Formation of the earth and the moon

Planet formation

In our last article we dealt with the formation of stars. Stars form from a disk of gas and dust. This disk is also responsible for the formation of planets. In this contribution we want to deal with the formation of our earth.

As the disk continued to spin, condense, and cool, the small grains of cosmic dust collided with each other, clumped together due to the gravitational pull, and grew larger and larger. Eventually, their mass was large enough that they exerted a considerable gravitational pull, which drew even more tiny particles of matter toward them and made them even larger, increasing their gravitational pull yet again. Once these growing clumps of matter reached a diameter of about 1 km, they had enough gravity to act like "gravitational vacuum cleaners," sucking in all the cosmic dust in their orbit as they orbited the Sun (Fig. 1).

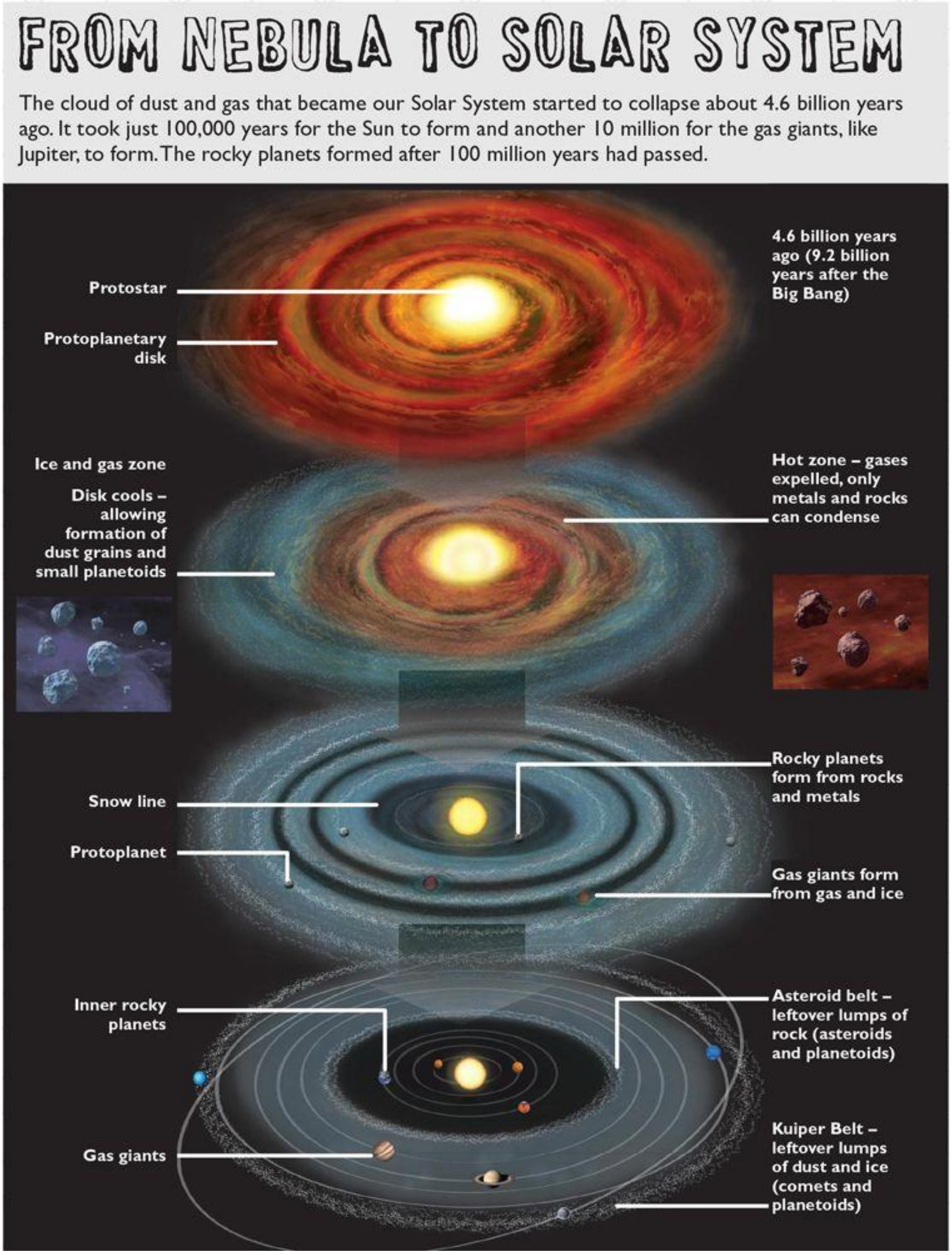
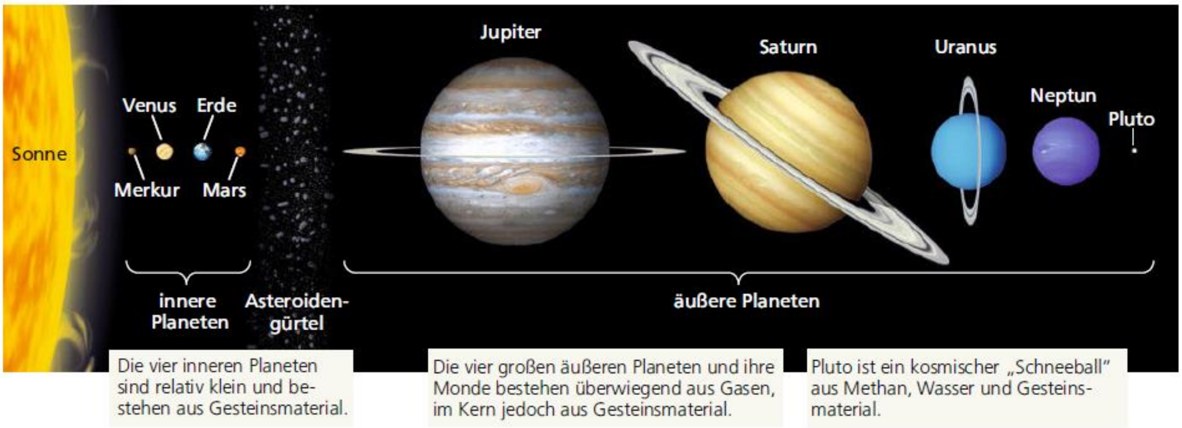


Fig. 1: Formation of the solar system

In 1905, geologist T. C. Chamberlain and astronomer F. R. Moulton referred to these small bodies as planetesimals. As these planetesimals grow larger, their gravitational pull increases, and they attract more and more loose cosmic debris until they form a clear circular orbit or track in the solar disk. This is especially true of gas giant planets such as Jupiter and Saturn, which form huge distinct orbits as they orbit the central star. The same is true for young solar systems like HL Tauri, where their own protoplanets have left tracks in their disk.

