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Cosmic Vision

Editorial

One might consider space science unrelated with our human history.

You, dear reader of *Spatium,* know that nothing could be more wrong. Without taking into consideration the cosmic past, our presence here on Earth appears to be a mere matter of course. It is on the stage of space science that our life reveals itself as the result of events commencing right in the universe's earliest moments. Take, for example, water, our body's major constituent: it consists of two hydrogen atoms united with one oxygen atom. While the first come unaltered from the unimaginable events in the Big Bang, some 14 billion years ago, the latter is the result of nuclear fusion processes in stars that shined and died long before our solar system saw the light of the day. No doubt: our roots are deeply anchored in the cosmos' distant past.

Not only, though. Take for instance the Sun: for 4.6 billion years our daytime star has delivered the warmth enabling life to evolve on Earth. Still, like every medal, the Sun has two facets as well: it emits not only the visual light, to which our eyes are so well adapted, but also ultraviolet radiation that is harmful to living cells. This dangerous part of the Sun's radiation creates the ozone layer, high above our heads in the atmosphere, whereby it is sorted out while the rest passes freely down to us earthlings: our existence depends most fundamentally also on the processes taking place hic et nunc in our cosmic front yard. These are but two examples of a chain of events in the history of the universe to which humans are just one response of Nature.

Space science helps us to understand the miracle of our existence. This may be one of the reasons why space science is at the core of the European Space Agency ESA (of which Switzerland is a founding member) and this is also why our Pro ISSI association invited Professor David Southwood, Director of ESA's Science Programme, to present the current status of the programme together with his visions for the years to come. The Cosmic Vision, ESA's master plan for space science, is federating the European skills together with those of other space-faring nations to address jointly the most fascinating topics in space research.

The present issue of *Spatium* summarizes Prof. Southwood's talk as well as the Agency's Cosmic Vision plan. We are indebted to Prof. Rudolf von Steiger, Director at ISSI, who cared about the scientific correctness of the present text.

The present issue of *Spatium* is also a summary of its forerunners; with the Cosmic Vision in mind, it sets the stage for all the fascinating results to be reported in future issues of Spatium.

Brissago, February 2010
Hansjörg Schlaepfer

Impressum

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Front Cover
A pilgrim transcending the medieval lore is shown in this magnificent wood engraving first published in *L'atmosphère: météorologie populaire,* by Camille Flammarion, Paris 1888. The original is attributed to an anonymous artist at the beginning of the Renaissance.

COSMIC VISION[1]

Hansjörg Schlaepfer, Brissago

Introduction

One might think that scientists know what is to be known about the universe. Since the dawn of mankind, humans have looked at the sky and tried to understand the mysterious world out there. Thousands of years ago, an early society erected the gigantic stones in Stonehenge, Great Britain, exactly in line with the midsummer sunrise. Four hundred years ago, Galileo Galilei directed his *cannochiale* to the sky that uncovered a world never seen before by human eyes. Fifty years ago, Sputnik I initiated a new era that led to today's fleet of spacecraft rushing through space in search of new discoveries. All these endeavours are nourished by the fascinating results of space research that still do not become increasingly sparse, but rather increasingly exciting: Nature's wealth of mysteries is boundless.

Now then, what are the remaining secrets of the universe scientists would like to know? Where do they expect the most enlightening discoveries to be made in the years to come? What are the key questions that the European Space Agency (ESA) intends to address in the future? The present issue of *Spatium* aims at providing some answers to these questions.

ESA was founded in 1975 not least based on the initiative of Swiss scientists and politicians to foster European efforts to explore space for peaceful purposes. From the very beginning, space research has been the very core of ESA and the overwhelming success of its scientific spacecraft has won it worldwide acknowledgement as one of the leading space agencies.

With the intention of harmonizing the endeavours of European academic and industrial communities, the Agency formulated the Horizon 2000 long-term plan for space science in 1984 that defined the priorities and programmes for the subsequent 10 to 20 years. Its successor, the Horizon 2000+ plan, was approved ten years ago; it constitutes the programmatic foundation of the scientific satellites and space telescopes currently in orbit. Building on past success to address the scientific, intellectual and technological challenges of tomorrow, ESA made another planning cycle in the first years of this new millennium which resulted in the Cosmic Vision plan outlined in the present issue of *Spatium*. It is basically built around the following four main areas of space research:

- **How did everything begin?**
- **What are the basic laws of physics?**
- **Are we really alone?**
- **What makes the solar system tick?**

Obviously, these questions are not specifically European; rather they are of interest for thinking humans all over the world. It is, therefore, one of the key elements of the Cosmic Vision plan to seek co-operation with other space agencies in order to not only benefit from the experience and skills gained elsewhere but also to share the costs of the anticipated missions. Beyond paving the way for fascinating results, the Cosmic Vision programme therefore contributes also to furthering the understanding of scientists and engineers all over the world.

[1] The present issue of *Spatium* is loosely based on a lecture given by Professor David Southwood for the Pro ISSI audience on 24 March 2009 and reported by Dr. Hansjörg Schlaepfer, Brissago.

How Did Everything Begin?

OMNIUM RERUM PRINCIPIA PARVA SUNT[2]

Marcus Tullius Cicero[3]

This is admittedly not quite a new question. Rather, generations before us have wondered already about how this world might have come into being. Great thinkers in all cultures have made their speculations ranging from the cyclic upcoming of what has been here forever to a universe with both, a definite beginning and a definite end. Cosmology, today, advocates a definite beginning, as described by the Big Bang model, while the future of the universe is still under debate.

The Early Universe

The Big Bang model is a physical concept of how the universe might have come into being[4,5]. It has won wide acceptance as it is firmly underpinned by observations one can make today. Yet, it fails to describe the very earliest – and most crucial – instances when time, energy and matter were born. At that moment, the physical properties of the emerging universe exceeded by far the grasp of our understanding. Some split second later, however, it expanded and cooled down and its parameters entered the reach of contemporary physics; from now on, the evolution of the universe becomes understandable. Not quite, however, as we will see later.

The First Light

A few minutes after the Big Bang, neutrons combined with protons to form the first deuterium and helium nuclei. These are the first building blocks of matter as we know today. About 380,000 years later, the temperature had cooled down to a value that allowed these nuclei to bind electrons resulting in the first neutral atoms. That was a great event as it permitted light to propagate freely through space from now on: the universe became transparent. It is certainly one of the most phantastic results of recent space research to probe this first light and to observe the universe in its earliest infancy.

This light is called cosmic microwave background radiation as it presents itself today as a microwave radiation from all over the sky. It was found accidentally by Arno Penzias[6] and Robert Wilson[7] with a ground-based detector in 1964. While initially it was thought to be isotropic, later spacecraft equipped with more sensitive instruments revealed tiny radiation (or equivalently temperature) differences in the order of 0.000,1 °C, **see Fig. 1.** The point here is that these early fine structures are essential for our existence as a perfectly homogeneous universe would be unable to form inhomogeneities such as stars and planets.

