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The formation and evolution of the Solar System

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Astronomers have built the main components of a scenario for the formation of the Solar System. Small planetary bodies accreted others by collisions within a rotating protoplanetary disk that formed at the same time as the Sun. While terrestrial planets near the warming Sun could accumulate only solid metallic and silicate material, the giant planets formed from ice and gas at lower temperatures. Each planet and satellite then followed its own specific evolution, depending upon the properties of its atmosphere and/or surface. Information about the origin and evolution of the Solar System is also provided by the comets, which can be considered as frozen fossils of the Solar System's early stages. On the borders of the outer Solar System, beyond the orbit of Neptune, the newly discovered Edgeworth–Kuiper belt is probably the reservoir where short-period comets are formed.

1. Introduction

The Solar System contains a very large variety of individual objects (eight or nine major planets, some with rings and many with satellites, minor planets or asteroids, comets of at least two kinds …). The sizes of these objects range from several ten thousands of kilometres (giant planets) down to micrometres (interplanetary particles). Even within a single class – terrestrial or giant planets, satellites, etc – each object shows unique features. Our Earth, for example, is the only planet in the Solar System on which there is, incontrovertibly, significant quantities of liquid water and, partly as a result, an active biosphere. This has transformed the very face of our planet, its biologically altered or deposited rocks and its atmosphere, which contains biologically produced oxygen.

How did these very different individual planets come about? Are they each of different origins or did they form from a common origin and evolve in different ways? What light does this throw upon the characteristics of our own Earth? To

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answer such questions are the objectives of planetary science, the study of the scientific properties of our Solar System, which attempts to understand the formation and evolution of the Solar System, and other systems like it.

Our knowledge of the nature of the bodies of the Solar System outside the Earth started about four centuries ago when, in 1610, Galileo Galilei pointed his new refracting telescope toward the planets and their satellites. He discovered mountains on the Moon, like those on the Earth, and he saw that Jupiter had satellites, like the Earth. Ground-based investigations have been, and still are, the main sources of information about the Solar System but, over the past few decades, planetary space missions have allowed the close-up exploration of a few targets. Among the long list of successful planetary missions launched by NASA, the European Space Agency (ESA) and the Soviet Union, we should mention, in particular, the major achievements of

- Viking (which landed on Mars, 1976),
- Venera 11/12, Pioneer-Venus and Magellan (exploration of Venus, 1978–1998),
- Voyagers 1 and 2 (which made a Grand Tour of the giant planets from Jupiter to Neptune, 1979–1989),
- Galileo (investigating Jupiter, 1995–2001) and
- Giotto and Vega (to Comet Halley, 1986).

2. The formation of planets

Eight of the Solar System's major planets orbit the Sun in nearly circular and co-planar orbits. The exception is Pluto, which, although it is literally a major planet, the ninth, it is now recognized as the largest of a newly discovered class of solar-system bodies. These are the trans-neptunian objects, which, as the name implies, orbit beyond Neptune (see Section 8).

The regular orbital characteristics of the major planets are the main justification for the Kant–Laplace theory, according to which the planets formed from the same nebula as the Sun, about 4.56 thousand million years ago. This protosolar nebula collapsed (Figure 1) into a protoplanetary disk of dust (carbon and silicate material), ice (water ice, as well as ices of other common gases such as carbon dioxide) and gas (mostly hydrogen and helium). Small lumps, called planetesimals, formed from the disk material. Planets formed from the build up of planetesimals within this disk, and the accretion by the planetesimals of gas and other material.

This model, now widely accepted, has also found support from the recent detection (by the Hubble Space Telescope, and by other means) of a large number of protoplanetary disks surrounding young stars outside our Solar System. The