Meanwhile, the energy of the nascent sun at the center of the solar system (99.9% of the total mass of the solar system) changed everything. Initially, the proto-sun's gravity attracted most of the matter in the original cosmic disk. As the solar nebula cooled, a temperature gradient developed from the center to the edge of the disk, which began to redistribute and shape the growing solar system. Near the protosun, temperatures exceeded 2000 °C, and everything was vaporized. While heavy volatile elements and compounds could condense near the sun, light volatile gases, on the other hand, were "blown away" by the solar winds. About 5 million kilometers from the protosun, temperatures were cool enough for rocky bodies to solidify. This is the so-called "rock line" where the smaller, inner rocky planets (Mercury, Venus, Earth and Mars) could eventually coalesce. In these the elements oxygen, aluminum, iron, nickel, silicon, magnesium and calcium have strongly enriched. Even farther out is the "frost line," where temperatures were -375 °C or less. This is cold enough to freeze not only liquid water into ice, but also carbon dioxide, methane (CH4), and ammonia (NH3). This characteristic composition is the most striking feature of the outer planets such as Jupiter, Saturn, Neptune, and Uranus, which are huge frozen balls of gas with very little rocky material (Fig. 2).



Die vier inneren Planeten sind relativ klein und bestehen aus Gesteinsmaterial.

Die vier großen äußeren Planeten und ihre Monde bestehen überwiegend aus Gasen, im Kern jedoch aus Gesteinsmaterial.

Pluto ist ein kosmischer „Schneeball" aus Methan, Wasser und Gesteinsmaterial.

Fig. 2: planets of our solar system

In 2018, scientists using the European Space Observatory's Very Large Telescope in northern Chile managed to get the first good image of a new planet in the making. It was found at a star called PDS70, which is more than 370 light-years away. This planet, named PDSb, is still condensing in the inner part of the planetary disk at a distance about 22 times the distance between the Sun and Earth. The image clearly shows that it intersects a circular orbit around the star at its center, as it would have in the early history of our solar system. The planet PDSb is a gas giant even larger than Jupiter, so it will not turn into a rocky, Earth-like planet like ours. Moreover, its surface temperature is still 1200 K, so it is still far from cooling to a frozen gas giant like Jupiter (Fig. 3).

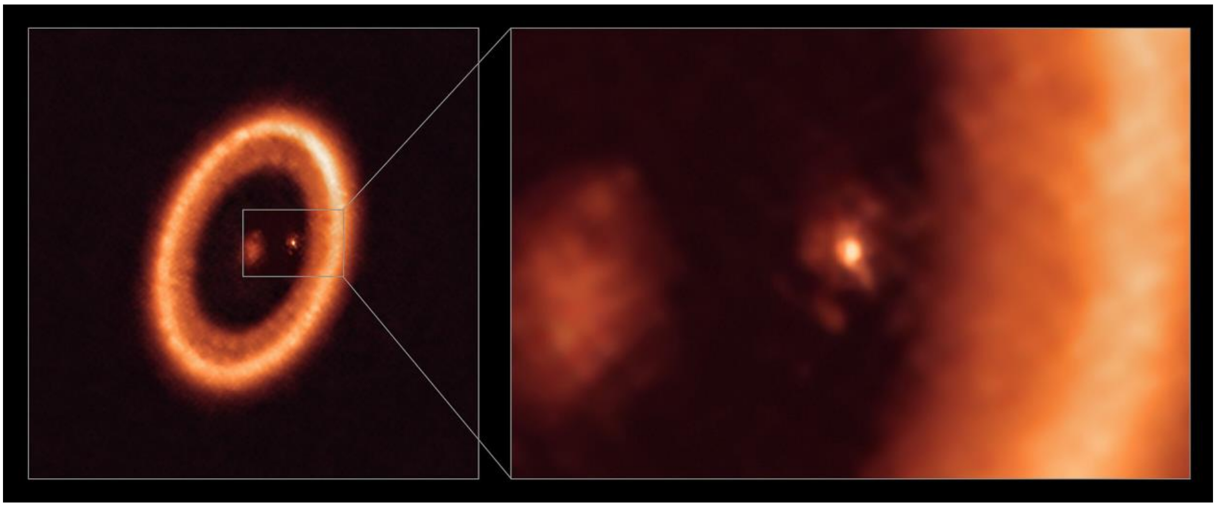


Fig. 3: Image of the protoplanetary disk of PDS 70 and the two exoplanets PDS 70 b and c.

After 3 million years, the planetesimals have clustered into larger and larger bodies until they reach diameters of 100 km or more and become protoplanets. At this point, their gravity and internal heat are sufficient to give them an approximately spherical shape. Much of the loose cosmic dust of the early solar nebula was attracted by the gravitational pull of the growing protoplanets (Fig. 1).

Then, about 50 million years after the formation of the solar nebula, a critical threshold was crossed. The protosun accumulated enough heat and energy to collapse by its own gravity and trigger nuclear fusion of its hydrogen into helium. This is the same reaction that occurs in the hydrogen bomb and powers fusion reactors. This reaction has allowed the Sun to become a full-fledged star, capable of burning for more than 10 billion years while powering the solar system. The energy from this massive fusion reaction was first released in the form of large bursts of solar wind, a huge stream of charged particles (known as plasma) that continuously flowed out of the Sun. This first intense burst of solar wind blew away much of the remaining cosmic dust from the inner solar system, almost completely clearing interplanetary space and preventing the inner planets from gaining much more mass.

Some planetesimals never become protoplanets. You can still see remnants of planetesimals in our solar system in the form of asteroids, comets, and meteors. The study of meteorites - meteors that contain enough material that they survive the fiery journey through Earth's atmosphere and fall to Earth's surface - is a rich source of information about the formation of the solar system. Comets - small objects that travel in distinct elliptical orbits around the Sun - provide even better information about this process because they were not exposed to the searing heat of passing through Earth's atmosphere.