The primary inhomogeneities stem from quantum fluctuations in the very early universe, which grew with time to macroscopic structures by gravitational attraction. However, the visible matter in the universe is insufficient for that process, so scientists have to resort to what they call Dark Matter[8] to explain these fine structures. Dark Matter designates a hypothetical form of matter that cannot be seen with electromagnetic waves – hence the attribute dark – but can be inferred from its gravitational pull on visible

2 Free translation: the beginnings of all things are small.
3 Marcus Tullius Cicero, 106 BC, Arpinum, today Italy, – 43 BC, Formia, today Italy, Roman politician and philosopher.
4 See *Spatium* 1: Entstehung des Universums, by J. Geiss.
5 See *Spatium* 3: Birth, Age and the Future of the Universe, by G. A. Tammann.
6 Arno Allan Penzias, 1933, Munich, American physicist and Nobel laureate in physics 1978.
7 Robert Woodrow Wilson, 1936, Houston, USA, American astronomer and Nobel laureate in physics 1978.
8 See *Spatium* 7: In Search of the Dark Matter in the Universe, by K. Pretzl.

matter. A random distribution of Dark Matter in the early universe could explain the clumping of matter seen as fine structures in the cosmic microwave background radiation. Since the nature of Dark Matter is still unknown, this unsatisfactory ad-hoc explanation constitutes one of the major challenges for scientists.

Not surprisingly, the cosmic background radiation is amongst the universe's most attractive objects and progress in space technology has been used repeatedly for new attempts to uncover its secrets. Treading in the footsteps of Russia's Relikt, NASA's Cosmic Background Explorer (COBE) and the Wilkinson Microwave Anisotropy Probe (WMAP), ESA launched the **Planck** spacecraft on 19 May 2009, a cornerstone of its horizon 2000+ programme. The mission is named after the German physicist Max Planck[9], who derived the famous Planck distribution of black-body radiation.

The spacecraft consists of a service module containing the necessary infrastructure and communication elements and a payload module with a 1.5 metre telescope.

Currently, the spacecraft is underway to its destination 1.5 million kilometres away from the Earth, opposite to the Sun where it will be shielded from solar radiation by the Earth's shadow. Here, its telescope will operate at a temperature of –230 °C, and a sophisticated cryogenic cooling system will keep the detectors close to absolute zero, i. e. at –273 °C. Such exotic operating temperatures are required in order to reach the sensitivity set by astrophysical limits. The detectors will be able to resolve temperature differences in the cosmic background in the order of one millionth °C by far exceeding the specifications of earlier missions. In addition, Planck will be the first spacecraft to observe the polarization of the background radiation.

Gravitational Waves

While it is an astounding undertaking to explore the fledgling universe, scientists would like to go back even further, right to its beginnings, when time, space and matter saw the light of the day. Obviously, however, electromagnetic waves cannot do it as they were continuously scattered by the hot plasma filling space during the earliest epoch. Fortunately, there is another option emerging: as early as some one hundred years ago, Albert Einstein[10] postulated the existence of tiny vibrations of gravitation, called gravitational waves. Gravitation is the phenomenon by which objects with mass attract one

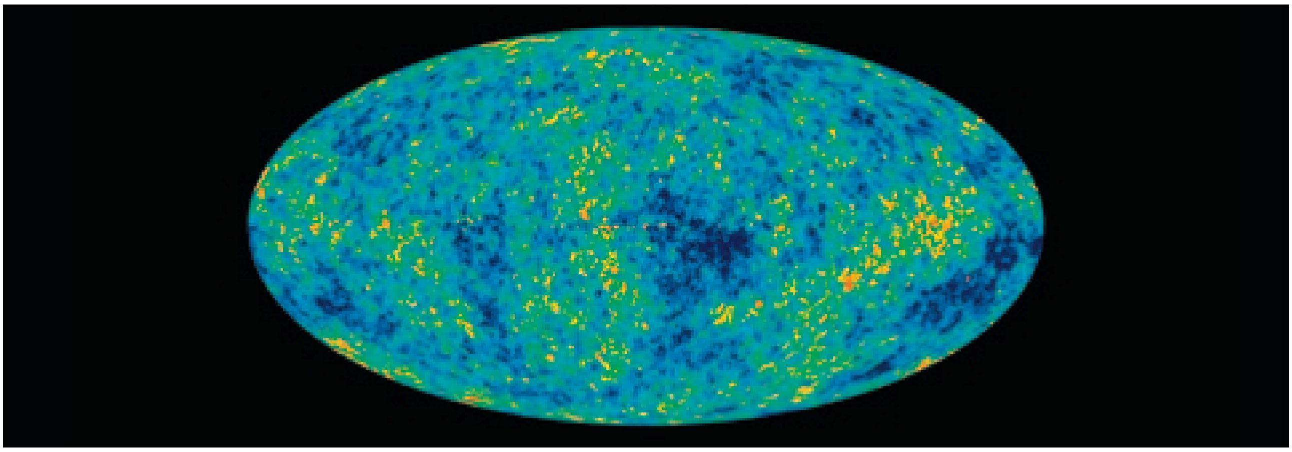

Fig. 1: The early universe based on NASA's Wilkinson Microwave Anisotropy Probe. The image reveals 13.7 billion year old temperature fluctuations shown as colour differences that correspond to the seeds that later grew to become the galaxies. The image shows a temperature range of ± 0.0002 °C. (Credit: NASA)

9 Max Karl Ernst Ludwig Planck, 1858, Kiel, Germany – 1947, Göttingen, Germany, German physicist and Nobel Prize laureate in 1918.

10 Albert Einstein, 1879, Ulm, Germany – 1955, Princeton, USA, German-born Swiss Nobel Prize laureate in 1921.

another. In our daily life, the Earth's gravity lends weight to objects with mass. If now these masses move, like for instance a planet orbiting the Sun, then their gravitation field moves as well. In Newton's theory of gravity, the gravitational interaction between two bodies is instantaneous. According to Einstein's law of special relativity, however, this is impossible, because the speed of light represents the limiting speed for all interactions. This leads to the concept of gravitational waves that propagate through space at the speed of light, **see Fig. 2.** According to theoretical calculations, such variations are extremely faint and this is probably why they could not be measured directly so far. Yet, they should possess the outstanding feature as compared to electro-magnetic waves of not being absorbed by matter. Thus, one expects them to allow for a glimpse back right through the plasma in the earliest universe. But this is still a long way off: neither has their existence been proven experimentally so far nor are the required technologies available. We shall return later to this fascinating subject when it comes to challenging our present day's physics.

