Astrochemistry

The Cradle of Life

Supported by

European Science Foundation and COST

EUROPEAN SCIENCE FOUNDATION

COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Within just the last two decades the existence of potentially life harbouring planets outside the solar system has moved from the realm of scientific speculation and science fiction into the world of reality and scientific research. Thanks to astrochemistry, our understanding of the universe has transformed from the early imaginings of the outer space as void dotted with lonely stars, to that of a cosmos of complex interstellar media filled with stars encircled by habitable worlds. The fascinating science presented here is an excellent example of how curiosity-driven research expands the horizons of our understanding about the universe, leading to innovation that pushes the modern technologies to yet unprecedented limits. Such achievements have become possible only through collaboration between scientists of different disciplines and countries. The European Science Foundation recognizes the utter importance of trans-national scientific collaboration by supporting large scale bottom-up European collaboration projects, such as EuroGENESIS and CompStar programmes which are presenting their research in this brochure.

With kind regards

Dr. Jean-Claude Worms
Head of the ESF Physics and Engineering Unit and Space Sciences Unit

It is a great honour for COST to welcome you to the exhibition Astrochemistry: Cradle of Life! The theme of this exhibition is one of the most fascinating and exciting areas of modern science: the investigation of the role of chemistry in the origins of life on Earth or other planets throughout the Universe.

We are proud that COST Action CM0805 'The Chemical Cosmos' is one of the driving forces behind this exhibition. The displays are particularly captivating – partly thanks to their unique setting in the Royal Belgian Institute of Natural Sciences. They demonstrate the value and excitement of scientific studies and aim to inspire future generations of scientists.

I strongly believe that science and technology can change our future and that the future of our society lies in the hands of enthusiastic visitors and aspiring (young) people like you. With your support, our society can innovate, rise up to challenges and make Earth a better place.

I wish you all the best in your adventurous tour through the world of Astrochemistry.

With kind regards,

Dr Ángeles Rodríguez-Peña
President of the COST Committee of Senior Officials

Astrochemistry; The Cradle of Life

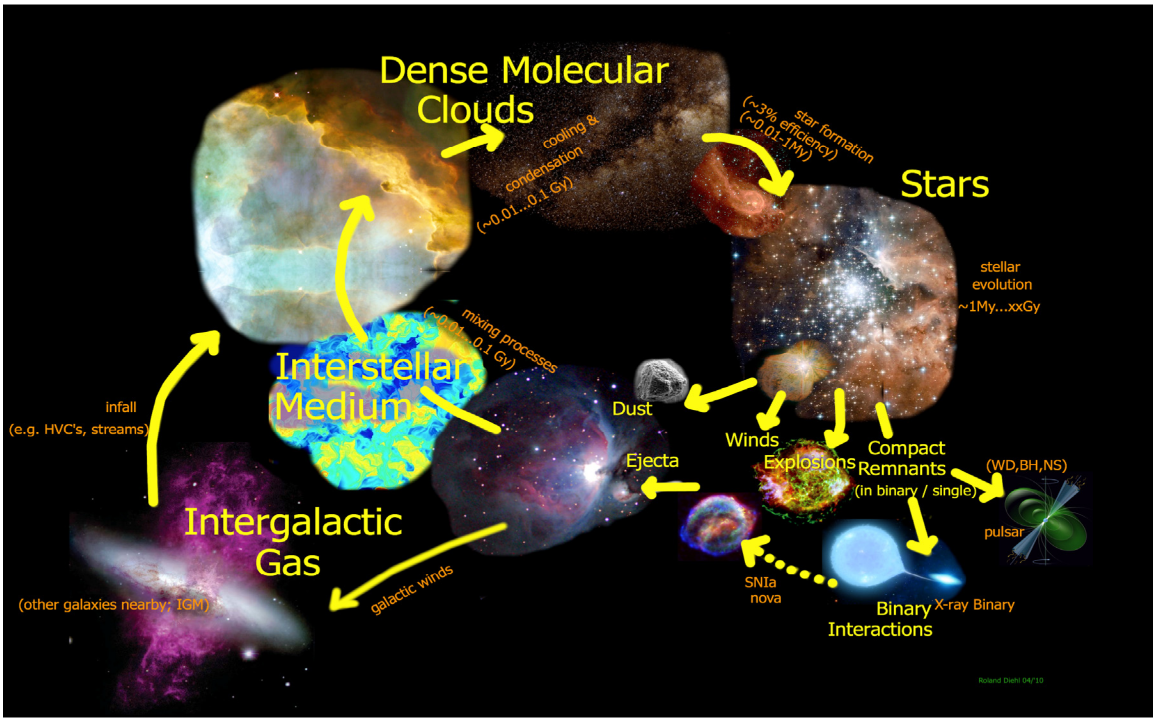
How and where life was formed in the universe is one of the greatest remaining mysteries of modern science. Credit: Centro de Astrobiología (CSIC-INTA).