Formation of the Earth

One of these protoplanets eventually became our Earth. It is about 149 million km from the protosun, a distance sometimes called the "Goldilocks zone" (Fig. 4). At this distance, it is neither "too hot" (otherwise it would become an overheated place like Venus, where the atmosphere is hot enough to melt lead) nor "too cold" (so that solar heating is so weak that the planet is frozen solid like Mars).

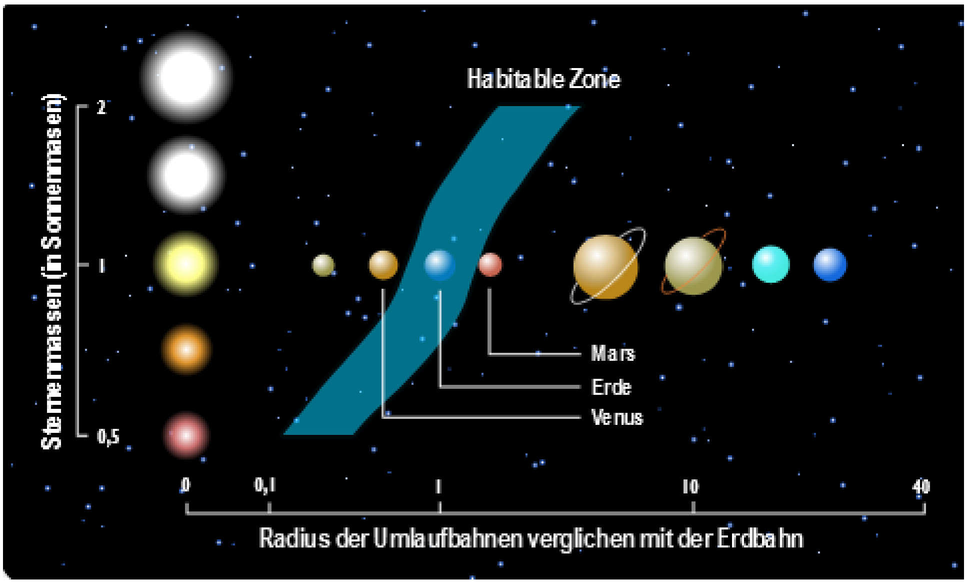
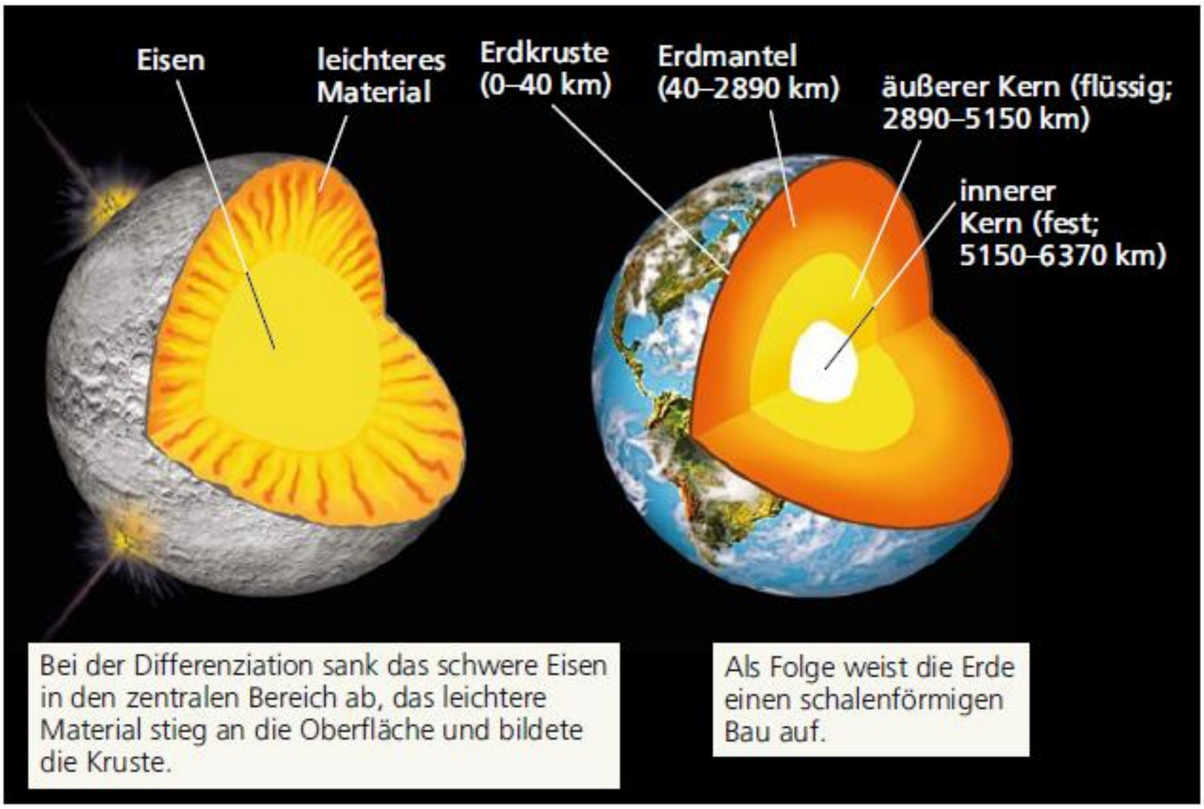


Abb. 4: Goldilocks zone

At the temperatures of the Goldilocks zone, the swirling clumps of matter and planetesimals concentrated, mixing the large quantities of the usual solid elements (silicon, aluminum, iron, nickel, magnesium, calcium, sodium, potassium) with lighter gases such as oxygen, nitrogen, carbon, helium, and especially hydrogen. When these elements first came together, they formed a well-mixed mass with uniform composition throughout Proto-Earth. Some of the heaviest elements, such as iron and nickel, sank to the center of the protoplanet because of their greater density. In contrast, the lightest gases, especially the very abundant elements hydrogen and helium, largely escaped into space because Earth's gravitational pull was not strong enough to keep them there (Fig. 5).

About 30-60 million years after formation, the differentiation of the Earth into mantle and core took place. During this process, the iron-nickel core (ratio 10:1) with a density of 10-13 g/cm^3 separated from the mantle, which has a density of 3-5 g/cm^3 (Fig.5).