Cosmic Inflation

As stated above, the Big Bang model is a powerful tool to describe the evolution of the early universe. Yet Nature does not lend itself to simple physical concepts: the Big Bang model fails to explain why some tiny fractions of a second after the beginning, the expansion rate of the universe experienced a sudden exponential boost. This phase is called cosmic inflation, but it is not known what caused this rapid expansion. Like in the case of the Dark Matter, scientists have to resort to an illustrative term describing the driving force behind comic inflation: Dark Energy[11]. Again, the name is telling but the underlying physics are not yet clear.

While this early inflation has been known for some 30 years, it came as the greatest surprise recently to learn that the universe has entered a new phase of accelerated expansion. Newtonian laws of gravitation would predict that the expansion is slowed down continuously as a consequence of the gravitational pull caused by matter. If the matter density in the universe were above the critical threshold, then the universe would finally collapse. On the other hand, it would expand forever – albeit at a decreasing rate – if the matter density were below that threshold. Now, extensive observations of distant galaxies made in recent years brought the striking news: the universe has again entered a phase of accelerated expansion. While Dark Energy is thought to be the responsible agent in this case, too, the underlying physics remain unknown. Even worse: both together, Dark Matter and Dark Energy seem to dominate the universe. This brings us to the harassing insight that the world consists mainly of constituents that we can neither see nor do we know what they are. Once again: Nature's wealth of mysteries is boundless.

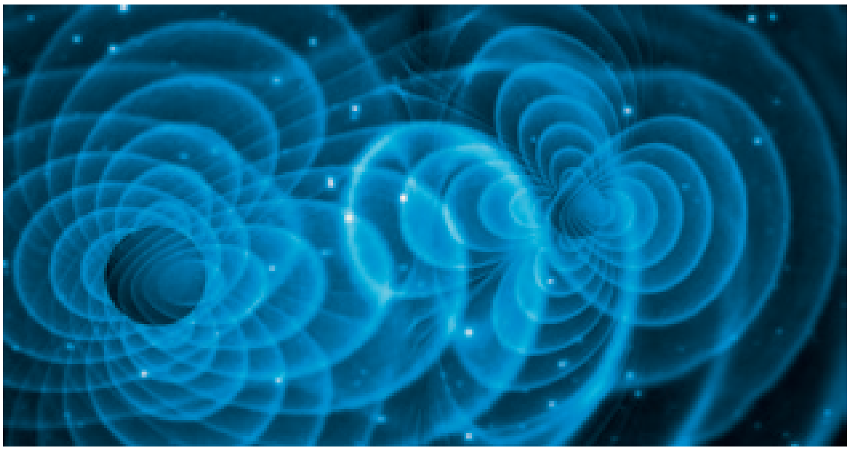

Fig. 2: Two merging black holes generating gravitational waves. Implemented on a powerful supercomputer, Einstein's theory of general relativity yields this magnificent portrait of a field of gravitational waves. (Credit: Chris Henze, NASA ARC)

[11] See *Spatium* 20: What the Universe Consists of: from Luminous to Dark Matter and Quintessence, by U. Wiese.

The Universe Taking Shape

Black Holes

The chain of open questions does not stop here; rather, recent observations show that the centres – at least of the majority – of galaxies (including our own Milky Way) are occupied by massive black holes. A black hole is a region of space where the gravitational field is so strong that nothing, including light, can escape its pull. It has a one-way surface, called an event horizon, into which objects can fall, but out of which nothing can come. The observations made so far seem to indicate that black holes are instrumental for the formation and evolution of galaxies due to their powerful gravity field, but it is not known how black holes are formed, nor is it known how they interact with their host galaxies during formation. As galaxies are amongst the building blocks of the universe, the understanding of black holes is deemed instrumental for the understanding of the cosmos at large.

In order to study the history of galaxies back to their formation epoch, a dedicated mission has been proposed, called the **International X-Ray Observatory (IXO),** a successor mission to earlier and most successful programmes. IXO is intended as a joint endeavour between the European, the US American and the Japanese space agencies to capitalize on the experience gained world-wide so far. It is expected to launch around 2020. IXO will basically consist of a very large telescope, much larger in any case than the dimensions of available and future launcher payload fairings. Therefore, special articulation technologies will be needed to deploy the optical system in space.

The Evolving Violent Universe

The Big Bang produced a meagre cocktail containing only two components: hydrogen and helium, flavoured by minor traces of other isotopes[12]. This mixture is in sharp contrast to the rich variety of chemical elements we find today, which is a *conditio sine qua non* for the complex molecules necessary for Earth-like planets and living systems. What then produces the additional chemical elements? All heavier elements are cooked in stars, and debris escaping from the violent explosion of super massive stars disperse them into the interstellar medium, **see Fig. 3**, where they are eventually collected by newly emerging stars and their planetary systems. By this process, the universe gets increasingly richer in heavier elements and poorer in the light primordial atoms, but the current small relative amount of heavier elements shows that the process of element formation is still in its infancy. In order to understand the complex life cycle of matter, an urgent requirement is to trace the history of black holes together with their host galaxies that contain the stars producing the heavier elements. Technically speaking, this means that the environment of black holes has to be observed in the x-ray and gamma ray regions of the electro-magnetic spectrum as matter accreted by black holes emits radiation at these wavelengths. An additional objective of IXO is therefore to observe black holes to understand the processes producing the wealth of chemical elements in the universe.

Fig. 3: The remains of an exploded star. The Crab nebula is the result of a supernova seen in 1054. It spans about 10 light-years. (Credit: ESA/NASA)

[12] See *Spatium* 13: Woher kommen Kohlenstoff, Eisen und Uran? by R. von Steiger.

What Are The Basic Laws of Physics?

DUBITANDUM AT VERITATEM[13]

Thomas of Aquinas[14]

Physics, as it stands today, is the result of generations of scientists' endeavours to try to understand Nature. The outcome of careful observations was distilled into laws that were probed subsequently by different, and often more elaborate, experiments. Many times, these experiments confirmed the validity of the newly found theory, but – and those are the truly interesting cases – sometimes Nature did not do what was expected from her and consequently the theory had to be discarded and replaced by a superior one. By necessity, these experiments were mostly made in laboratories i. e. in Earth-bound environments. This, however, has major implications: the range of environmental conditions in terms of pressure, temperature, gravity, etc. that are achievable by technical means is limited. The physics resulting thereof could be termed *laboratory physics* with its laws valid within the achievable range of physical parameters but not necessarily outside. When it comes to understanding the processes in space, *laboratory physics* suffers severe limitations as the relevant parameters may be orders of magnitudes outside the range reached in conventional laboratories.

Exploring the Limits of Contemporary Physics

There are several possible routes towards *space physics.* One can try to simulate the relevant physical conditions in ground-based laboratories. This is the approach taken by the European Organization for Nuclear Research (CERN) in Geneva. The new Large Hadron Collider (LHC) will accelerate particles to the highest energies reached so far and bring them to collision with each other. Although the energy levels will be several orders of magnitude below those in the Big Bang, there is justified hope to get important indications where the weaknesses of current physical models reside.