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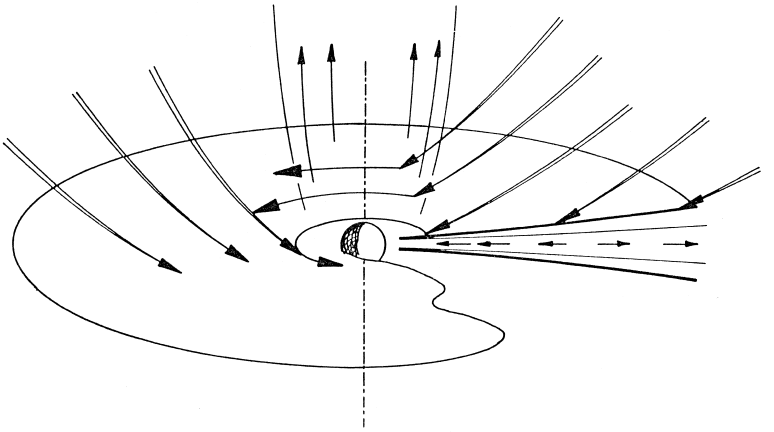


Figure 1. The protoplanetary disk resulting from the collapse of the protosolar nebula. The inner parts of the disk moved inward to form the Sun, while the outer parts moved further outward. A flow of gas, called the solar wind, generated by the Sun, created an outflowing jet along the rotation axis. The figure is taken from P. Cassen and D. S. Woolum (1999) The origin of the solar system, in *Encyclopedia of the Solar System* (Academic Press).

investigation of other star systems at the start of their evolution has confirmed the hypothesis of the Kant–Laplace theory.

As a planet forms, the impact of infalling material and the decay of radioactive material within the planet release heat, under an insulating blanket, which is the body of the planet. Melted material settles under gravity. This process differentiates the material of the planet into concentric shells, such as the molten iron core of the Earth, and its solid crust. It is at this stage that a planet with a strong enough gravity (about 100 km in dimension or larger) takes the characteristic spherical form of a recognisable world.

Leaving Pluto aside again, we can distinguish two kinds of planets. The terrestrial planets (Mercury, Venus, the Earth and Mars) are relatively small, dense and close to the Sun. At larger distances from the Sun, the giant planets (Jupiter, Saturn, Uranus and Neptune) are much bigger and less dense. The giant planets each have a large number of satellites, the terrestrial planets fewer, none in some cases, just one for the Earth and two for Mars and these are special cases (see Section 3)).

Only the terrestrial planets have an observable surface. Mercury has a dry, heavily cratered surface, much like the Moon. The surface is evidently old, its features surviving with little erosion for several thousands of millions of years. The Magellan spacecraft probed beneath Venus' opaque clouds by radar to reveal

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a stark, dry landscape of craters, volcanoes and lava flows. This surface seems relatively young, less than a thousand million years old, with some major changes of unknown cause having occurred in the surface some 800 million years ago. Earth's surface is mostly liquid and frozen water, with mobile tectonic plates and active volcanoes. The mobility and the water mean that the surface rocks of the Earth are of mixed ages, some very young, from thousands of years up to 3.5 thousand million years. Mars is a dry desert (but see below). Its rocks are also of mixed ages but, in general, they are older than the Earth's. Its surface has rocky plains, sand dunes, craters, rift valleys, cold polar regions of water ice and dry ice, and recently active volcanoes. One, Olympus Mons, is the largest mountain in the Solar System, being 550 km at its base and 27 km high, with a volcanic caldera 90 km in diameter.

The atmospheres of the terrestrial planets are made of molecular nitrogen, carbon dioxide, water and, in the case of the Earth, oxygen. In contrast, the giant planets are mostly composed of hydrogen and helium, with traces of methane, ammonia and other hydrogen-rich molecules.

3. The role of collisions

Although one might think that solar-system bodies, once formed, evolved in isolation, in an empty space, this was actually not the case. Collisions between them played a crucial role in the early stages of the history of the Solar System. In fact, it was the mutual collisions of many planetesimals that built the major planets and produced the characteristic features of the orbits of the major planets, namely that they are nearly circular and co-planar.

Even after the planets had fully formed, there were major individual collision events that transformed some of them. It is believed that the Moon was formed a few hundred million years after the creation of the Solar System by a collision between the proto-Earth and a Mars-size protoplanet. The two bodies merged to form a planet containing an iron core (like the Earth) and a ring of lighter debris that accumulated into the Moon. Likewise, the tilted rotation axis of Uranus, which rolls around the Solar System on its equator, with its axis of rotation almost in the ecliptic plane, might also have resulted from an early massive collision.