Bei der Differenziation sank das schwere Eisen in den zentralen Bereich ab, das leichtere Material stieg an die Oberfläche und bildete die Kruste.

Als Folge weist die Erde einen schalenförmigen Bau auf.

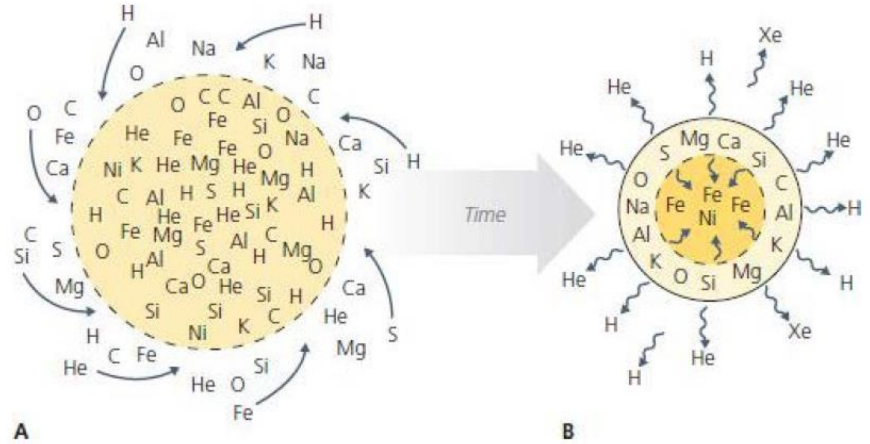


Figure 7.7 Earth's elemental distribution. **A.** When the earth first condensed, it was a random mixture of the common elements in the solar system, especially gases like hydrogen and helium but also rarer materials like oxygen, aluminum, silicon, magnesium, iron, calcium, sodium, carbon, sulfur, and other elements. More material was continually drawn into this swirling mass by gravity. **B.** When the earth melted due to the excess heat from several sources, the elements separated out by density and the earth developed layers. The lightest gases (H, He) were too light to be held in by the earth's weak gravity and escaped. The heaviest elements (Fe, Ni) sank to the center. Those less dense solid elements that that remained (Si, Al, O, Ca, Na, Mg, K, and some Fe) were left behind to form the mantle.

Fig. 5: Differentiation of the Earth into layers and mantle.

Simple deposition by gravity alone is not sufficient to explain the differentiation of the Earth into its layers, with an iron-nickel core surrounded by a silicate rock mantle. To completely divide the Earth into layers with completely different compositions would require enough heat to melt the entire planet. This would cause almost all of the dense iron and nickel to sink into the center of gravity, while the less dense silicates would float on top. Where did all this heat come from? There are several possible sources. The early proto-Earth was full of unstable elements that decayed radioactively.

Radioactive decay releases a tremendous amount of heat, about 50% of the heat is released in the first half-life. All the major radioactive elements found in the Earth today, such as uranium-238, uranium-235, rubidium-87, and potassium-40, were in their first half-life and were much more abundant at the beginning of the Earth's formation, so their heat production was greatest.

However, there are also meteorites such as the carbonaceous chondrite that date from the early days of the solar system when the Earth was just forming. They suggest that another element may be responsible for most of the heat production. These meteorites contained unusual amounts of the rare isotope magnesium-26, which is a daughter product of the radioactive decay of aluminum-26. Aluminum-26 decays very rapidly, with a half-life of only 700,000 years, so nothing of Earth's original aluminum-26 remains. However, it was apparently very abundant in the early condensing proto-Earth, so it must have been the most important element in the melting of the Earth.

Much cosmic debris remained in the early condensing proto-Earth, so that the Earth was under constant meteorite bombardment (Fig.6). The impact of a meteorite represents an enormous amount of kinetic energy, which is converted into thermal energy upon impact with the Earth. The dating of meteorite impact craters on the Moon indicate that the early solar system was still undergoing an intense bombardment that did not subside until about 3.9 billion years ago. Among these impacts was the one in which a piece of the Earth's mantle was blown off, forming the Moon. Thus, the Earth would have received additional heat from the impacts of chunks of rock from space. As the chunks of iron and nickel sank into the Earth's core, they released a lot of potential energy. Like any other form of energy, potential energy cannot be destroyed, but must be converted into another form of energy, namely heat.

Fig. 6: Earth under constant meteorite bombardment.

Inside the Earth, strong gravitational forces prevail, increasing not only the pressure but also the temperature. This is sufficient to melt many of the materials that eventually formed the Earth's mantle. This is also why the Earth's outer iron-nickel core is liquid. Finally, as the Earth's densest materials began to sink toward the center, they also changed the Earth's angular momentum. If the Earth were as small as a figure skater, it would spin faster as a result. However, the Earth is too massive to respond to this small change in angular momentum, but the energy change has to go somewhere - so it is converted to heat. At the end of this process, about 4.5 billion years ago, the Earth had its discrete layers of an iron-nickel core and a magnesium-silicate-rich mantle. It was still too hot to allow a crust on the outside to cool, so the Earth had only two primary layers.

Formation of the moon

For thousands of years, people have stared at the Moon and wondered what it was made of and how it was formed. There have been all sorts of ridiculous or silly ideas, such as the notion that the Moon was made of cheese, but few serious hypotheses have been proposed by the scientific community. The ideas fell into three broad categories:

The capture theory (Fig. 7) postulates an independent formation of the Moon in another region of the solar system. It was gravitationally captured during a close encounter with the Earth. This hypothesis provides a good explanation for the large density difference between the Earth and the Moon, but not for the large chemical and isotopic similarity. There are other problems with this hypothesis: for one thing, the Moon's orbit around the Earth is almost in the same plane as the Earth's orbit around the Sun (deviating only 5° from our plane around the Sun), and it moves in the same direction as the Earth, which would be unlikely if an object coming from space at a different angle were captured. Such an orbit would most likely oscillate around the Earth in any plane except the plane of the Earth-Sun system. Furthermore, when a large body is captured by gravity, either a collision occurs or the object flies back into space with an altered orbit. In order for the Moon to be slowly captured by Earth's gravity and remain in orbit without collision or escape, Earth had to have a very dense atmosphere at the time that extended much farther than it does today to cause friction and drag and slow the object down. There is no evidence that the Earth's atmosphere was that much thicker then. If the Moon were an exotic object captured by Earth's gravity, its composition would be radically different from Earth's. After the Apollo missions brought back samples, scientists studying the lunar rocks were able to test this, which confirmed the chemical and isotopic similarity to Earth's rock.