On the other hand, space provides the natural laboratory for developing *space physics*[15]. The advent of space technology has indeed allowed scientists to exploit space as their new laboratory. This wider approach would cover laboratory physics as a special case but include and correctly describe the processes in space as well. This approach may take two alternative forms. One concept refers to the observation of matter under extreme conditions like for instance in the vicinity of black holes as described earlier which then would constitute a further task of the IXO mission. An alternative approach implies the test of current physical models with the ultimate precision allowed by the then available technologies. This might lead to discovering deviations between prediction and observation and hence give indications where current physical models suffer deficiencies. Space again is the ideal laboratory for this approach: Earth-orbiting spacecraft can offer platforms that are extremely quiet, orders of magnitude better than Earth-bound laboratories that are subject to vibrations from tectonic (and possibly human) activities. In addition, some experiments may require extreme cryogenic conditions difficult to reach on Earth and last but not least space offers the dimensions making new types of experiments feasible.

In such marvellous space-borne laboratories one can challenge the basic laws of physics, such as for example Galilei's theory finding that all objects fall at the same rate in a common gravitational field, **see Fig. 4**. This is the objective of a mission proposal called **Galileo Galilei.** It consists of test masses of different material encaged in a spacecraft that is held drag-free, i.e. shielded from any acceleration caused by residual matter in space and by the pressure

[13] freely translated: through doubts towards the truth.
[14] Thomas of Aquinas, ca. 1225–1274, philosopher and theologian in the tradition of scholasticism.
[15] See *Spatium* 14: Grundlagen der Physik im extraterrestrischen Test, by M. C. E. Huber.

of sunlight. In this environment, the behaviour of different test masses will be monitored which eventually could reveal any so far unknown gravity-like force acting differently on different material.

Another mission proposal, called **Einstein Gravity Explorer,** deals with clocks: Albert Einstein postulated that under the effect of gravity, time is stretched. Therefore, all clocks must experience the same effect by running slower with increasing gravity but it is not known whether different types of clocks are affected the same way. This is not merely a theoretical oddity but rather most relevant for satellite navigation systems such as the US Global Positioning System GPS or the European Galileo system.

These are only two examples amongst an impressive multitude of proposals made by the European physics community in response to ESA's Cosmic Vision 2015–2025 call for proposals. Availability of technological and financial resources as well as partnership opportunities will play a decisive role when it comes to implementing one or any of these ideas.

Fig. 4: A beautiful legend states that Galileo Galilei found the law of free fall while visiting the leaning tower of his home town Pisa around 1590.

The Gravitational Wave Universe

Up to now, most information from space reached us via electro-magnetic waves. Before Galileo Galiei, it was the naked eye that observed the stars. Then, telescopes brought a quantum leap regarding resolution and sensitivity. In the nineties of the last century, space-borne telescopes, like for instance the magnificent **Hubble Space Telescope,** made a further major step allowing scientists to overcome the limitations set by the Earth's atmosphere. Yet the limitations of electro-magnetic waves remained.

As indicated above, replacing electro-magnetic waves with gravitational waves could open a completely new window to the universe. As this subject is currently of highly speculative character, ESA together with NASA has defined a step-by-step approach where each step contains manageable risks. The first milestone is the **LISA Pathfinder** mission set for launch in 2011. Its scope is to prepare the required technologies for detecting and exploiting gravitational waves. Based on the experience gained, the subsequent step will be the launch of the **Light Interferometer Space Antenna (LISA)** mission proper around 2018, **see Fig. 5.**

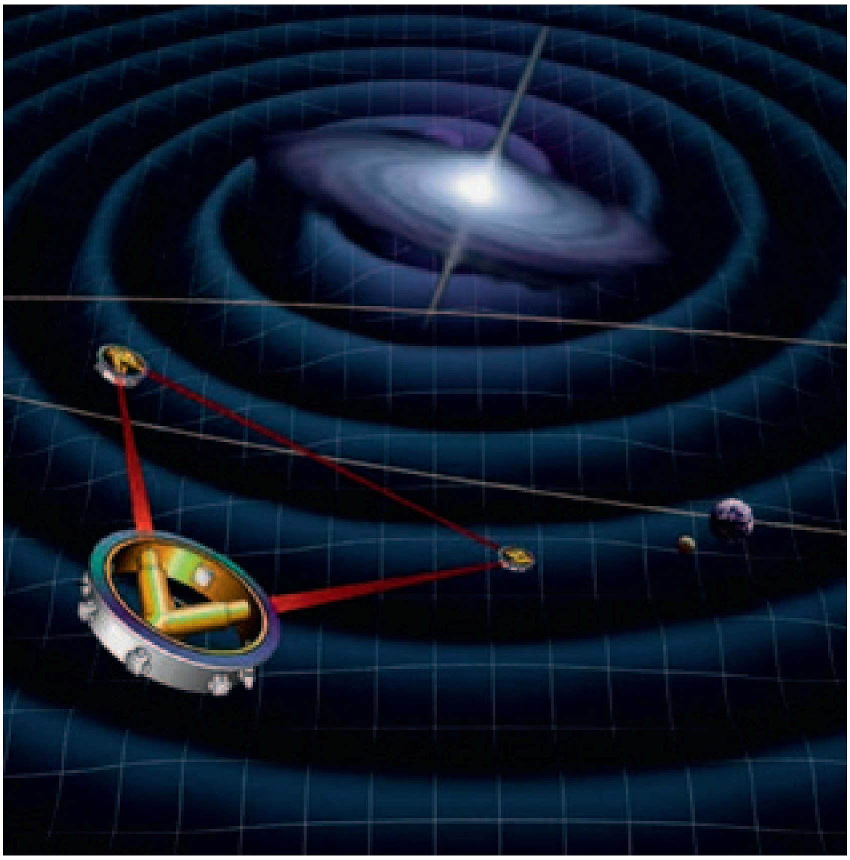

Fig. 5: Artist's concept of the Laser Space Antenna (LISA) mission. This programme aims at detecting gravitational waves from a variety of cosmic sources. The concept calls for three identical spacecraft orbiting the Sun on an equilateral triangle with an arm's length of 5 million kilometres. They each contain two test masses which under the effect of gravitational waves experience vibrations that will be a measure for the local strengths of the gravitational waves. (Credit: ESA/NASA)

Basically, LISA consists of three identical test masses placed on an equilateral triangle with an arm's length of 5 million kilometres. These test masses are free-floating in spacecraft that shield them from any adverse effects in interplanetary space. Any tiny modulation of the gravity field caused by gravitational waves will cause the test masses to individually follow the local gravity gradient. The distances between the test masses are monitored with nanometre precision (10^{-9} m) using highly accurate laser-based techniques. Although LISA might not be able to detect gravitational waves originating from the Big Bang, it will detect other sources, such as black holes and merging binaries (two stars orbiting around their common centre of mass) and thus constitute a crucial cornerstone in the research of this new category of waves and an important test of Einstein's general relativity. A later space mission (scheduled for the 2015 to 2025 time frame) will then specifically address the primordial gravitational waves that emanated from the Big Bang.