In the first 500 million years of the life of the Solar System, the bombardment of the surfaces of the planets continued as asteroids and comets struck the surfaces of the planets, creating craters. The bombardment continues today at a reduced rate. On the atmosphere-less planet, such as Mercury, and on the Moon even the oldest craters remain visible to this time.

Our Earth was not an exception to this planetary bombardment, although wind and rain have eroded most craters. The 1.4 km Barringer Meteor Crater in Arizona

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was the first of about 150 terrestrial impact craters that was recognized. The 26 km Ries Crater at Nördlingen in Bavaria is the result of such a natural catastrophe that took place about 15 million years ago, the largest such crater in Europe. St Georgs-Kirch in Nördlingen is probably the only church built from meteor-shocked impact-created stone. In Europe, Finland has the largest density of impact craters, not because it has been particularly unlucky, but more because its geologists have been active in identifying craters in its geology, which is favourable for their preservation and exposure.

Large meteoritic and cometary impacts may have significantly altered the Earth's climate. Most astronomers (but certainly not all geologists) attribute the Cretaceous–Tertiary boundary between geological strata and the extinction of the dinosaurs to a global climate change produced by the impact 65 million years ago of a meteorite with what is now the Yucatan peninsula of Mexico.

Such collisions on to planets, although much less frequent today, do still happen. The most recent undisputed large impact on to Earth was in 1908, in Siberia. As a very recent example, Comet Shoemaker–Levy 9 collided with Jupiter in July 1994. The whole scientific community watched the successive explosions generated by the 20 fragments of the disrupted comet. This spectacular event, similar examples of which are expected to occur at a rate of once every few centuries, allowed the real time study of the response of a planetary atmosphere to a major meteoritic impact.

A near collision can, in some cases, result in the capture of the smaller body by the larger, so that it remains in orbit without impact. Mars has two small moons, Phobos and Deimos, that were probably asteroids captured in this way. Some asteroids themselves have captured tiny asteroids, little more than boulders, as moons.

4. The evolution of the terrestrial planets

The terrestrial planets have some characteristics in common, including their size and their rocky surfaces. The composition of their primitive atmospheres was also probably comparable. The formation of carbon monoxide, nitrogen and hydrogen was favoured by the chemical conditions, and hydrogen escaped. As a result, carbon monoxide, carbon dioxide and nitrogen, and water now dominate the atmospheres of the terrestrial planets. Nevertheless, the terrestrial planets also exhibit remarkable differences, especially in their surface temperature and pressure 730 K and 93 bar[1] on Venus, 290 K and 1 bar on the Earth, about 210 K and 0.006 bar on Mars. Mercury is too small for its gravitational field to have retained any atmosphere, and the same is the case for the Moon and nearly all the other satellites and minor planets.

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The current presence of a large amount of oxygen in the Earth's atmosphere is due to the appearance of life. So the main difference, regarding the atmospheric composition of the terrestrial planets, is the presence of massive quantities of water on Earth, while only traces of water are found on Venus and Mars.

How could the terrestrial planets, starting from relatively comparable conditions, have evolved in such drastically different ways? A qualitative explanation can, at least partly, be found in the fact that their distances from the Sun are such that water is predominantly in the form of gas on Venus, liquid on Earth and ice on Mars.

The primitive Venus probably contained massive quantities of gaseous carbon dioxide and gaseous water. These two gases are both very active components of the greenhouse effect, that is to say they are transparent to light, so that sunlight penetrates an atmosphere made of these gases and warms the planet's surface, but opaque to infrared radiation, so that the warmth of the surface is trapped. The greenhouse effect on Venus has run away, heating its surface and atmosphere by about 500 K more than would otherwise be the case, towards the 730 K temperature presently observed. The atmosphere was then warm enough for gaseous water to dissociate and for the hydrogen and oxygen to combine chemically with something else or escape. Venus' atmosphere today is principally carbon dioxide.

