The Origin of Life

Index to this page

To account for the origin of life on our earth requires solving several problems:

- How the organic molecules that define life, e.g. amino acids, nucleotides, were created;
- How these were assembled into macromolecules, e.g. proteins and nucleic acids, — a process requiring catalysts;
- How these were able to reproduce themselves;
- How these were assembled into a system delimited from its surroundings (i.e., a cell).

A number of theories address each of these problems.

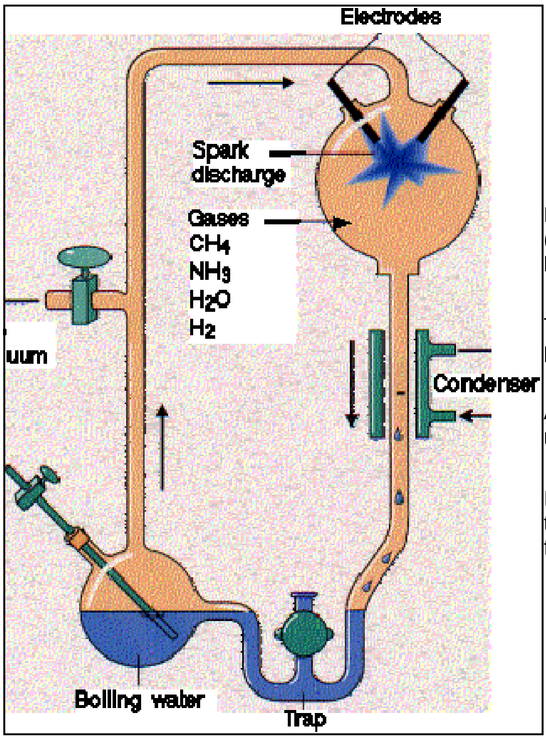
Abiotic Synthesis of Organic Molecules

As for the first, three scenarios have been proposed: organic molecules

1. were synthesized from inorganic compounds in the atmosphere
2. rained down on earth from outer space
3. were synthesized at hydrothermal vents on the ocean floor

1. Miller's Experiment

Stanley Miller, a graduate student in biochemistry, built the apparatus shown here. He filled it with



- water (H_2O
- methane (CH_4)
- ammonia (NH_3) and
- hydrogen (H_2)
- but no oxygen

He hypothesized that this mixture resembled the atmosphere of the early earth. (Some are not so sure.) The mixture was kept circulating by continuously boiling and then condensing the water.

The gases passed through a chamber containing two electrodes with a spark passing between them.

At the end of a week, Miller used paper chromatography to show that the flask now contained several amino acids as well as some other organic molecules.

In the years since Miller's work, many variants of his procedure have been tried. Virtually all the small molecules that are associated with life have been formed:

- 17 of the 20 amino acids used in protein synthesis, and
- all the purines and pyrimidines used in nucleic acid synthesis.
- But abiotic synthesis of **ribose** — and thus of **nucleosides** — has been much more difficult.

One difficulty with the primeval soup theory is that it is now thought that the atmosphere of the early earth was **not** rich in methane and ammonia — essential ingredients in Miller's experiments.

2. Molecules from outer space?
The Murchison Meteorite
This meteorite, that fell near Murchison, Australia on 28 September 1969, turned out to contain a variety of organic molecules including:

- purines and pyrimidines
- **polyols** — compounds with hydroxyl groups on a backbone of 3 to 6 carbons such as glycerol and glyceric acid. Sugars are polyols.
- the amino acids listed here. The amino acids and their relative proportions were quite similar to the products formed in Miller's experiments.

The question is: were these molecules simply terrestrial contaminants that got into the meteorite after it fell to earth.
Probably not:

- Some of the samples were collected on the same day it fell and subsequently handled with great care to avoid contamination.
- The polyols contained the isotopes carbon-13 and hydrogen-2 (deuterium) in greater amounts than found here on earth.
- The samples lacked certain amino acids that are found in all earthly proteins.
- Only **L** amino acids occur in earthly proteins, but the amino acids in the meteorite contain both **D** and **L** forms (although **L** forms were slightly more prevalent).

Representative amino acids found in the Murchison meteorite. Six of the amino acids (blue) are found in all living things, but the others (yellow) are not normally found in living matter here on earth. The same amino acids are produced in discharge experiments like Miller's.

Glycine	Glutamic acid
Alanine	Isovaline
Valine	Norvaline
Proline	N-methylalanine
Aspartic acid	N-ethylglycine

The ALH84001 meteorite
This meteorite arrived here from Mars. It contained not only a variety of organic molecules, including polycyclic aromatic hydrocarbons, but — some claim — evidence of microorganisms as well.
Furthermore, there is evidence that its interior never rose about 40° C during its fiery trip through the earth's atmosphere. Live bacteria could easily survive such a trip.