Two of the great unanswered scientific questions are: ***How did life begin on Earth? Is there life elsewhere in the Universe?*** These are questions that have fascinated humanity for centuries. The 21st century may at last see answers to these questions as we obtain a better understanding of the chemistry of the universe and explore planets around other stars.

Europe is at the forefront of such research supporting a range of collaborative projects that both explore the fundamental chemistry necessary to understand how the elements and molecules necessary for life are made and explore the planets of our solar system and beyond for evidence of life.

This booklet summarises the current state of the art in the field and the projects and collaborations that have been assembled to conduct this research programme.

The Origin of the Elements and the Nuclear History of the Universe

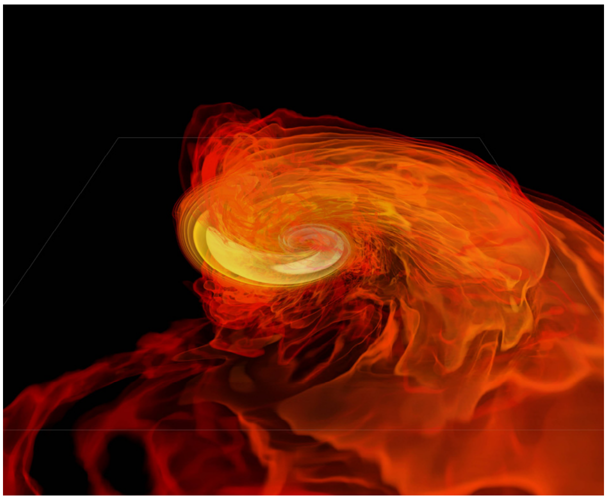


The Cosmic cycle of matter. The first stars formed from the ashes left over by the Big Bang. Matter is continuously processed in these nuclear furnaces and ultimately expelled through a suite of gentle and/or explosive events, such as supernova explosions. This material, enriched in chemical elements heavier than hydrogen and helium, may give rise to a new generation of stars.

The nuclear history of the Universe begins with the Big Bang, when the ashes from the primordial explosion were transformed into hydrogen, helium, and a few trace elements. Nuclear astrophysics – the science that studies the origin of the elements in the Universe – conducts multidisciplinary research that combines studies in theoretical astrophysics, observational astronomy, cosmochemistry and nuclear physics. New tools and developments have revolutionized our understanding of the element genesis: supercomputers provide astrophysicists with the required computational capabilities to study the evolution of stars in a multidimensional framework; the emergence of high-energy astrophysics with space-borne observatories opens new windows to observe the Universe; cosmochemists isolate tiny pieces of stardust embedded in primitive meteorites, giving clues on the processes operating in stars as well as on the way matter condenses to form solids; and nuclear physicists measure reactions near stellar energies, through combined efforts using stable and radioactive ion beams.

Stars form by the collapse of dense parts of giant molecular clouds, containing large amounts of hydrogen and helium. Because of the intense gravitational pull, these balls of plasma contract until thermonuclear fusion reactions begin. A suite of different nuclear processes operate in these stellar nuclear furnaces.

The Origin of the Elements and the Nuclear History of the Universe



Left: ***VLT image of the Crab nebula, a supernova remnant, drawings of which were recorded by Chinese astronomers and the Anasazi Indians of North America in July 1054 AD. Supernovae are the factories of chemical element production.*** **Credit:** ***http://apod.nasa.gov/apod/ap991122.html*** ***Right: snapshot of a numerical simulation of the merger of two neutron stars. High-density matter of the stars is swept in the interstellar medium, enriching its content of heavy elements. Credit: Koppitz (ZIB, AEI), Rezzolla (AEI) : http://numrel.aei.mpg.de/images***

Stars up to 10 times the mass of our own Sun live billions of years before they end their lives with a gentle ejection of their outermost layers, while the innermost regions are reshaped into compact objects of planetary size known as *white dwarfs*. These stars constitute the likely sites for the synthesis of most of the C, N and approximately half of the elements heavier than Fe. More massive stars face a more violent fate, a *supernova* explosion, leaving either a *neutron star* (i.e. stars with mass of about 1.5 times that of the Sun, but a radius of only a dozen kilometers) or a *black hole*. Such supernova explosions are predicted to be the source of the majority of nuclides in the Galaxy.