Are We Really Alone?

CHANCE AND NECESSITY

Jacques Monod[16]

Life on Earth evolved along random modifications of genetic material on the microscopic level and subsequent tests for usefulness on the macroscopic level. Such modifications occurred without finality, just by chance, whereas their results had to satisfy the necessity for higher reproduction success in order to become established. These basic mechanisms governing the evolution of life are well-known. In contrast, the emergence of systems capable of self-reproduction from an abiotic environment remains a great mystery. Today, we are in a unique moment of history where the technological means become available to exploring other places in the universe for life. Are we really alone? We still do not know it, but space research is addressing this old question with stunning new means.

From Gas and Dust to Stars and Planets

Earth is our place in the universe. The Sun together with the Earth and the other planets condensed out of a large proto-solar nebula of interstellar gas and dust some 4.6 billion years ago[17] **(see Fig. 6).** While the evolving Sun grasped by far the greatest part of nebular matter, some was left over and subsequently aggregated to the other members in the solar system, such as planets, asteroids and the uncountable smaller bodies towards the outer rim of the solar system. The solar mass was sufficiently high as to ignite nuclear fusion processes in its core, where the hydrogen stemming directly from the Big Bang is fused to helium in a chain of thermonuclear reactions. The tremendous energy output from these processes caused the young Sun to shine: a new star was born.

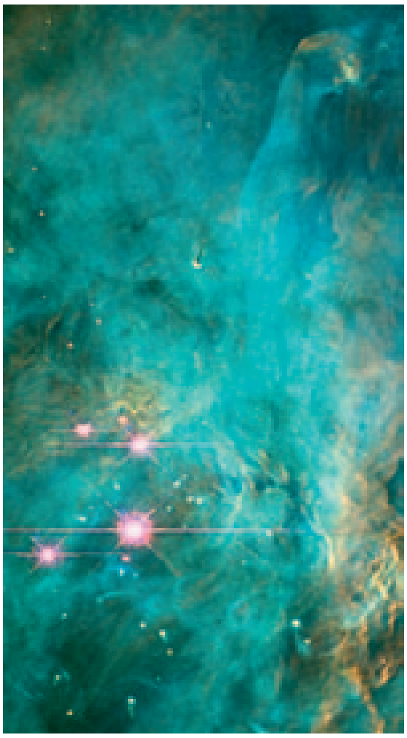

Fig. 6: In the Great Nebula of Orion new stellar systems are forming in gigantic clumps of gas and dust. (Credit: J. Bally, D. Devine & R. Sutherland, D. Johnson, HST, NASA)

The Earth's Biography

Meanwhile, the later Earth was a hot ball of liquid matter made up from chunks in the evolving proto-solar nebula. The heavier elements, like iron, migrated towards the Earth's core, while the lighter elements, like silicon, floated up to the surface. The latter solidified when the Earth cooled down sufficiently thereby forming the first continental crust. The iron core for its part generated the Earth's magnetic field that shields us today so efficiently against the solar wind and the Sun's deadly stream of high energetic particles.

Initially, there was no atmosphere as the Earth's gravity is too weak to hold the two most abundant gases in the proto-solar solar nebula, hydrogen and helium. The intense solar wind swept them off out to space. In contrast, the heavier volcanic gases emanating from the Earth's interior, like methane, formed the early atmosphere. Yet it was devoid of oxygen, and therefore

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[16] Jacques Lucien Monod, 1910, Paris – 1976, Paris, French biologist, Nobel Prize laureate 1965.

[17] See *Spatium* 6: From Dust to Planets, by W. Bentz.

also of ozone that is generated from oxygen by the ultraviolet radiation of the Sun[18].

Some 4.3 billion years ago, the Earth's surface temperature fell below 100 °C allowing the first oceans of liquid water to form. About 500 million years later, the young Earth, like all inner planets, underwent a dramatic phase of heavy bombardment by large interplanetary chunks of matter. The great maria such as Imbrium or Serenitatis still visible on the Moon's surface bear testimony for those violent days. One of the most intriguing puzzles in Earth's long history is that life seems to have emerged shortly after this cataclysmic period. Possibly, the heavy impacts provided the required energy and chemistry for complex organic molecules to build up[19, 20].

The Emergence of Life

After its first emergence, life did not make much progress for eons, almost two billion years. Certainly, early organisms interacted with and influenced their environment thereby unintentionally paving the way for later, higher forms of life. One striking example is the atmosphere. In the beginning it contained no oxygen. Then, cyanobacteria and other organisms released oxygen as a waste product of their metabolism into the atmosphere. Over millennia, its oxygen content steadily increased to reach values as high as today already some 500 million years ago. It was at that time, in the Cambrian period, that life generated most of the current divisions of life in a relatively short time period. The availability of oxygen seems to have been one of the key conditions for the emergence of new, and more complex organisms as oxygen breathing provides much more energy than anaerobic processes. Moreover, the Sun's ultraviolet radiation could now produce an ozone layer from the atmospheric oxygen which in turn provided an efficient shelter against the parts of the sunlight that can alter genetic material. The higher genetic stability reached thereby may have given a further boost to the evolution of more complex organisms.

Since then, uncountable new species emerged, of which, however, the greatest part were erased by catastrophic events: the history of life on Earth is a history of repeated mass extinctions. These may have been caused for example by dramatic temperature declines leading to an Earth covered with ice, or by the impact of large meteorites that stirred up so much dust into the atmosphere that only small remaining amounts of sunlight could reach the surface and support life there. In spite of all these setbacks, never were all species extinct, and the survivors were able to pass on their genetic heritage to later generations.

Life in the Universe

Equipped with what we know about the evolution of life on Earth, we can now embark on the search for life in the universe. Obviously, a first prerequisite is a planet within the habitable zone around its central star. The habitable zone is defined as the space around a star where water on a planet can exist in liquid form; not too close, as the star's heat would evaporate the water, and not too far, as the star's radiation would be too feeble and the water would freeze. Until 1995, it was not known whether planets really exist around stars outside the solar system. It was therefore a great discovery when Michel Mayor[21] and Didier Queloz[22] of the University of Geneva announced their detection of the first planet orbiting another star. Advances in observation technology have since allowed detection of more than 300 such exoplanets. Although the currently known exoplanets are mostly large gaseous planets, like Jupiter, which are unsuitable for life as we know it, they confirm the existence of planetary systems around sun-like stars and it is most probably a question of further progress in technology to find Earth-like planets as well.

