 310 years at a distance of between six and eight billion kilometers.

Haumea (2003 EL$_{61}$)
Haumea joined the class of dwarf planets in September 2008. Discovered in 2003, its shape resembles that of 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.

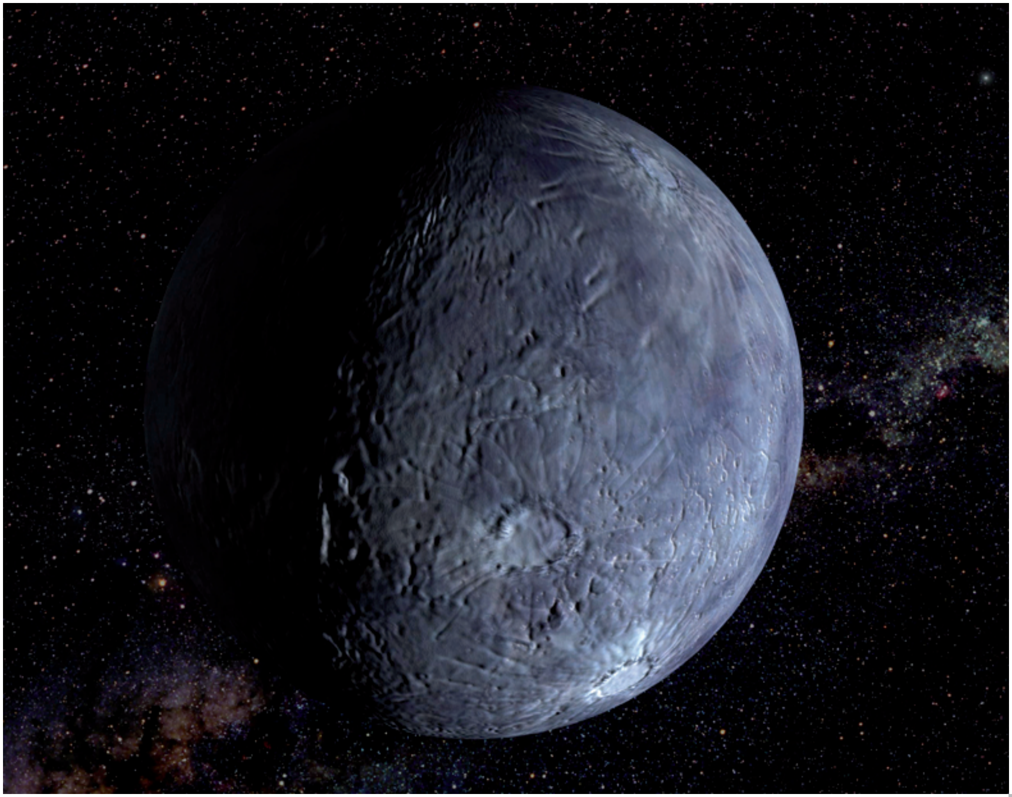
Picture: Pluto and its moons Charon, Nix, and Hydra. (© NASA, ESA, H. Weaver (JHUAPL), A. Stern (SwRI), and the HST Pluto Companion Search Team)

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, besides Pluto, there are many other 'planets' whose orbits lie outside that of Neptune. Apparently, Pluto was merely discovered first 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 an article 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 QB_1, 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. KBOs 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 disk of gas and dust which surrounded the newly-born Sun about 4.5 billion years ago. The planets formed as a result of collisions between such primitive minor bodies. This being so, KBOs may be regarded as samples of the material from which the planets were originally built, samples whose chemical composition has not changed. This explains why they are so important for planetary research.

Another reason why scientists are so greatly interested in KBOs is that they suspect that the short-period comets might originate in the Kuiper belt. KBOs may change their orbits under the influence of Neptune and the other outer planets. When this happens, the occasional KBO finds its way into the interior of the Solar System. On its approach, it is heated by the Sun so that part of its icy material evaporates, forming a coma and ultimately a tail. Thus KBOs are transmuted into comets.