On the Earth, water is mostly in liquid form. The water absorbed the carbon dioxide. On Earth, the greenhouse effect always remained moderate, it adds only about 30 K to the temperature that the Earth would have otherwise. As a result, the Earth's surface temperature has remained remarkably constant as a whole over its history, although a rise of only a few degrees, such as that forecast to be provoked by greenhouse gas emissions from the burning of fossil fuel, can produce dramatic regional changes. This apparently self-sustaining stability of the terrestrial climate may have been an important factor in favour of the development of life and gives grounds for general optimism about its future, tempered by specific concern for our own species and the weather where we live. Oxygen first appeared in the Earth's atmosphere as a result of the appearance of life in the oceans. Life evolved from the oceans to the surface of the Earth when that became possible, i.e. at the time when the oxygen produced an ozone layer, able to protect the surface through the absorption of the solar ultraviolet flux.

Mars is ten times less massive than the Earth. Its early atmosphere was more tenuous than on the primitive Earth. The greenhouse effect must then have been moderate so the planet's atmosphere cooled and rarefied.

There are several plausible arguments that favour the past existence of liquid water (and possibly even a liquid ocean) on the surface of Mars. Some of its impact craters (called rampart craters, or more onomatopoeically, 'splosh craters') are

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Figure 2. Evidence for ponding in a Martian crater, as observed by the Mars Global Surveyor spacecraft. This image is of a crater that shows evidence that it may once have held a small lake. The dark floor material may represent sediment transported into the crater by seeping water. The picture is approximately 25×30 km (Mars Global Surveyor, MRPS88923, NASA).

surrounded by petal-shaped lobes, which suggest the presence of viscous or liquid material below the surface that was melted and pushed up and out at the time of the impacts. Some Martian valleys, found in old cratered regions, show sinuous structures, such as dry water courses, and some valleys and craters show terraced sides that might plausibly have been eroded by liquid water and have stains as if from evaporating lakes (Figure 2). If this was the case, the Martian atmosphere was probably denser and warmer in the past and water could still be trapped under the surface in the form of permafrost.

How did the atmosphere of Mars disappear? If liquid water was present in the past, could life have appeared in the liquid water during this period? These major

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questions will be addressed by the future space missions devoted to the exploration of Mars, including the European Space Agency's Mars Express and Beagle Lander, due to arrive at Mars at Christmas time 2003.

5. The giant planets and their satellites

The four giant planets are two pairs. On the one hand are Jupiter and Saturn, the gaseous giant planets. They have masses of 318 and 95 earth-masses respectively, and are mostly composed of hydrogen and helium. The other two, Uranus and Neptune, are 15 and 17 terrestrial masses respectively, and are mostly made of ices. At the distance of the outer pair from the Sun, it seems that less protosolar gas was available for them to accrete. Perhaps Uranus and Neptune completed their formation later than Jupiter and Saturn, after the dissipation of the protosolar gas by the young Sun. Things tend to happen relatively slowly in the very outer zones of the Solar System, because the temperatures and orbital speeds are low.

The two classes of giant planets show another difference due to the temperature: Uranus and Neptune being significantly colder than Jupiter and Saturn. This means that many molecules condense on Uranus and Neptune that remain gaseous on Jupiter and Saturn. For example, gaseous ammonia, phosphine and water are detectable only in the tropospheres of Jupiter and Saturn. The white colour of Jupiter and Saturn is most likely due to the presence of ammonia ice clouds (Figure 3). We still do not know which compound is responsible for the colour of the Great Red Spot of Jupiter, an earth-sized meteorological feature (anticyclone) that has been stable over several centuries; it might include sulphur or phosphorus molecules, in gaseous or solid form.

The satellites of the outer planets exhibit a huge variety of conditions. Each object is individual, being the result of its specific evolution. A large number of the satellites, including the biggest ones, have nearly circular orbits close to the equatorial plane of their planet. As was observed by Galileo, the four largest satellites of Jupiter orbit in this way, like a miniature Solar System. This suggests that they were formed like the Solar System, from a disk that orbited their parent planet. Only the more massive planets have been able to act like a sun in this way, which is why the terrestrial planets do not have similar satellite systems. Other satellites of the outer planets, mostly the smaller ones, show a wide variety of inclinations and eccentricities of their orbits, which suggests that they were asteroids that were captured by the planet that they now orbit.