Many stars form binary or multiple systems, with some hosting a compact object in short-period orbits, such that mass is transferred between the star and this companion. This may lead to violent stellar events, such as *type Ia supernovae, classical novae, X-ray bursts, or even stellar mergers*. Type Ia supernovae constitute the major factory for iron-peak elements in the Galaxy. In addition, when two neutron stars in a binary system merge via the emission of gravitational waves to form a black hole, they eject freshly produced heavy elements, further enriching the metal content of the interstellar medium.

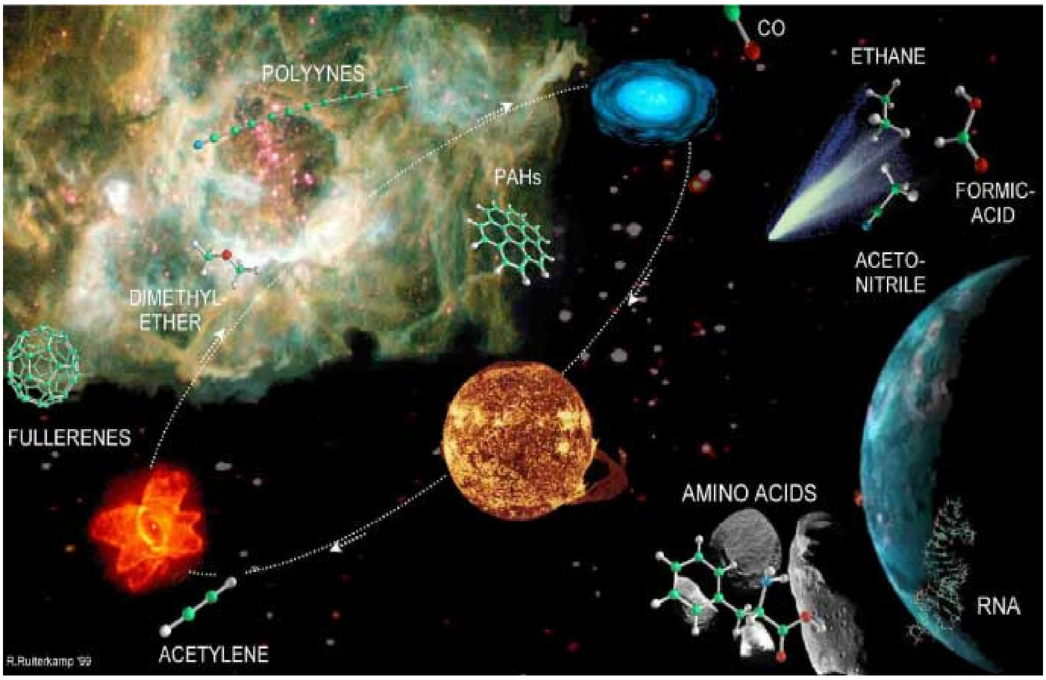
For more details on the origin of the elements and the life and death of stars see the EuroGENESIS and COMPSTAR websites:

http://www.esf.org/activities/eurocores/running-programmes/eurogenesis.html

and

http://compstar-esf.org

Space Chemistry; Where are molecules made ?

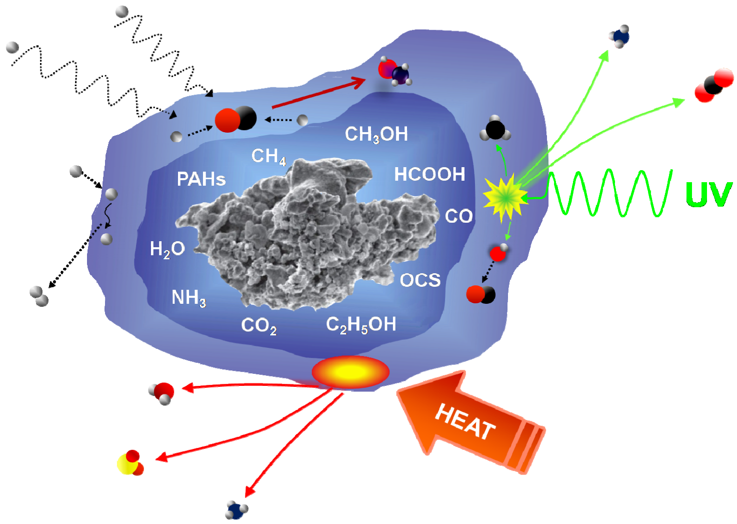


Those regions between the stars known as the interstellar medium are rich in chemistry and the birth place of stars. Credit R Ruiterkamp (1999)