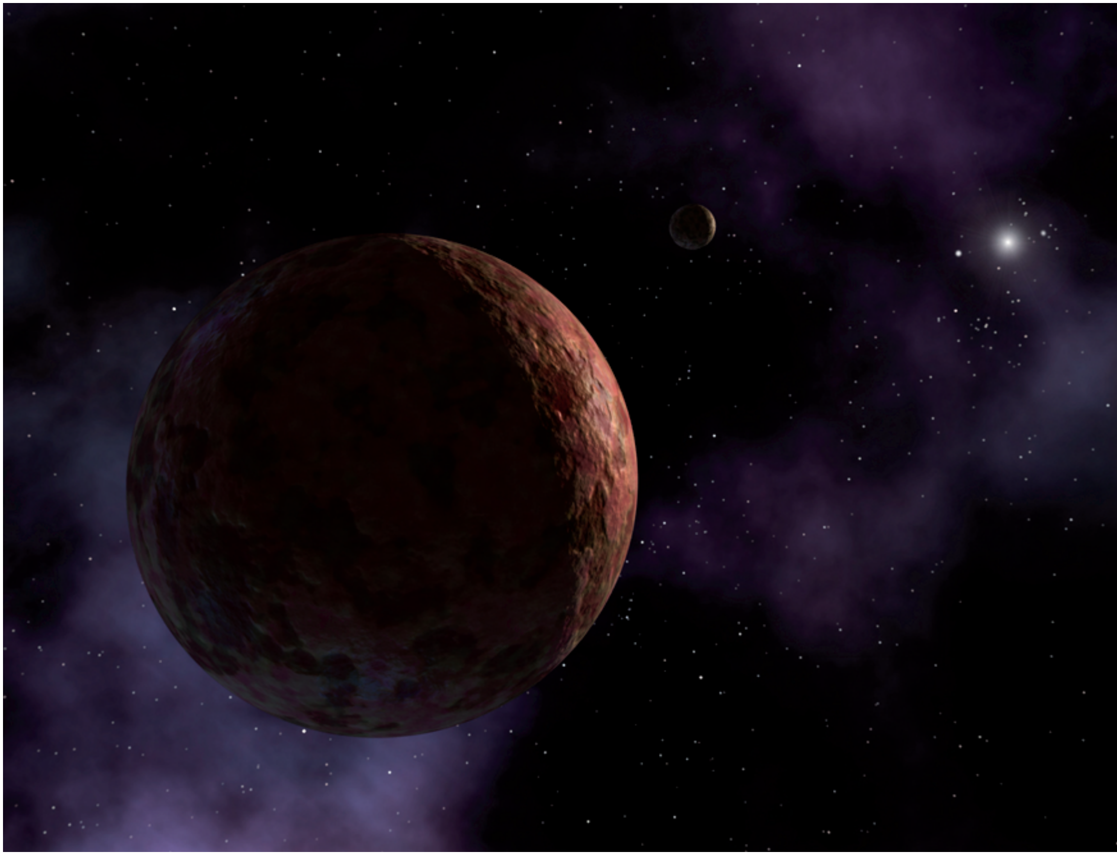


Picture: Artist's view of the Kuiper Belt Object Quaoar. (© NASA and G. Bacon (STScI))

The Kuiper belt should not be confused with the Oort cloud, an enormous reservoir of comets surrounding the Solar System like a shell that is supposed to contain billions of icy bodies. Long-period comets are said to have their origin in this cloud. Situated far beyond the Kuiper belt, it reaches out to a distance of one or two light years from the Sun. Contrary to the Kuiper belt, however, there have been no direct observations so far to prove that the Oort cloud exists.

Today, it is believed that Pluto itself is a KBO. If it could ever get close to the Sun, it would probably appear as 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 KBOs 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 = 150 million kilometers). The largest specimen found so far is Sedna, a small planet that was discovered in 2003. With an estimated diameter of 1,500 to 1,800 kilometers, Sedna is not much smaller than Pluto (diameter: 2,390 kilometers). Sedna's origin is a mystery. The most probable solution is that it originated in the zone of the large planets from which it was ejected by their powerful gravitational force.

As the sensitivity of the telescopes and other instruments that are available to astronomers keeps increasing, it is certain that many more members of this mysterious 'fringe population' of the Solar System will be discovered in the years to come. Very probably, it is only a question of time until Pluto loses its status as the largest (dwarf) planet beyond Neptune: even now, the KBO Eris is thought to have a diameter of 2,400 kilometers at least, which makes it larger than Pluto.