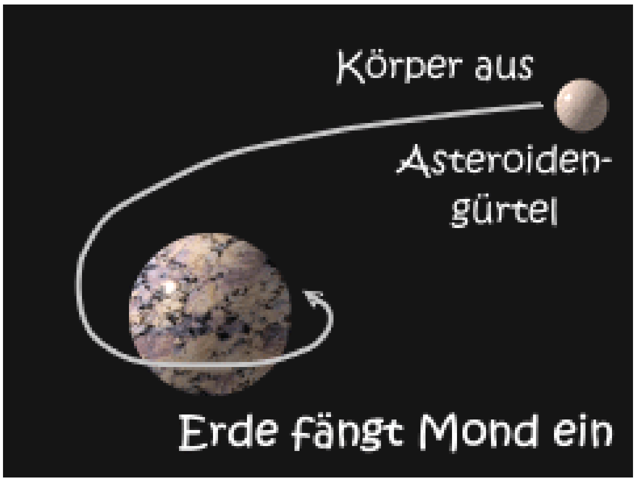


Fig. 7: Capture Theory

The second hypothesis, the "double planet hypothesis" (Fig. 8) can explain this chemical similarity. This scenario, first proposed by astronomer George Darwin (son of Charles Darwin) at the end of the 19th century, states that the Moon was formed from the original, rapidly spinning undifferentiated Earth matter. During this rapid rotation, molten Earth matter flew into space and formed the Moon. Some astronomers even suggested that the Pacific Ocean basin is a remnant of this event. This scenario seemed plausible for many years, although plate tectonics in the 1960s had shown that the Pacific basin is not an ancient scar, but is covered by very young lavas, most of which are less than 140 million years old. Furthermore, the "double planet model" cannot explain the density difference and the much too small core of the moon.

Fig. 8: double planet hypothesis

However, the collision hypothesis (Fig. 9) can explain both the chemical similarity and the density difference: According to this hypothesis, the proto-Earth and a Mars-sized planet (Theia) collided at the end of core-mantle differentiation. This event is called

"Giant Impact". In the process, the Earth was ripped open deep into the mantle and its rotation was greatly accelerated. Part of the intermixed mantle material of Proto-Earth and Theia was hurled into the near-Earth environment. From this, the chemically and isotopically similar moon formed. Most of Theia's core material coalesced with that of Proto-Earth, which is why the moon has a core that is much too small for its size and a density that is too low. This hypothesis assumes that core formation on Earth was already well advanced or completed at the time of the Giant Impact.

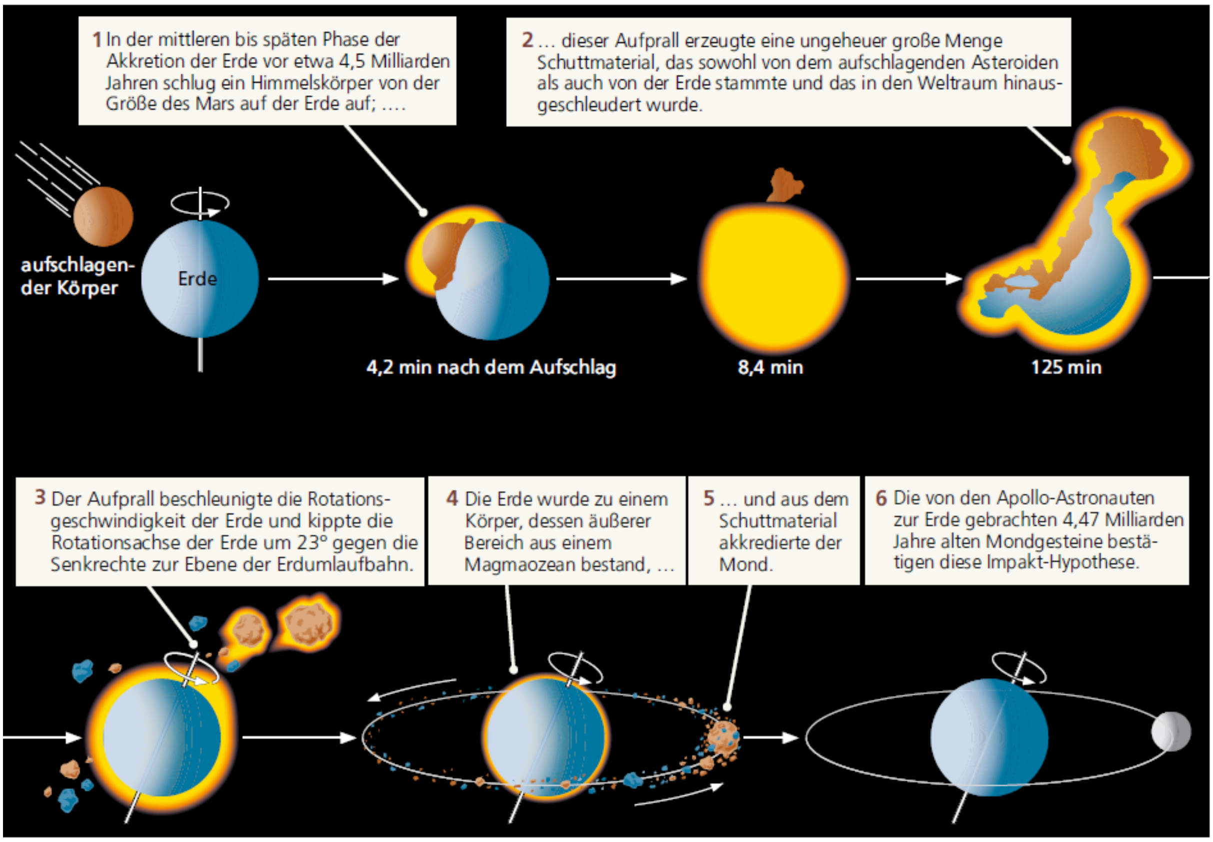


Fig. 9: Collision Hypothesis

The lunar rocks brought by Apollo 11 to Apollo 17 did not resemble the early Earth in composition. Nor were they an exotic composition, as if they had been a gravity-captured body from outside the Earth. Instead, they were composed of a form of calcium plagioclase-rich gabbro known as anorthosite and its volcanic equivalent, the familiar black lava known as basalt. In other words, their composition closely resembled that of the upper mantle, where the lavas that erupt as basalt on the ocean floor or in volcanoes originate. If the Moon is composed almost entirely of material like that of the Earth's mantle, with very little iron or nickel like that found in the Earth's core, then it must be a piece of the Earth's mantle that formed after the primordial Earth separated into a core of iron and nickel and the mantle of silicate minerals. In other words, the Moon was formed after the Earth had cooled and coalesced and its layers had differentiated and separated.