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18 See *Spatium* 21: Ozone, by Y. Calisesi.
19 Roger M. Bonnet and Lodewijk Woltjer: "Surviving 1,000 Centuries", ISBN 978-0-387-74633-3.
20 See *Spatium* 16: Astrobiology, by O. Botta.
21 Michel Mayor, 1942, Echallens, Switzerland, Swiss astronomer at the University of Geneva.
22 Didier Queloz, 1966, Swiss astronomer at the University of Geneva.

Recently[23], the joint CNES/ESA programme **Corot** detected an obviously rocky exoplanet less than twice the size of Earth orbiting a sun-like star. In fact, such a planet could harbour life. The Corot mission was launched in late 2006. It consists of a telescope specifically designed to observe planetary transits. This method is based on detecting a planet by the small drop in the brightness of a star during the phase when the planet covers a small part of the star's disk.

From Exo-Planets to Biomarkers

Today, observation technologies facilitate the discovery of exoplanets and allow researchers to make an estimation of their orbital parameters and their masses. But they do not provide any information regarding possible biological activities on the exoplanet. To get a step forward, one must first try to define what the term life could designate. Unfortunately, life is by far too complex an entity to be seized by a definition; thus, we find ourselves in the embarrassing situation of searching for something we cannot define. To overcome this dilemma, astrobiologists have defined a set of biomarkers that are substances used as indicators for biologic processes. Based on the history of life on Earth, oxygen and methane are accepted as the most important biomarkers. This is – it must be admitted – a very Earth-centric definition of biomarkers that could possibly exclude finding different forms of life. Engineers and scientists designing new space missions will certainly open the scope of their instruments sufficiently to detect other forms of biological activities as well.

Lacking a wider view on what life is, the search for extraterrestrial life begins with searching for biomarkers in the universe. More precisely, it consists of probing the atmosphere of an exoplanet for biomarkers. Spectroscopy is the preferred observation method as the emission spectra of gases are excellent footprints for identifying them wherever they are throughout the universe. Thus, the required technological principles are basically known. The outstanding challenge, however, resides in the fact that the radiation of the star is by orders of magnitudes greater than that of the exoplanet and the distance to the nearest star is in the order of 4 light years, i.e. some 10^{13} kilometres from the Earth. Looking for exoplanets is like trying to see the difference between the feeble light from a candle next to a lighthouse from a point 1,000 kilometres away. This task is by far beyond present-day technologies; rather, it is expected that the required means might be developed by 2030 making a specific terrestrial planet finder mission feasible. But there is still a long way to go.

In the meantime, ESA is studying the **Darwin mission,** a flotilla of four or five spacecraft designed to search for likely places for life outside the solar system. Darwin will survey some thousands of the nearest stars, look for small, rocky planets and probe their atmospheres for the most relevant biomarkers. While one spacecraft will act as a central communications hub, the others

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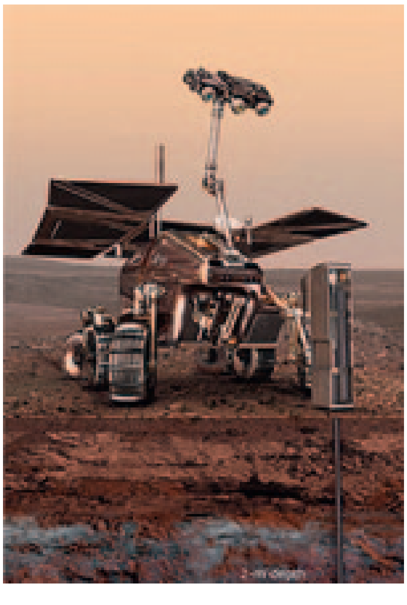
will function as light collectors that redirect the light collected by their telescopes to the central hub spacecraft. Here, the different beams will be superimposed and processed in a way that allows the flotilla to simulate a single telescope with the aperture roughly the size of the distance to the light collector spacecraft. Such large apertures are mandatory to image exoplanets and probe their atmosphere; interferometry is used to cancel out the light of the much brighter central star. Exhaustive preparatory work on technology development is required before it becomes even feasible to set up a schedule for the Darwin mission.

Fig. 7: ESA's Mars Rover is shown in this artist's view drilling a hole in the Martian surface in search of subsurface life. (Credit: ESA)



Life and Habitability in the Solar System

Mars

Some promising places within our own solar system await inspection, which are much closer to us than exoplanets. Mars is one of the most auspicious addresses. Probably, the Red Planet hosted an atmosphere that disappeared some one billion years ago. The planet's surface is full of erosion patterns that resemble those generated by rivers on Earth. These are telling signs of abundant liquid water in a distant past. We do not know, why the atmosphere disappeared and left the Martian surface a dead desert and whether similar processes could deprive the Earth from its atmosphere – with dramatic consequences for its biosphere.

Mars has been a favourite destination of spacecraft since the early days of space programmes. NASA has sent an armada of orbiters and robotic rovers to the Red Planet. ESA launched the **Mars Express** spacecraft in mid 2003. The spacecraft reached its destination six months later and has orbited the planet since. Although its design life has been completed it continues to monitor the planet's surface successfully. The spacecraft is equipped with a high resolution stereoscopic camera that delivers outstanding imagery and elevation information. In addition, it disposes of a sounding radar that maps the sub-surface structure to a depth of a few kilometres in search of water and ice.

Recently, its spectrometer instrument observed patterns of methane in the Martian atmosphere that cannot be explained by known atmospheric chemistry and physics. In addition, these methane concentrations seem to overlap in some regions with concentrations of water vapour. This could be interpreted as stemming from a common underground source which in turn would provide important new hints to evaluate the hypothesis of present life below the surface of Mars.

ESA has bundled its forthcoming Mars exploration programme under the heading *Aurora*. One of its key missions is **Exo Mars** intended to explore promising sites on Mars with a robotic vehicle. The mission calls for the development of a Mars orbiter, a descent module and a Mars rover. The Mars orbiter is to reach Mars and put itself into orbit around the planet. On board is a Mars rover within a descent module. The Mars descent module will deliver the rover to a specific location. The rover **(see Fig. 7)** is intended to travel a few kilometres over the planet's rocky surface and to operate autonomously by using onboard software and optical sensors. Its main mission objective is to search for signs of past or present life. To this end, it carries a 40 kilogramme exobiology payload including a lightweight drilling system with a reach of 2 metres below the surface. Launch is scheduled for 2013.

The next milestone in the Aurora programme will constitute the launch of the challenging **Mars Sample Return** mission in the 2020–2022 time frame. This spacecraft is composed of several modules serving the flight to Mars, the landing on its surface, collecting samples at promising sites and conserving them in a contamination-secure container which then are returned back to Earth. Before implementing such a complex mission profile, a series of technologies need to be prepared and tested in orbit first.