Even the four Galilean satellites of Jupiter, which have a common origin, show strong differences in their surface properties and composition. An interesting case is Io, the only solar-system object, apart from Earth, on which active volcanoes have been found. It lies close to Jupiter and to another Galilean satellite, Europa,

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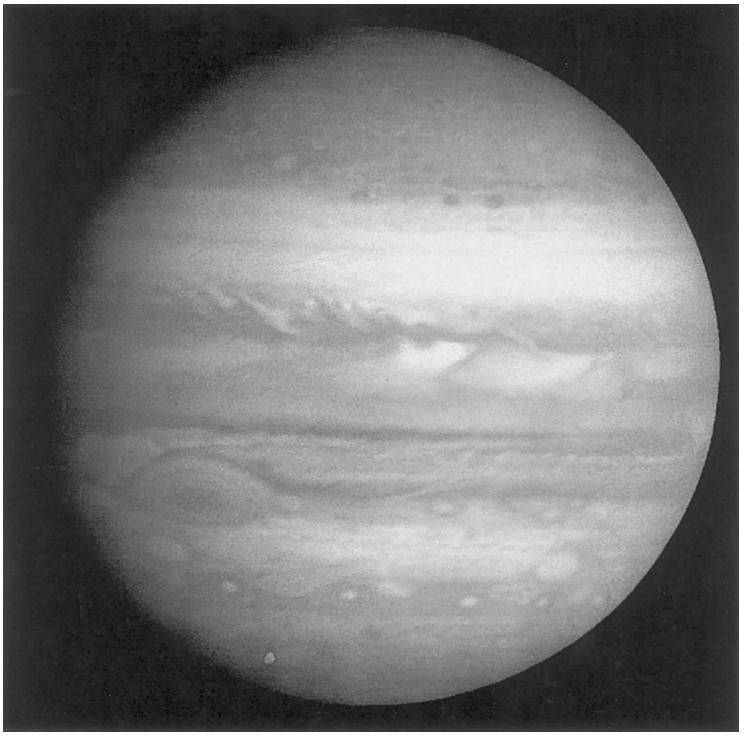


Figure 3. The planet Jupiter as observed by Voyager 1. The parallel structure in belts (darker regions) and zones (brighter regions) is easily noticeable. The white cloud of the zones is attributed to ammonia ice, at a pressure level of about 0.5 bar. In the southern hemisphere, the Great Red Spot is an anticyclonic feature as large as the Earth; it has been stable over four centuries (NASA).

which produces tidal effects that constantly remodel the surface of Io. Apart from Io, now too hot, the other Galilean satellites are mostly covered with water ice. In the case of Europa, the ice crust is cracked like ice floes, and shows other features, which suggest that the solid ice surface is floating on liquid or viscous material below the surface. This might be an ocean of water. Europa might then be the only solar-system object outside the Earth where liquid water is still present, which would have potential implications for the search of extraterrestrial life.

Another outer satellite of considerable interest is Titan, Saturn's largest satellite. Its nitrogen-rich atmosphere has a surface pressure comparable to the terrestrial atmosphere (1.5 bar) and contains many hydrocarbons and nitriles. These molecules are also found in the interstellar medium and lead to the formation of more complex molecules. It is thought that these molecules in their turn produce so-called prebiotic molecules that are the forerunners of

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biochemistry. In this way, Titan is a privileged target for studies in exobiology (the study of extraterrestrial life and the conditions for its development), representing an example of a prebiotic atmosphere that might imitate the Earth's atmosphere in its first few hundred million years. Titan is a prime target of the Cassini space mission, which was launched in 1997 and will reach Saturn in 2004, starting a four-year investigation of Saturn, its rings and its satellites. This ambitious project, jointly developed by NASA and ESA, includes a probe, Huygens, which will parachute through the atmosphere of Titan to investigate its so far unseen surface.

6. The terrestrial and the giant planets

The distinction between terrestrial and giant planets can be explained as a result of a temperature gradient within the protosolar disk. At small distances from the Sun (out to a zone between Mars and Jupiter), where the temperature was above several hundred degrees, only metals and silicates could be in solid form. The ices melted and, with other gases, were expelled by the heat of the Sun from the inner regions. The metal and silicate material led to the formation of planets with up to one earth-mass. There was little material nearby for them to grow further in mass.