When Theia (the Greek name for the mother of Selene, the goddess of the moon) hit the Earth with an impact at an angle, material was thrown sideways from the Earth into orbit. The energy of this impact would have been incredible! Trillions of tons of material would have been vaporized, and the Earth's temperature would have risen to 10,000

°C. Once this debris began to orbit the Earth (at one-tenth the distance the Moon is today), it would have gradually clustered together and, over the course of about 1,000 years, would have coalesced into the primordial Moon.

The heat of its own radioactive minerals would later have completely remelted parts of the Moon, and most of the Moon would have remained in the same composition as the Earth's mantle, while the melting also caused huge eruptions of basaltic lava flows that formed the magma oceans that today form the dark "seas" on the lunar surface. Meanwhile, the Moon has a tiny iron core only 330-350 km in diameter, thought to be a remnant of Theia's core left behind after the collision; most of Theia's own iron-nickel core must have been added to Earth's core.

When did all this happen? Again, the lunar rock samples provide the answer. Using radiometric dating methods, many laboratories have dated lunar rocks. Most are at least 4 billion years old, suggesting that the surface of the Moon formed early and has changed little since then. Finally, the Moon has none of the forces that change Earth's surface: It has no atmosphere, no water, no weathering, and no plate tectonics. The only major changes on its surface are huge impacts that have left craters, and most of the crater debris has been dated to be more than 3.9 billion years old, meaning most of the impacts occurred early and not much has happened since.

The oldest pre-impact rock data for the Moon is currently 4.44 billion years old. This is much younger than the meteorites dating back to the formation of the solar system. Thus, the Moon is definitely younger than the events that formed the Solar System and Earth, as well as the melting and differentiation episode that separated the Earth's core from its mantle. Since the original proposal of the giant impact hypothesis, analysis of lunar rocks has yielded much additional circumstantial evidence supporting the origin of the Moon from the Earth's mantle. Nearly all geochemical isotopes studied since the discovery of lunar rocks have shown that the Moon and the Earth's mantle have the same chemical composition.

The existence of a large moon as a companion to Earth has several consequences: The Moon and Earth are gravitationally bound to each other. In the beginning, the moon was probably only about 80 000 km away, while today it is 384 000 km away. Due to the proximity, enormous tidal forces acted at the beginning, which were possibly 100 times stronger than today. Thus much energy was supplied to the earth mantle and prevented its rapid cooling. However, the tidal friction also acted on the moon, causing it to lose its proper rotation and slowly move away. The Earth's rotation also slowed down, and the Earth's day lengthened from about 8 hours to 24 today. We have tidal friction to thank for the Earth's strong magnetic field and the ebb and flow of the oceans. The existence of a coastal strip that dried up for a short time and then flooded again probably stimulated evolution in the direction of continental settlement.

Formation of the crust and oceans

The Giant Impact is of crucial importance for the development of the early Earth. The shock of this impact disrupted the Earth deep into the mantle and at the same time heated it extremely. A molten magma ocean formed with surface temperatures exceeding 2000 °C and intense convection. The strong tidal friction of the young Earth-Moon system heated the Earth additionally. Thus it degassed a large part of its water and carbon dioxide from the mantle into a very dense protoatmosphere. Over the next 30-60 million years or so, the surface then slowly cooled to about 1000°C. A first peridotitic to basic crust formed on the Earth's surface, but it was not stable because of its high density. Water vapor and CO2 continued to form an extremely dense atmosphere. The water vapor partial pressure is estimated to be > 200 bar, the P CO2 to be 50-200 bar. Thus, the early atmosphere had 250-500 times the pressure of the Earth's atmosphere today.

During the period of 100-400 million years after the Giant Impact, the Earth's surface cooled to a temperature below 200 °C. Due to the high pressure of the atmosphere, water vapor now began to condense and a continuous rain, presumably lasting for thousands of years, began; it formed the proto-ocean (Fig. 10).

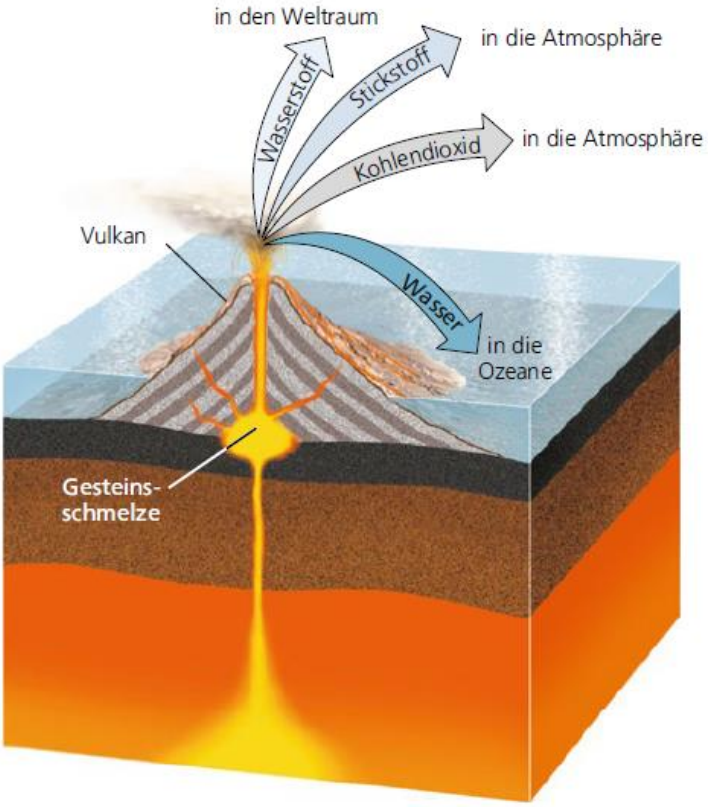


Abb. 9.6 Durch Vulkanausbrüche gelangten in der Frühzeit der Erdgeschichte große Mengen Wasserdampf, Kohlendioxid und Stickstoff in die Atmosphäre und Ozeane. Der leichtere Wasserstoff verflüchtigte sich in den Weltraum

Fig. 10: Formation of oceans

For decades, most geologists assumed that the cooling of the Earth's crust was too slow to have occurred much earlier than about 4.0 billion years ago. Most believed that the Earth took 500-600 million years to cool below the boiling point of water after it formed.