Moons in the Outer Solar System

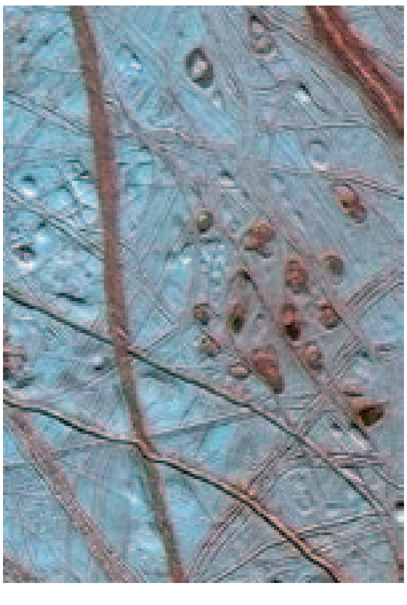
As defined above, the habitable zone is the space around a star where liquid water on a planet's surface could exist. This is true as long as the radiation from the central star is the dominant source of energy. There exist, however, additional sources that can produce enough heat to allow surface liquid water far outside the habitable zone. One such heating mechanism is the strong gravity field of a large planet operating on a moon circling it on an appropriate orbit. The changing position of the moon in relation to the planet's gravity field gives rise to changing forces on the moon's body which in turn leads to tidal effects on the moon. These tides cause internal heating of the moon which can be a valid alternative to heating by the Sun.

Europa, one of Jupiter's companions, is one such mysterious world in the outer solar system. Discovered as early as 1610 by Galileo Galiei, Europa has a diameter of 3,100 kilometres, roughly the same as our Moon. It possesses a tenuous atmosphere containing oxygen. Its surface is a relatively young icy crust, **see Fig. 8**. Europa is probably heated internally by Jupiter's strong gravitational field which could keep the ocean below the icy surface liquid and drive geological activity, both basic requirements for life to emerge there.

In order to probe the potential ocean on Europa for biologic activity, it would be necessary to drill a hole through the ice crust and to operate a small life science laboratory there. Unfortunately, it is not known how thick the ice really is and if there is actually liquid water below. So, the current status of information about Europa's internal structure and the technical challenges of such a mission do not yet allow for the planning of a dedicated mission in the next 20 years. Rather, intermediate steps are more realistic, such as for instance ESA's **Laplace**[24] mission.

The Laplace mission is named after the French astronomer Pierre-Simon Laplace, whose work was pivotal to the development of mathematical astronomy. The purpose of the mission is to explore the complex Jovian system as a whole, with special emphasis on studying Europa's habitability in the global context of the Jupiter system. Laplace is planned as a trilateral endeavour between ESA, NASA and the Japanese space agency JAXA. Each of these participants will contribute one spacecraft. ESA will provide the Jupiter Planetary Orbiter to probe planet Jupiter, NASA will be responsible for the Europa orbiter, while JAXA's share will consist of the Jupiter Magnetospheric Orbiter. The three spacecraft will cruise jointly to destination during 5 to 7 years, and then separate to individually explore their objects. Currently, the Laplace mission proposal is in the industrial assessment study phase.

Fig.8: Miraculous Europa. One of Jupiter's moons, Europa is thought to possess an ocean of liquid water beneath its icy surface. This image reveals characteristic surface ridges and cracks along with domes and dark reddish spots. (Credit: NASA).



[24] Pierre-Simon, marquis de Laplace, 1749, Beaumont-en-Auge, France – 1827, Paris, French mathematician and astronomer.

What Makes The Solar System Tick?

THIS WORLD'S MOST INCOMPREHENSIBLE FACT IS ITS COMPREHENSIBILITY.

Albert Einstein

Understanding the solar system is a basic prerequisite for understanding the universe. The solar system offers so to say the playground where the cosmic processes can be observed in a – relatively – convenient distance, be it by means of telescopes or by space robots. In addition, the Earth's cosmic environment, and especially the Sun, is the most important with regard to our planet. So putting a high priority on the exploration of the solar system is more than justified.

From the Sun to the Edge of the Solar System

The Sun dominates the solar system[25]. Its magnetic field is the source of the solar wind, a stream of particles that rush away to eventually meet with the interstellar medium[26]. This is the edge of the solar system, called the heliopause. The Sun also emits, in events called solar flares, energetic particles that would be a deadly threat to life on Earth if they were not efficiently shielded by the Earth's magnetic field that safely redirects them out to space. On the other hand, both the solar wind and the energetic particles carry valuable information regarding the composition of the Sun and the processes at its surface and in its corona. This allows studies of regions on the Sun that are not accessible to in-situ exploration because of the excessive heat. Thus, the Sun has been a priority object for the first generations of scientific spacecraft and it will remain so in future.

In the frame of the Cosmic Vision programme, ESA intends to launch the **Solar Orbiter** mission to study the Sun. Solar Orbiter, planned as a collaborative effort with NASA, will be the first satellite to provide close-up views of the Sun's polar regions providing images from high latitudes. It will be able to tune to the Sun's rotation around its axis for several days, and it will therefore be able for the first time to see solar storms building up over an extended period of time from the same viewpoint. The spacecraft will orbit the Sun in an elliptical orbit that brings it as close as 0.23 AU[27] to our daytime star, where it will experience 20 times the radiation intensity compared to that on the Earth. The intense solar radiation will therefore be Solar Orbiter's main design driver. The spacecraft will be three-axis stabilized and possess a sunshield that will always be pointing towards the Sun to protect the scientific instruments aboard against the heat from the Sun.

Mercury

Next to the Sun is Mercury, an extremely hot world, with surface temperatures up to 400 °C, as its orbit is only between 0.3 and 0.46 AU. Due to the technological challenges set by such conditions relatively little is known about Mercury. ESA, together with JAXA, is currently preparing the **BepiColombo**[28] mission scheduled for launch in 2014 with arrival at Mercury some six years later after complex orbital manoeuvres around the Moon, Earth, Venus and Mercury itself. It consists of two individual spacecraft: the Mercury Planetary Orbiter intended to map the planet, and the Mercury Magnetospheric Orbiter. Amongst the instruments intended for Mercury exploration is the Laser Altimeter, a

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25 See *Spatium* 2: Das neue Bild der Sonne, by R. von Steiger.
26 See *Spatium* 17: The Heliosphere, by A. Balogh.
27 1 Astronomical Unit (AU) equals 150 million kilometres, the distance between the Sun and the Earth.
28 Giuseppe Colombo (better known by his nickname Bepi Colombo), 1920, Padova, Italy – 1984, Padova, Italian scientist, mathematician and engineer.

complex electro-optical instrument that emits light pulses towards the surface of Mercury, where they are reflected and subsequently collected by the receiver. The Physikalisches Institut of the University of Bern together with Swiss industry is currently involved in the design and development of this instrument, which will allow scientists to make a detailed reconstruction of the planetary surface.