It was originally thought that those dark regions between the stars – the interstellar medium – was completely empty. However, we now know that the interstellar medium contains large clouds of gas and dust and it is in such regions that all the stars and planets are formed. Furthermore recent observations have revealed that a range of complex molecules are present in these regions. Indeed more than 150 different molecules have now been identified in star/planet forming regions, including species we are familiar with on Earth such as water and carbon dioxide but also simple alcohols (such as methanol and ethanol) and formic and acetic acid (vinegar).

But how are these chemicals formed? This might seem a trivial question, but in fact the extremely low temperatures (around -263°C) and low pressures in the interstellar medium are not suitable for "normal" chemical reactions to occur. We can think of a chemical reaction as a collision between two or more chemical reactants that results in the formation of new molecules. In order for such a collision to be successful and new molecules to be formed, the reacting species must have enough energy to overcome any energy (reaction) barriers that usually exist for such a formation processes. At the low temperatures found in the interstellar medium, the colliding species do not have enough energy to surmount these barriers. In addition, many reactions require the presence of another (third) collision partner to help stabilise the chemical products by removing some of its excess energy and so avoid the product molecule fragmenting. At the very low pressures in the interstellar medium, the probability of such a three-body collision is so small as to be negligible even on the timescale of billions of years.

Space Chemistry; Where are molecules made ?



Chemistry in the interstellar medium leading to complex molecular formation may occur on the surface of small particles of ice covered dust irradiated by starlight and cosmic rays. Credit RSc

So how does chemistry happen at all in these interstellar clouds? The answer lies in the presence of the dust found in the clouds. These dust grains, probably composed of carbon and silicon, provide a surface on which atoms, and other reactive molecular fragments, can combine. Molecular hydrogen (H_2), the most abundant and important molecule in the Universe, is formed by this route. Other simple molecules such as water, ammonia, carbon dioxide and methanol and other small organic molecules are also formed in this way and freeze out to form icy mantles that cover the surface of interstellar dust grains.

Why are these molecules so important? We now know that these molecules play a crucial role in the formation of stars and planets. Over time these cold clumps of gas and dust collapse under the influence of gravity. During this collapse the gas is strongly heated and if this heat cannot be removed from the system then the collapse stops and a star cannot be born. The presence of molecules in the collapsing gas cloud allow this heat to be disposed as it is radiated away through the rotational and vibrational transitions in the molecules (the same transitions that allow us to observe and identify them in the first place!

The ice covered dust grains found in the cold interstellar medium are also bathed in cosmic radiation (ultraviolet light, ions and electrons) which can lead to new chemical reactions within the ices. These chemical processes can even lead to the formation of those molecules that are the ingredients of life such as amino acids nucleic acids and simple sugars. Hence the strange and unexpected apparently impossible chemistry that occurs in the cold, dark, diffuse regions of space provides the first steps in the synthesis of those molecules from which we are all formed.

Understanding this rich chemistry in the interstellar medium is the subject of several major European research collaborations including the COST action CM805 ‘The Chemical Cosmos’ and the EU Framework Initial Training Network, LASSIE.

The Origins of Life

How were the molecular constituents needed for life created on Earth? Were they formed in an early Earth atmosphere as the result of chemistry triggered by sunlight or lightening (left image?) Or were they delivered to Earth by comets and meteorites (right image)? Credits UPI Photo /Landov E. Weiß: "Bilderatlas der Sternenwelt" 1888

How were the molecular constituents assembled to form life as found on Earth? and ***Do such conditions exist elsewhere in the Universe?*** At present we do not have answers to these questions but a new science, that of '***Astrobiology***', explores these questions and provide insights into whether life may exist on other planets throughout the Universe.

In order to form life (at least life as we presently recognise it) simple organic molecules must have assembled to form increasingly complex molecules until at last DNA was created. DNA is a very special molecule since it can reproduce itself and thus it carries the 'genetic code' that is necessary to make any living creature.