Picture: Artist's view of the Kuiper Belt Object Sedna with the Sun as a bright star. (© NASA/JPL)

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 March 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 ultraviolet 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
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

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

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

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

Meteosat 1	23 Nov 1977	MOP 2/Meteosat 5	02 Mar 1991
Meteosat 2	19 Jun 1981		
Meteosat 3/P2	15 Jun 1988	MOP 3/Meteosat 6	20 Nov 1993
MOP 1/Meteosat 4	06 Mar 1989		
		Meteosat 7	02 Sep 1997

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		

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

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 1A	17 Mar 1988	IRS P3	21 Mar 1996
IRS 1B	29 Aug 1991	IRS1 D	29 Sep 1997
IRS 1E (IRS P1, Misserfolg)	20 Sep 1993	IRS P4 (Oceansat 1)	26 May 1999
IRS P2	15 Oct 1994	IRS P5 (Cartosat 1)	17 Oct 2003
IRS 1C	28 Dec 1995	IRS P6 (Resourcesat)	05 May 2005

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

Prognoz: Russian series of Earth observation satellites, observation of oceans, natural resources, and atmospheric processes, Prognoz 1: failed on 14 Sep 1988

Prognoz 1	26 Apr 1988	Prognoz 3	10 Sep 1992
Prognoz 2	14 Feb 1991	Prognoz 4	17 Dec 1992

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 3	04 Jun 1991
OKEAN 2	28 Feb 1990	OKEAN 4	11 Oct 1994

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

FY-1A	06 Sep 1988	FY-1B	03 Sep 1990

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 4	21 Sep 2001
OrbView 2	01 Aug 1997	(Misserfolg)	
OrbView 3	26 Jun 2003		

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		

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

Terra (EOS AM-1)	18 Dec 1999

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

Cluster: Observation of the interactions between Earth and Sun, consisting of four identical space probes in Earth orbit

Cluster	16 Jul 2000

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

EO-1	21 Nov 2000

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*

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, goal: 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*

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*		

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*

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: 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*

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*

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 on Mare Nubium, 4,316 images during approach*
Ranger 8	*17 Feb 1965 to 20 Feb 1965*	*Impact on Mare Tranquillitatis, more than 7,000 images during approach*
Ranger 9	*21 Mar 1965 to 24 Mar 1965*	*Impact on 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 on the area of Oceanus Procellarum*
Luna 8	*03 Dec 1965 to 06 Dec 1965*	*System tests for landing, impact on the area of 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 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 ca. 5.18 million km², 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 on 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, besides color and black & white images from Moon also images from 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 June 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 June 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 will be impact on the lunar surface, which will be observed by the S-S/C

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 the parking orbit around Earth, malfunction of the 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 nearly1,500 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*	*Russia 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 the 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 the climate and geology*
Mars Reconnaissance Orbiter	*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*

Missions to the 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*
Dawn	*27 Sep 2007*	*Orbiter to 4 Vesta (arrival 2011) 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

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	Orbiter to 4 Vesta (arrival 2011) 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*
CONTOUR	*03 Jul 2002*	*Close flybys at the 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/Churyu-mov-Gerasimenko, afterwards landing on the nucleus*
Deep Impact	*12 Jan 2005*	*Flyby at comet Tempel 1, release of an impactor to the nucleus, observation of the impact*

Missions to the Kuiper belt

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

How to obtain image data

The Regional Planetary Image Facility (RPIF)

While reading this small brochure you may have wondered if there is any provider in Germany from whom these resources can be obtained. Obviously a lot of the material can be found on the Internet today, but it may sometimes be easier to use the help of someone who is more experienced with this kind of research and who might take the entire workload off one's hands, given that working with the Internet often requires the knowledge of foreign languages.

This is where the Regional Planetary Image Facility (RPIF) comes into play. The RPIF functions as a reference library for planetary image data. Its job is to archive and maintain all data acquired by space missions of all planetary objects of our Solar System, except Earth observation data.*

The RPIF library was established in 1985 under an agreement between DLR and NASA, and began to operate four years later. After working several years as part of the Remote Sensing Section at the Institute of Optoelectronics in Oberpfaffenhofen, the RPIF was transferred to the Institute of Planetary Research in Berlin Adlershof in 1992. The RPIF is part of an international network of image libraries coordinated by NASA. Worldwide there are 17 of these institutes, nine of which are located in the USA, five in Europe and one each in Canada, Japan, and Israel. The Berlin RPIF basically provides for the entire German-speaking region. The individual image libraries are in close contact via data networks. They are all linked up with NASA's Planetary Data System (PDS) and offer extensive database research options.

The collection

The library holds digital image data, spectral data, along with the relevant positional data of each space probe. To back up these data there are documentations, maps, and a selection of journals and other scientific publications. All data are documented, catalogued, and available to all users whether they be from the academic research community or from the general public. The data are also used internally for DLR's own research, such as the evaluation of project-related material, for the preparation of space missions, or for dissertations and theses.