By contrast, at larger heliocentric distances, where the environment was much colder, most of the elements except hydrogen and helium were in the form of ices (water, carbon dioxide, methane, ammonia, etc). The light elements from which these gases and ices are made (hydrogen, helium, carbon, nitrogen, etc) are much more abundant in the Universe (Figure 4) than the heavy elements from which the solid materials are made (silicon, oxygen, iron, nickel, etc). As a result, the outer planets were formed with larger masses and, according to models, their sizes may have reached 10–15 earth-masses. This initial mass was, in turn, sufficient to accrete further gaseous material (up to 100 times the earth-mass) from the surrounding nebula and this led to the formation of the giant planets.

7. The small bodies: asteroids and comets

Apart from the eight major planets and their satellites, other small bodies populate the Solar System. Most of the asteroids, or 'minor planets', lie in orbits between Mars and Jupiter, in the so-called 'main asteroid belt'. They have nearly circular orbits with low inclinations. In this part of the protosolar disk, strong tidal effects generated by the proximity of Jupiter disturbed the accretion process and a larger planet could not form. With diameters smaller than 1000 km, asteroids have a gravitational field too small to retain an atmosphere. Collisions between asteroids have generated numerous smaller fragments. Their surfaces are carbonaceous,

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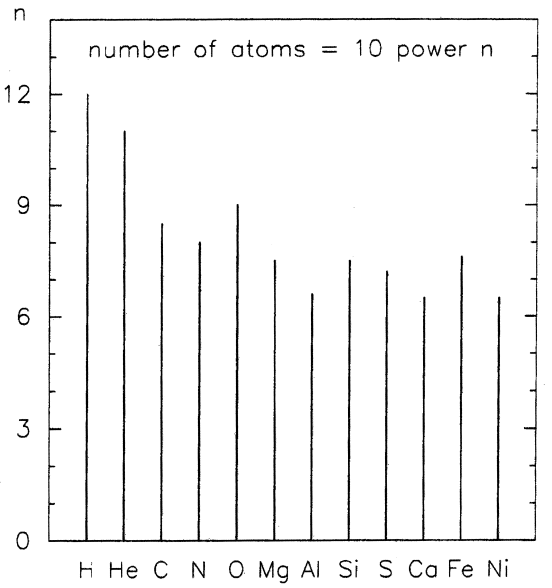


Figure 4. Cosmic abundances of the elements, derived from spectroscopic analysis of the Sun, complemented by chemical analyses of meteorites, and terrestrial and lunar rocks. The lightest elements (hydrogen and helium) and their isotopes were formed in the Big Bang. The heavier elements, up to Fe, were synthesized in stars. The figure is taken from D. Benest (2001) Solar system: formation. In P. Murdin (Ed) *Encyclopedia of Astronomy and Astrophysics* (IOPP/Nature).

rocky or metallic, depending on the asteroid's history and from where in a larger asteroid the material of the asteroid came, i.e. it could be a fragment of a crust or a core.

At larger heliocentric distances, and located on highly elliptical orbits, comets are even smaller than asteroids (usually less than 10 km in size) and mostly composed of water ice. Most of the long-period comets are believed to be located in a structure called the Oort Cloud, at a distance approaching 1 light year from the Sun. They probably did not form there, as the available matter would not be sufficient for accretion. It is generally believed that these comets formed in the vicinity of the giant planets, then were sent into the Oort Cloud by orbital perturbations induced by these planets. Occasionally, a comet falls from the Oort Cloud into the vicinity of the Sun. Comets Hyakutake and Hale–Bopp, which appeared in 1996 and 1997 respectively, were both new comets, probably on their first visits to the Sun. When a comet approaches the Sun, its surface melts and it sheds material around its nucleus; this material forms the comet's tail of dust.