There are two possible origins for the organic molecules on the early Earth, one terrestrial and one extraterrestrial. A 'primeval soup' of organic molecules could have been created in the early Earth's atmosphere through the action of sunlight or by lightening. This theory was supported by experiments conducted by Urey and Miller in 1950's who showed that 23 amino acids could be formed in a simple electrical discharge of water, methane, ammonia and hydrogen.

Alternatively the simple organic molecules may have been delivered to earth in the form of comets and meteorites. This theory has been supported by recent discovery of glycine, the simplest amino acid, in samples returned from the comet Wild-2. Glycine and twenty other amino acids have also been found in meteorites.

The Origins of Life

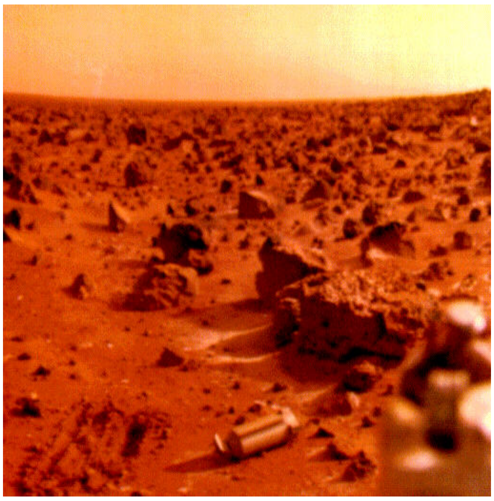
The origins of life on Earth remain a mystery but perhaps began around vents in the ocean floor (left image) or in hot pools around volcanoes and geysers (right image). Credits xx

Where are the organic molecules assembled to form DNA? There are many different theories but most agree that it took place in water, perhaps in hot pools such as those found near volcanic vents and geysers or around hot vents in the depth of the oceans where hydrogen-rich fluids emerge from below the sea floor and interface with carbon dioxide-rich ocean water. Recent expeditions have discovered many new forms of life around these vents, life which is perhaps not only the oldest on Earth but may be similar to that on other ocean supporting planets across the universe.

The chemistry of life is of course complex but gradually amino acids must have been organised into proteins whilst for cellular life lipid structures must have been formed to assemble into the membrane structures needed to create cellular structures within which DNA can be stored and replicate. How this occurred we still don't know but we do know that it occurred on what was a relatively short astronomical time scale since the oldest fossils of microbe-like objects are 3.5 billion years old, only one billion years after the formation of the Earth itself, while in 2.4 billion year old rocks we have found evidence of photosynthesis, the chemical process that dominates the lifecycle of plants.

To learn more about research into the origins of life and how European scientists are developing the new science of Astrobiology look at the website of the European Astrobiology Network Association (http://www.astrobiologia.pl/eana/).

Exploring the planets

Mars, the Red planet (left image) has fascinated humanity for centuries with stories of Martians. Recent voyages to Mars have revealed a barren desert like surface but perhaps in the past it was able to support life, which may still survive beneath its surface. Credit NASA/JPL

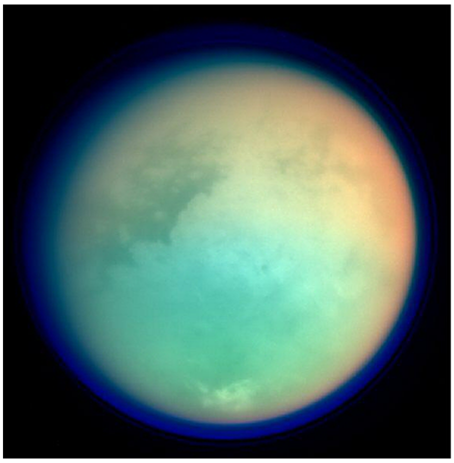
The exploration of our own Solar system continues with the European Space Agency (ESA) and NASA combining resources in joint missions to the planets and moons that are amongst the most exciting voyages of human discovery of the 20^{th} and 21^{st} century.

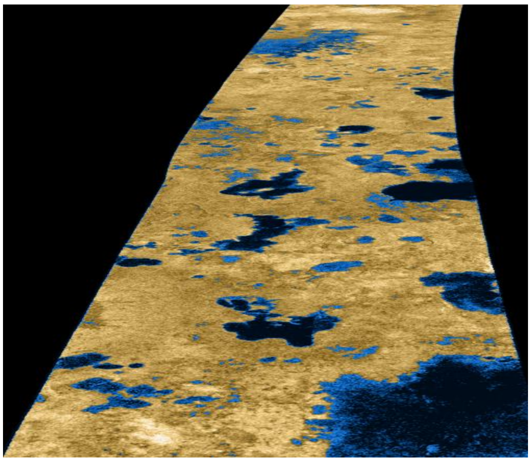
Mars has fascinated humanity for a long time since it is the closest in nature to Earth and in its early history may have been able to support life with flowing rivers across its surface and giant volcanoes making it similar to present day Iceland and Siberia. Indeed some believe that remnants of that early life may still exist deep in the Martian soil or could be found as fossils on its surface.