Then in 2014, scientists made a startling discovery in some sand grains from Australia. More specifically, it was a handful of sand grains made of zircon (zirconium silicate or ZrSiO4) from a much younger sandstone in the Jack Hills of Western Australia (Fig. 11). Each individual grain can be dated by uranium-lead methods, resulting in a scatter of ages. However, the oldest grains give an age of 4.374 billion years, which was confirmed and re-dated by John Valley and his colleagues in 2014. The current record holder for the oldest crustal material on Earth (i.e., not a meteorite or lunar rock) is thus 4.4 billion years. With these sand grain dates, we are getting closer and closer to the age of lunar rocks and meteorites, but there is still a gap of about 160 million years between 4.4 billion and 4.56 billion.

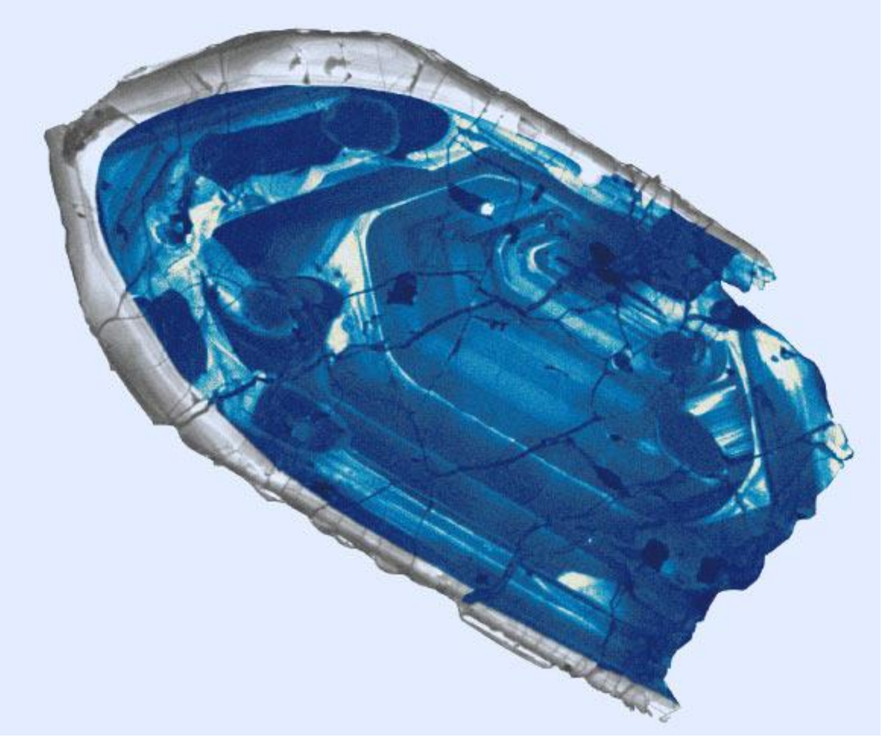
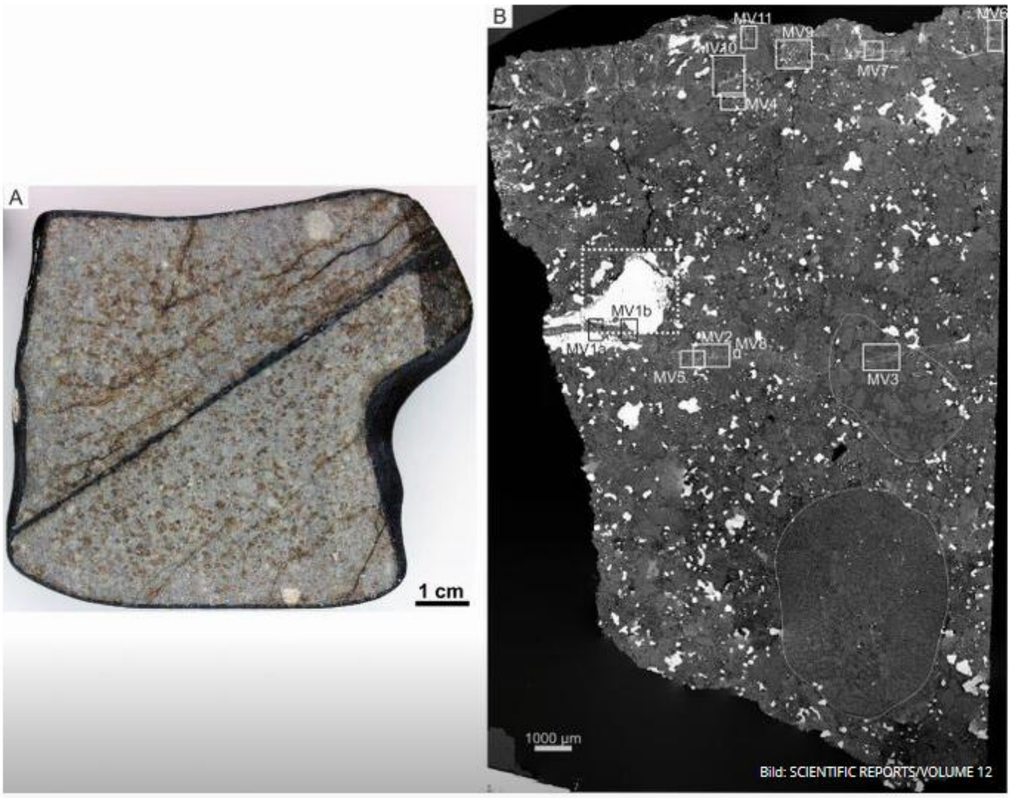


Fig. 11: Zircon crystals from Jack Hills.