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In some cases, the comet may be disturbed in its journey between the planets and become periodic. The most famous example is Comet Halley, with a period of 76 years. It is, of course, famous because Edmund Halley applied Isaac Newton's newly discovered Theory of Gravitation to what appeared to be several different comets, and saw that the orbits of three were identical. Conjecturing that these three were successive appearances of the same comet, he successfully predicted its posthumous return. Comet Halley last appeared in 1986 and was investigated by a fleet of five space probes, the only comet to be seen close up. The nucleus of Comet Halley is peanut-shaped, 15 km long and 7–8 km wide. It is remarkably black, with a low reflectivity, or 'albedo' of 4%. Where it has melted, its surface water ice is partly covered by a crust of tarry organic material. In addition to water, all observed comets contain a large number of molecular ices, including many organic compounds, which have been also detected in the interstellar medium. Comets could be a transport mechanism to deliver prebiotic chemistry to planets, this might have happened to our own Earth.

Because they are very small objects, which spend most of their lifetime in a very cold, unevolving environment, comets (and especially the non-periodic ones) are both frozen in temperature and frozen in time. They are considered to be samples of the conditions of the Solar System at the time of its formation. An ambitious space mission, named Rosetta, is being developed by ESA for an in-depth exploration in the next decade of Comet Wirtanen, in order to analyse the comet as a fossil from this epoch.

8. Beyond the outer planets: the new frontiers

After the discovery of Uranus by William Herschel in 1781, astronomers looked for a more distant giant planet that could account for its orbital perturbations, and this is how Neptune was found by Urbain Leverrier and Johann Galle in 1846. Another systematic survey, based on the same principles, led to the discovery of Pluto in 1930. A further (unsuccessful) search for a substantial trans-plutonian 'Planet X' went on for several decades. This long track led eventually to the generally unexpected discovery of a new family of numerous small solar-system bodies, the trans-neptunian objects. Over the past ten years, over a hundred objects have been detected at distances beyond the furthest planets, with typical diameters of a few hundred km. Like Pluto, which now appears to be the biggest member of this family, their orbits show significant inclinations and eccentricities. One of the biggest of these newly discovered trans-neptunian objects, Varuna, discovered in 2001, has a diameter of 900 km.

What is the origin of this family? Its existence was actually predicted, on theoretical grounds, by an Irish amateur astronomer Kenneth Edgeworth and by

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Gerard Kuiper several decades ago. The so-called Edgeworth–Kuiper belt includes objects that accreted from planetesimals in this region, and were far enough from the giant planets to escape orbital perturbations due to their gravity fields. It is also the reservoir for short-period comets which, for the same reason, kept their original orbits; this is why these comets' orbits are characterized by a low inclination.

9. From solar-system planets to exoplanets

On the basis of the data on the orbits, dynamics, physical properties and chemical composition of solar-system bodies, it has been possible to build a scenario of the formation and evolution of the Solar System. Is this scenario robust? If it was, we could reasonably expect that it would also be at work for other planetary systems outside our own. This happy thought has been supported, in particular, by the discovery of more and more protostellar disks around young stars.

However, astronomers have recently become more worried by the characteristics of the newly discovered exoplanets (see the accompanying article by Jean Schneider in this issue of the *European Review*), which demonstrate that what happened in the Solar System is far from being the only way that planetary systems can form and evolve. The exoplanets found so far have at least half the mass of Jupiter and more than half of them are in the immediate vicinity of their suns, with orbital periods of a few days. They do not look like our Solar System, and seem to have formed or evolved differently. There is, of course, a strong observational bias in this distribution, since the present techniques do not allow the detection of Earth-mass planets, and have not been applied for long enough to detect long-period planets like the giant planets of our Solar System. We are thus not yet able to detect the exact equivalent of our Solar System around any other star. However, the discovery of a large number of exo-giant planets near their star (which seems to occur in about 3% of solar type stars, according to current information) demonstrate that other scenarios exist for planetary formation and evolution.

At the present rate of progress, within a decade, we will have a much more complete view of the properties of exoplanets. The COROT mission, presently under development by the Centre National d'Etudes Spatiales, should be able to detect planets of a few terrestrial masses. Later, terrestrial exoplanets will become detectable with space missions such as Kepler or Eddington, both presently under development at NASA and ESA. In parallel, the passage of time will allow the detection of large planets located at considerable distances from their stars. It will then become possible to acquire more complete statistics on all kinds of exoplanets and to find out just why our planetary system seems to be, thus far to our

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knowledge, so different from many others. We will then understand better how the environment of our own Solar System came about.

Further reading

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