Since the 1960's a series of space craft have mapped Mars and explored the chemistry of its atmosphere. The most recent European mission, ***Mars Express***, detected surprising concentrations of methane and evidence of recent volcanism on Mars. In 2004 two NASA Rovers (named *Spirit* and *Opportunity*) were landed on the surface and for several years drove across the Martian landscape providing a wealth of information on Martian geology. They were originally designed to operate for a few weeks but unexpected wind processes have repeatedly cleaned their solar panels, and together with their excellent design and operations changed their lifetime from weeks to years.

In 2018 the EU, through ESA, will send its own Rover to Mars. ***ExoMars*** will be designed to search for life on Mars being equipped with a drill, which will enable it to probe beneath the Martian surface. Thus perhaps then we will find evidence of 'Martians', at least in bacterial form!

Exploring the planets





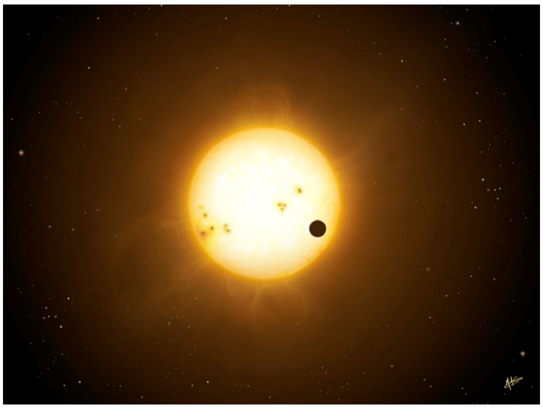
Titan the largest moon of the Solar system is shrouded in a 'haze' (left image) but beneath lies a fascinating world of lakes and seas but made of methane and other hydrocarbons not water as on Earth. Credit NASA/JPL

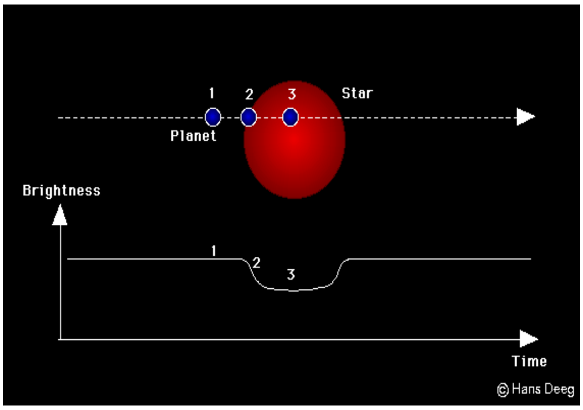
Titan is the largest moon of the planet Saturn, the only moon known to have a dense atmosphere (with a surface pressure close to that of the Earth atmosphere) and the only object in the solar system (other than of course Earth) to show permanent liquid bodies on its surface. Thus, in many ways, Titan is the most Earth like place in our Solar System.

The joint US/EU NASA/ESA Cassini-Huygens mission has provided us with a fascinating picture of this strange world. The atmosphere of Titan is largely composed of nitrogen with several percent of methane. Minor components lead to the formation of clouds, not of water, but of methane and ethane and a nitrogen-rich organic smog that hides its surface from view. Titan therefore, like Earth, has its own climate—including wind and rain— which creates surface features such as "sand" (in fact made of organics and water ice) dunes, rivers, lakes and seas (filled with liquid methane and ethane) and shorelines, and, like on Earth, is dominated by seasonal weather patterns. There are also mountains and volcanoes on Titan's surface. Titan is therefore thought to be similar to the early Earth, although at a much lower temperature and (in an underground liquid ocean) may host microbial extraterrestrial life or, at least, provide a prebiotic environment rich in complex organic chemistry. It has also been suggested that a form of life may exist on the surface, using liquid methane as a medium instead of water and acetylene and hydrogen as main energy source; and anomalies in atmospheric composition have been reported which may be consistent with the presence of such a life-form, but which could also be due to an exotic non-living chemistry.