Venus

Mercury, together with Venus, Earth and Mars are collectively termed the terrestrial planets, since they are all primarily composed of silicate rocks like the Earth, in contrast to the gas giants like Jupiter and Saturn and the outer planets Uranus and Neptune. Even though the terrestrial planets have many similarities, they are very different: Venus, the second planet from the Sun, is enshrouded in a dense atmosphere containing mainly CO_2 with some N_2, but it has no magnetic field. This planet is currently being explored by ESA's **Venus Express** mission. The Earth in turn has both, an atmosphere and a magnetic field, which are key prerequisites for the emergence of life.

Venus Express has revealed many secrets about our Morning Star. While this planet is similar to Earth in terms of size, gravity, and bulk composition, it is covered with an opaque layer of clouds of sulphuric acid, preventing its surface from being seen from space in visible light. It is thought that Venus once possessed Earth-like oceans in the past, but these have totally evaporated in the meantime. There are only a low number of impact craters on Venus' surface, indicating that its surface is relatively young, approximately half a billion years, and that strong geological activity is continuously reshaping it.

Mars

Mars[29] is the fourth planet from the Sun in the solar system. The Red Planet is the destination of past, current and future space missions. Mars research is strongly focused on the search for past or present life as described above, but since Mars is one of the four terrestrial planets, it merits in-depth research per se as it helps us to understand our own planet. In addition, its environmental conditions are relatively favourable for remote sensing and in-situ exploration, quite in contrast to Mercury and Venus. Mars possesses a rich variety of surface patterns stemming from meteorite impacts (craters), volcanism (calderas, volcanoes) and erosion (possibly liquid water), but also polar caps (frozen CO_2 together with possibly water ice).

The Giant Planets and Their Environments

Outside the orbit of Mars follow the gas planets Jupiter and Saturn, both consisting mainly of hydrogen and helium with probably a rocky core at their centre. Uranus and Neptune, the outermost planets, are probably built up from an inner rocky core, enshrouded in an icy mantle of water, ammonia and methane and a gaseous outer shell of hydrogen and helium.

The Saturnian system was the object of the most successful ESA/NASA **Huygens-Cassini** mission which culminated in the landing of the Huygens probe on Titan's surface on 14 January 2005[30]. It has a diameter of 5,150 kilometres (roughly 50% larger than our Moon). Its thick atmosphere is rich in organic compounds. Some of them would be signs of life if they were on our planet. The wealth of data received by Huygens and Cassini answered many previously strongly debated questions but, and this is the fascination of science, it opened at least the same number of new questions, such as whether the organic substances on Titan will help us to discover how life began on Earth.

It is therefore not surprising that scientists are currently planning a further mission to probe the Satur-

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29 See *Spatium* 5: Earth, Moon and Mars, by J. Geiss.
30 See *Spatium* 15: Titan and the Huygens Mission, by N. Thomas.

nian system. To this end, ESA has incorporated the **TANDEM** (**T**itan **and** **E**nceladus **M**ission) in its Cosmic Vision plan. It is intended to continue the research made by Huygens-Cassini and specifically to carry out an in-depth investigation of the two most enigmatic Saturnian moons, Titan and tiny Enceladus. The latter has been found to be an extremely exciting world. Its diameter is of the order of 500 kilometres, equivalent to only some 15% of the Earth's Moon. In its south polar region there are organic-laden jets of water vapour and dust-sized ice particles emanating from the surface, possibly from a liquid water reservoir just below the icy surface, similar to Jupiter's moon Europa described above. As liquid water is one of the key requirements for the emergence of life as we know it, Enceladus is one of the few likely places for life in the solar system.

Asteroids and Other Small Bodies

Most of the proto-solar nebula matter was collected by the Sun and the planets. The tiny remaining part thereof formed uncountable small bodies on a variety of orbits, mostly far off the Sun. As leftover building blocks of planet formation maintained deep frozen since the beginnings of the solar system, they offer important clues to the chemical mixture from which the solar system formed.

In order to explore these primordial objects, ESA has proposed the **Marco Polo**[31] mission together with JAXA with a possible launch date in 2017. The scope of this endeavour would be to collect and return samples back from a Near Earth Object (NEO) such as a meteorite, an asteroid **(see Fig. 9)** or a comet. The mission is named after one of the earliest western people who built up good relations between Europe and Asia. The mission scenario calls for a mother spacecraft that is to carry out a global characterization campaign of the potential target object. This process should deliver information on all major surface hazards on the NEO and determine the most scientifically rewarding sampling sites. Then, it will release a lander and possibly a couple of small hoppers that will analyse surface/sub-surface materials. After a number of sampling rehearsals, the main spacecraft will finally touch down on the surface to collect the sample. Thereafter, it will take off from the NEO and be placed on an Earth return trajectory, where it will arrive some five years after launch, to release its re-entry capsule containing the samples. Marco Polo is intended to provide the first opportunity for detailed laboratory study of the most primitive material in the solar system.

Fig. 9: Asteroid Itokawa, recently visited by the Japanese spacecraft Hayabusa, exhibits a very rough surface interrupted by astonishingly smooth areas. It has an overall length of some 500 metres. (Credit: ISAS, JAXA).

[31] Marco Polo, ca. 1254–1324, merchant of the Venetian Republic who made a pioneering journey to Asia that later opened the famous Silk Road.

Conclusion

Since the dawn of mankind, humans have looked at the sky and tried to understand the mysteries of the cosmos. Space research and space technology are the answer of this generation to that old dream. It continues the work of the great earlier thinkers, from Aristotle to Copernicus, Galilei, Newton, Einstein and many others. In contrast to their day, however, space research has become today a complex undertaking that exceeds by far the possibilities of one single person, and often even that of a nation. Exploring the cosmos has become a truly global endeavour. Beyond delivering fascinating results, space research is a uniting agent for all the people involved world-wide in search of bringing further the legacy of their intellectual predecessors.

Yet, all research, space research not excluded, has to pass some utility requirements in order to find the tax payer's consent. Certainly, one of the most influential results of space exploration has been the picture of our blue planet taken by the Apollo 8 crew, some 40 years ago, showing a fragile Earth surrounded by the immense dead void of space, **Fig. 10.** This image, together with later research results, has furthered the perception of the finiteness of reserves on Earth and given rise to growing concern about the use of the natural resources at the expense of a vanishing diversity of life.

May this issue of *Spatium* contribute to the readers' awareness of the unique responsibility humans are given in Earth's history!

Fig. 10: Earth-rise seen from the Moon. This wonderful image was taken by the Apollo 8 crew on mankind's first journey to round the Moon in December 1968. (Credit: NASA)

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