The available material mainly stems from American missions but also European and Soviet/Russian ones. The table shows an overview of the current collection. This database, which is almost complete with regard to the American missions, makes the RPIF a first-choice supplier of planetary images in Germany providing an excellent basis for research in this field.

It is via the RPIF that NASA shares the data both from its present and future space missions. At the time of writing, the library is receiving data from the Cassini mission in the Saturnian system and from current Mars missions. In addition, Mars data are being supplemented by current images from the European probe Mars Express, in which the DLR Institute of Planetary Research is actively involved as the provider of the High Resolution Stereo Camera. Also available are a number of Earth images from NASA's Space Shuttle program.

In addition to the original image material there is a large collection of maps, which has meanwhile grown to a respectable 2,400 items, a collection of digital image datasets and slides, as well as of 16-mm films, videos und DVDs. These digital image data and slides, all available to the general public, constitute the main body of the library's holdings. The collection is of particular interest to journalists, teachers, but also to an interested lay audience.

* *Earth data are kept in the archives of the German Remote Sensing Data Center (Deutsches Fernerkundungsdatenzentrum, DFD) of DLR in Oberpfaffenhofen: http://www.dlr.de/caf*

Public relations

To facilitate the use of the RPIF and its large collection, an open-access research area is available to all users, including the general public. Access is provided to documents from NASA, the Jet Propulsion Laboratory (Pasadena/California) and the National Space Science Data Center (Greenbelt/Maryland). Computerized catalogs permit data selection via a random keyword search function.

Gathering information and researching data is free of charge. Copies of images in small numbers can be delivered by the RPIF at net cost price. Larger numbers of copies, especially for research purposes, must be ordered from the National Space Science Data Center, with the assistance of the RPIF if required. Besides catering for individual users, the RPIF offers lectures and tutorials on various subjects to groups of students, or as part of teacher training programs. Moreover, the RPIF presents itself at numerous symposiums, exhibitions and trade shows.

You can find an overview of the current collection, especially of all publicly accessible image resources, on our homepage: **http://www.dlr.de/rpif/**. In addition to materials such as posters, image series or do-it-yourself kits you will also find the complete catalog in PDF format.

Our projects

The RPIF is committed to archiving and making available to the interested public worldwide, data on past missions (such as Galileo, Mars Pathfinder, Deep Space 1), ongoing missions (Mars Express, Venus Express, Cassini, Rosetta, Dawn) and space missions currently in preparation (ExoMars, BepiColombo), in which the Institute is actively involved.

The Galileo project was the most multifaceted and the most complex unmanned mission to explore Jupiter and its Galilean Moons so far. Launched in 1989, the orbiter – after a journey of several years through our Solar System – sent back fascinating images of moon Io with its active volcanoes, and of the icy moons, Europa, Ganymede and Callisto, from 1996 onwards. The chemical composition of the Jovian atmosphere was analyzed with the aid of an atmospheric probe that had been released months before the orbiter's own entry into the Jovian system. The mission ended in July 2003.

Deep Space 1, launched in October 1998, was NASA's first mission under its "New Millenium" program. Its purpose was to study details of the Borrelly comet, following a flyby of the Braille asteroid. The mission included a variety of spaceflight experiments involving the testing of equipment, such as a solar powered ion propulsion system. The probe carried a camera and a plasma spectrometer to study the surrounding plasma as well as the asteroid's and comet's surfaces.

Overview about missions, from which data sets are available

Planet	*Mission*
Mercury	*Mariner 10, MESSENGER*
Venus	*Mariner 10, Pioneer Venus, Venera 15 & 16, Galileo, Magellan, Venus Express, MESSENGER*
Earth	*Galileo, SIR-C/X-SAR, Topex/Poseidon, Jason-1, Clementine, Kidsat, SRTM, TERRA, Space Shuttle*
Moon	*Lunar Orbiter 1-5, Apollo, Galileo, Clementine, Lunar Prospector, Cassini, SMART 1, 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*
Asteroids	*Galileo, NEAR, Cassini, Deep Space 1*
Jupiter	*Voyager 1 & 2, Galileo, Cassini*
Saturn	*Pioneer 11, Voyager 1 & 2, Cassini-Huygens*
Uranus	*Voyager 2*
Neptune	*Voyager 2*
Comet Shoemaker-Levy 9	*Galileo, Hubble Space Telescope, Data from several Observatories*
Comet Hale-Bopp	*Data from several Observatories*
Cometes	*Deep Space 1, Stardust, Hubble Space Telescope*

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/

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

The Institute was also engaged in the Mars Pathfinder Mission, where it participated in the scientific evaluation of Rover image data. The stereoscopic images shot at the Rover landing site were transformed into photogrammetric datasets and studied in a multispectral analysis.