To find out more about our exploration of the Solar system (and beyond) look at the Europlanet web site (http://www.europlanet-eu.org/outreach/).

Exploring New Worlds; The Search for Exoplanets





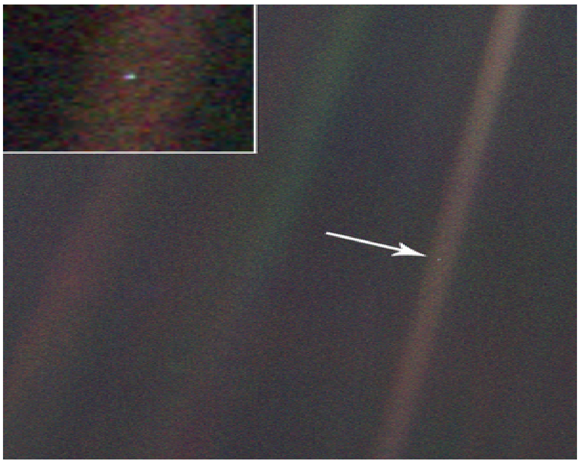
Left image; Detecting a planet as it passes in front of its star leads to a small reduction in the brightness of the star (right image) by such a 'transit method' we can detect planets orbiting other stars. Credits XXX

Our ability to detect planets around other stars was one of the most dramatic advances in astronomy in the late 20th century, perhaps bringing closer the day when we will be able to identify life elsewhere in the universe.

Planets around other stars are known as ***exoplanets*** and as of May 2011 some 550 planets have been detected. Unfortunately most of these are giant planets of the size of Jupiter or larger and are inhospitable places being huge 'gas giants' close to their star. These observations do not preclude the presence of other Earth like planets but rather is a consequence of the method by which they are detected since larger planets are easier to detect than smaller ones. For example one method is the so called 'transit method' which detects the presence of a planet by small reduction in light from the star as the planet passes across it, like an eclipse on Earth. The reduction in the amount of star light is tiny (maybe less than one percent) and there may be other reasons for such small changes such that the transit method suffers from many 'false positives' and planets detected in this way must be confirmed by another method. Spectroscopy can be used to measure small changes in the spectral emission of stars due to the 'Doppler effect' the same phenomena that makes a train whistle or ambulance siren sound different as it approaches and goes away from you. The Doppler effect is due to the mass of the planet influencing the star through its gravitational interaction and so this method also detects larger planets lying close to the star.

Despite these huge technical problems more planets are being detected every month and as the methodology is refined smaller planets further from the star are being detected, Indeed we now know that some stars have solar systems like our own, for example the star Gliese 581 had 4 confirmed planets whilst the star Sol has 8 - the same number as in our own solar system. By placing a telescope in space the effects of the Earth's atmosphere can be removed and higher resolution is possible allowing smaller planets to be detected. In February 2011 after just four months of observations NASA's Kepler telescope identified 1,235 possible planets associated with 997 stars.

Exploring New Worlds; The Search for Exoplanets



Left image; The Earth as viewed by the Voyager space craft from the edge of our solar system. A 'pale blue dot. This is how we are viewing exoplanets whose composition we can only speculate (right image) but which in this century we might reveal. Credits

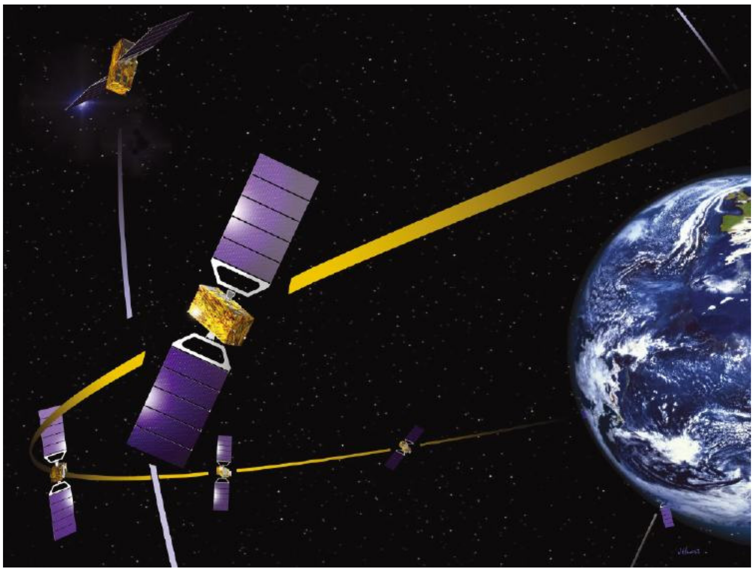
The ultimate aim of the study of exoplanets is to discover an Earth like planet around another star and search for life on its surface. The discovery of life on another planet will undoubtedly be one of the most astounding scientific discoveries of humanity. It is a quest that we may fulfill in this century !