Those same tiny zircon sand grains contained even more surprises. Not only did they provide the oldest known data, but when scientists analyzed the ratio of the two oxygen isotopes found in them, they found evidence of the early hydrosphere. These zircons contained oxygen isotopes that indicated that the Earth had liquid water on its surface as early as 4.4 billion years ago! Prior to this discovery, geologists had always assumed that the Earth took a long time to cool from its molten state 4.56 billion years ago. However, the Jack Hills zircons turn this assumption on its head. If they truly indicate the presence of liquid water on Earth 4.4 billion years ago, then it took Earth only about 160 million years to cool from its molten state to a state below the boiling point of water. This evidence also suggests that there could not have been that many meteorite impacts in that time span, or the oceans would have evaporated over and over again.

But where did the water of the early Earth come from? Traditionally, geologists thought it was water trapped in the Earth's mantle as it cooled, gradually escaping through volcanoes in a process called degassing (Fig. 10). However, recently chemical analyses of extraterrestrial objects have agreed with the chemistry of Earth's oceans (especially carbonaceous chondrite meteorites). This suggests that much water was trapped in the debris of the early solar system (of which the chondrites are remnants) (Fig.12). The same is true of lunar rocks, which do not contain much water today, but were apparently wetter when the solar system was formed. If so, then the Earth was born with water already present as it cooled and condensed. The surface temperature only had to drop below 100 °C for the water to form the first oceans.



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Im "Kakowa Meteoriten", der 1858 in Rumänien eingeschlagen hat, wurden nun Spuren von Wasser entdeckt. Rechts sind die Schmelzadern zu sehen.

Fig. 12: Chondrites

One explanation we can rule out is comets. Although comets are often called "dirty snowballs" because they are composed mainly of water ice and dust, chemical analyses of four comets show that their geochemistry is very different from that of Earth's water. This allows the popular notion that comets impacted the early Earth and merged to form its oceans to be discarded.

During ocean formation, water-soluble volatiles in the atmosphere were washed out and soluble precipitates were dissolved on the Earth's surface. They accumulated as salts (e.g., NaCl) in the ocean. Since the water vapor was now mostly bound in the ocean, the pressure in the atmosphere decreased. However, the P CO2 was probably still around 50-200 bar. The ocean probably covered most of the Earth's surface, with only small, insular mainland areas protruding.

Evaporation of the ocean water and its renewed precipitation started the hydrological cycle. Weathering and sediment formation slowly set in. Water that could penetrate cracks and fissures in the basic to peridotitic crust hydrated minerals such as olivine and pyroxene to form hydrous serpentine and chlorite with lower density (Fig.13). This made the crust lighter and allowed it to remain on the surface longer than the short-lived peridotite crust. Among the oldest crustal rocks, besides the mentioned Jack Hills crystals, are the Greenstone Belts, whose oldest formations in Canada are about 4.3-4.4 billion years old.

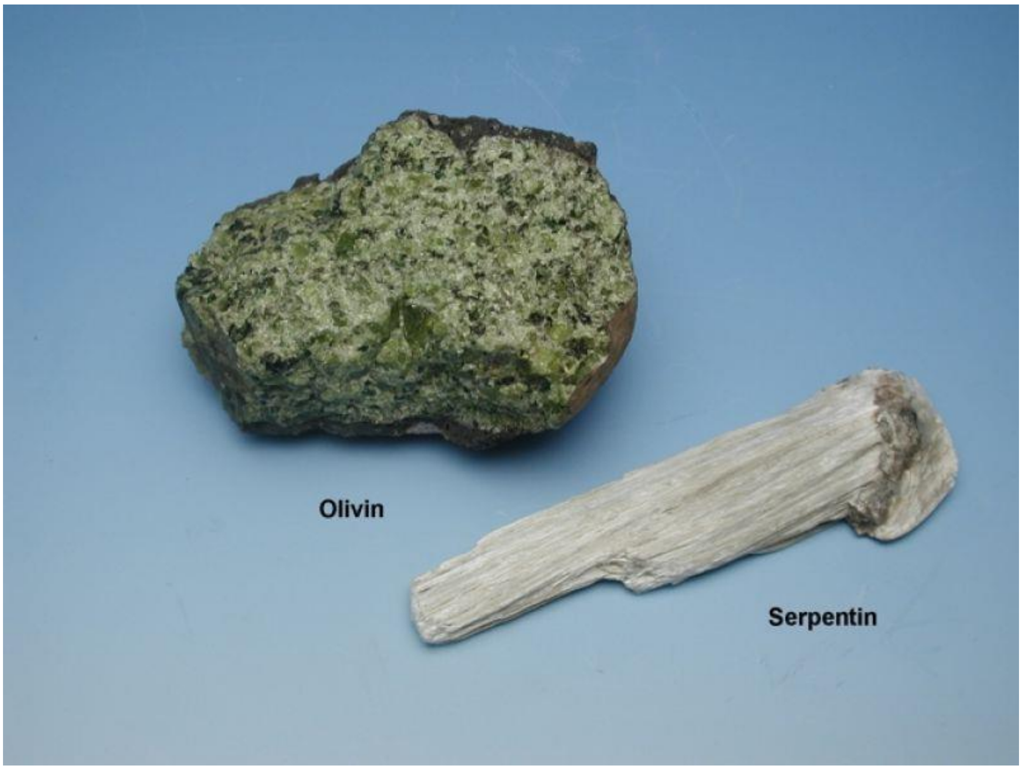

Fig. 13: Formation of serpentine minerals from olivines.

During the subduction of the crust, water was brought into the mantle by the dipping crustal parts, they caused a reduction of viscosity and intensified convection in the mantle. Gradually, basaltic and finally granitoid magma could differentiate from peridotitic magma, forming a permanent crust. Today, the granitoids are present as highly metamorphic gneisses, which probably intruded or accumulated around the greenstone belts as SiO_2-rich magmas.

The process of continental crust formation, which started in this way, lasted for a very long time. The main crust formation phase was probably between 3-1 billion years before today. From the Phanerozoic on, crust formation and crust recycling in the mantle almost balance each other. Today, the basaltic, oceanic crust covers about 60%, the granitic, continental crust about 40% of the earth's surface.

Here we have it now: the early earth with its moon. It has an earth core of iron and nickel, the earth crust and the oceans were formed. Life did not exist at the beginning of the earth's formation. Before we explore this, in the next post we will look at some other physical conditions of the Earth: the Earth's magnetic field, the formation of plate tectonics and the continents, and the basics of the climate of the early Earth.

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