Ever since July 2004 the Cassini Mission has been exploring Saturn, its ring system, its magnetosphere and moons. Launched in 1997, the probe performed several swing-by maneuvers and reached the planet seven years later, and will be orbiting it at least 134 times until the end of 2012. On board it carried Huygens, the European atmospheric and landing probe that was used to explore the atmosphere and surface of Saturn's moon Titan. Close flybys of the icy moons have already produced some spectacular results. The probe crossed a gap in the ring system twice, allowing the exploration of cloud-shrouded Titan with all available remote sensing equipment. DLR is taking part in several experiments of the Cassini mission, including in particular those involving the visible light and infrared mapping spectrometer subsystem (VIMS). It has also contributed to the cosmic dust analyzer and the ultraviolet spectrometer as well as to the ISS camera experiment.

The European Mars Express mission was launched on 2 June 2003 and consists of an orbiter and an UK-made lander module which, unfortunately, did not survive its touchdown on the Martian surface. ESA planned this mission in the wake of the failed Russian Mars 96 undertaking, hoping to put to use the supplementary instruments originally built for Mars 96 and to reach some of the scientific goals they had been built for. The second model of the High Resolution Stereo Camera (HRSC), for one, which had originally been developed for Russia's Mars 96 mission was used to continue the important task of mapping the entire Martian surface in high resolution, color and 3D. The camera has been demonstrating its unique capabilities ever since early 2004 on an ongoing basis.

The European Rosetta mission, whose launch date was postponed in January 2003, has been on its way to comet 67/P Churyumov-Gerasimenko since 2 March 2004. Originally the mission was to explore comet Wirtanen, a plan that had to be abandoned as a result of the delay of its launch. The current status is that Rosetta will start to orbit comet Churyumov-Gerasimenko in 2014 and deploy its lander, Philae, to study the comet's nucleus after several months of studying the surface from orbit. The Institute is participating in several of the mission's scientific experiments. Its main contributions are the VIRTIS spectrometer on the orbiter as well as the ROLIS camera, the MUPUS thermal sensor and the SESAME sensor package on the lander which will analyze the properties of cometary material.

Dawn, launched on 27 September 2007, is heading for two extremely unalike objects, asteroid 4 Vesta and the dwarf planet 1 Ceres. The probe's scientific payload includes a camera modeled after the ones already in use on the Mars Express and Rosetta missions, which were developed at our Institute jointly with the Max Planck Institute for Solar System Research. It delivers images of Vesta in seven colors and of Ceres in three colors. The probe also carries an Italian-made spectrometer and a further European instrument. The probe is to reach Vesta in mid-2011, and subsequently spend nine months exploring the asteroid. Following another three-year flight, dwarf planet Ceres will be the object of study for nearly a year.

Since 2005, research has renewed its interest in planets on the inner orbits. After NASA's MESSENGER mission to Mercury launched in 2004, Europe's space agency ESA launched Venus Express on 9 November 2005, extending its own exploration of the inner Solar system to Earth's sister planet, which is roughly of the same size. The probe's design is similar to that of the Mars Express orbiter. Moreover, a number of adaptations were made on instruments built as back-ups for the Mars Express and Rosetta missions to meet the requirements of this mission. The

DLR Institute for Planetary Research has contributed a camera that explores the planet's dense atmosphere, as well as participating in the spectrometer experiment. Venus Express entered into an orbit around the planet on 11 April 2006, and will orbit it at least until the end of 2009.

Finally, to complement the American MESSENGER probe currently on its way to Mercury, the European BepiColombo mission is to make another significant contribution to the mapping and exploration of the planet. The mission consists of two components, which will orbit the planet as two separate space vehicles. The Mercury Planetary Orbiter (MPO) built by ESA is to explore the surface, while the Mercury Magnetospheric Orbiter (MMO) built by Japan's space agency, JAXA, is to study the magnetic field and the way it interacts with solar wind. The DLR Institute of Planetary Research will participate as principal investigator in the operation of a MPO-borne Laser altimeter which will study, with a high level of precision, the differences in elevation on the planet's surface. The spaceship will be launched in August 2013 and reach Mercury after a six-year cruise in August 2019. For the year 2017, a joint US/European orbiter mission has been scheduled to enter and explore the Jovian system, called the Jupiter System Observer.

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