In June 2011 we have been able to observe 10 exoplanets directly using telescopes, all are Giant Jupiters with toxic hot atmospheres, so hot that the infrared emissions (heat) from the planet can be observed. Such hot planets preclude life (at least as we know it) from developing but the methodology is developing and in the next few decades we expect to be able to not only detect earth sized planets but be able to study their atmospheres.

So how do you detect life on such a distant planet ? Complex life such as ourselves is at the end of a long evolutionary chain and so we must think of how life on Earth might appear to an observer outside our solar system before we could 'communicate' with radio and TV signals. We can ask the question how has life changed the Earth? The most obvious result of life on Earth has been the role of photosynthesis through which planets ejects molecular oxygen (O_2) into the terrestrial atmosphere leading to the formation of an ozone (O_3) layer. Detection of ozone may therefore be a 'biosignature' of plant life on the exoplanet. Similarly the diction of some organic compounds such as methane might provide evidence of life. Spectroscopic observations of the atmospheres of exoplanets thus provides the best method to probe for life on exoplanets whose position in their own solar system we believe to be suitable for life – that is in the 'habitable zone' where liquid water (needed for cell structures) can exist.

However we must be prepared to be surprised and as we explore our own Earth and find life capable of surviving extreme conditions (even inside nuclear reactors) so we must be ready to find life in the strangest places in our universe.

Space; New Technologies and New Jobs for Europe



***An artistic conception of the Galileo satellite communication network. The European Union's complimentary system to the US Global Positioning System (GPS) and the Russian GLObal NAvigation Satellite System (GLONASS providing Europe with an independent service*. Credit ESA**

Space research is not just an academic activity. Europe is the centre of a large multinational space industry that in 2009-10 reported a turnover of5.5 billion Euros and employed more than 31,000 people including large international companies such as EADS Astrium and Thales Alenia Space (employing more than 18000 people) and over 150 smaller companies employing some 7000 staff. The industry is distributed across Europe with major industry sites in Germany, France and Italy and large (and growing sites) in UK, Spain and Belgium.

The space industry designs, builds and launches a range of satellites for both telecommunications and Earth observation, the latter vital for weather forecasting and navigation. The European Union is currently building, **Galileo**, a global navigation satellite system to complement the US GPS based system.

Europe's space industry is central to the success of the European Space Agency's (ESA) planetary and space exploration programme with its mission 'to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world'. ESA currently employs some 2200 drawn from all of the EU's member states and in 2011 will have a budget of €3994 million. The European space industry provides the instruments and technology for the next generation of space missions.

The industry is also central to Europe's military organisation its satellites supporting NATO in its recent operations in Iraq, Afghanistan and Libya.

Space; New Technologies and New Jobs for Europe

The International Space University (ISU) based in Strasbourg is one of Europe's educational centres that specializes in training students at masters level in space technology. Nevertheless Europe continues to suffer from a lack of trained personnel to meet the needs of its technology based industries. Credit ISU

To sustain Europe at the forefront of astronomical and space research and to provide the highly skilled workforce that Europe's space industry needs requires a constant influx of highly trained scientists, engineers and information technology specialists. These must be drawn from Europe's universities some of which specialise in higher level training in space technology.

Although there has been a rise in Maths, Science and Technology (MST) Students during the last decade, all European nations continue to be concerned by the continued lack of European graduates to meet the demands of the technology based sector particularly as commercial and economic rivals such as India and China are seeing rapid increases in MST graduates. Furthermore the gender gap remains with the number of females on MST degrees continuing to be low.

The lack of highly trained MST graduates is of major concern to Europe's space industry such that if it is not addressed Europe may lose its competitive advantages to the US and increasingly to the new space nations (India, China, Brazil).

For more details on Europe's space industry see Eurospace http://www.eurospace.org/ and for the mission and activities of the European Space Agency see www.esa.int

This booklet was assembled by members of several European collaborations who we gratefully acknowledge

This booklet was supported by:

The European Science Foundation and the Cooperation in Science and Technology, COST