Link to a discussion of the possibility of life on Mars and more on the ALH84001 meteorite.

Organic molecules in interstellar space
Astronomers, using infrared spectroscopy, have identified a variety of organic molecules in interstellar space, including

- methane (CH_4),
- methanol (CH_3OH),
- formaldehyde (HCHO),
- cyanoacetylene (HC_3N) (which in spark-discharge experiments is a precursor to the pyrimidine **cytosine**).
- polycyclic aromatic hydrocarbons
- as well as such inorganic building blocks as carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), hydrogen sulfide (H_2S), and hydrogen cyanide (HCN).

Laboratory Synthesis of Organic Molecules Under Conditions Mimicking Outer Space
There have been several reports of producing amino acids and other organic molecules by taking a mixture of molecules known to be present in interstellar space such as:

- ammonia (NH_3)
- carbon monoxide (CO)
- methanol (CH_3OH) and
- water (H_2O)
- hydrogen cyanide (HCN)

and exposing it to

- a temperature close to that of space (near absolute zero)
- intense ultraviolet (uv) radiation.

Whether or not the molecules that formed terrestrial life arrived here from space, there is little doubt that **organic matter** continuously rains down on the earth (estimated at 30 tons per day).

3. Deep-Sea Hydrothermal Vents
Some deep-sea hydrothermal vents discharge copious amounts of hydrogen, hydrogen sulfide, and carbon dioxide at temperatures around 100°C. (These are not "black smokers".) These gases bubble up through chambers rich in iron sulfides (FeS, FeS_2). These can catalyze the formation of simple organic molecules like acetate. (And life today depends on enzymes that have Fe and S atoms in their active sites.)

Assembling Polymers

Another problem is how **polymers** — the basis of life itself — could be assembled.

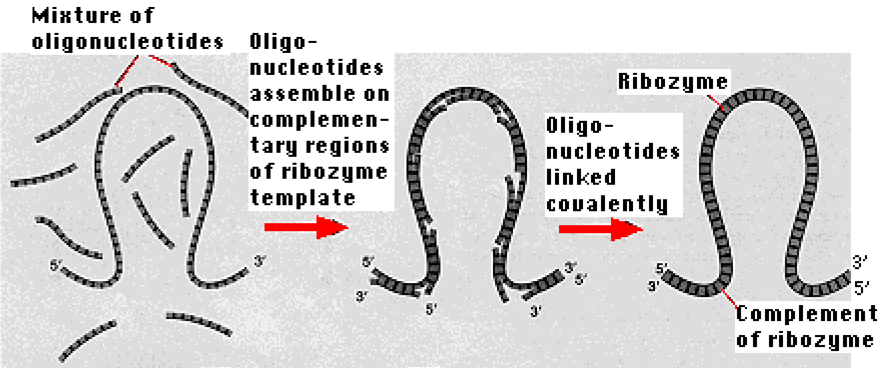
- In solution, hydrolysis of a growing polymer would soon limit the size it could reach.
- Abiotic synthesis produces a mixture of **L** and **D** enantiomers. Each inhibits the polymerization of the other. (So, for example, the presence of **D** amino acids inhibits the polymerization of **L** amino acids (the ones that make up proteins here on earth).

Link to a discussion of enantiomers.

This has led to a theory that early polymers were assembled on solid, mineral surfaces that protected them from degradation, and in the laboratory polypeptides and polynucleotides (RNA molecules) containing about ~50 units have been synthesized on mineral (e.g., clay) surfaces.

An RNA Beginning?

All metabolism depends on enzymes and, until recently, every enzyme has turned out to be a protein. But proteins are synthesized from information encoded in DNA and translated into mRNA. So here is a chicken-and-egg dilemma. The synthesis of DNA and RNA requires proteins. So



- proteins cannot be made without nucleic acids and
- nucleic acids cannot be made without proteins.

The discovery that certain RNA molecules have enzymatic activity provides a possible solution. These RNA molecules — called ribozymes — incorporate both the features required of life:

- storage of information
- the ability to act as catalysts

Link to a discussion of **ribozymes**.

While no ribozyme in nature has yet been found that can replicate itself, ribozymes have been synthesized in the laboratory that can catalyze the assembly of short oligonucleotides into exact complements of themselves. The ribozyme serves as both

- the template on which short lengths of RNA ("oligonucleotides" are assembled following the rules of base pairing and
- the catalyst for covalently linking these oligonucleotides.

(The figure is based on the work of Green and Szostak, **Science 258:**1910, 1992.)

In principal, the minimal functions of life might have begun with RNA and only later did

- proteins take over the catalytic machinery of metabolism and
- DNA take over as the repository of the genetic code.

Several other bits of evidence support this notion of an original "RNA world":

- Many of the cofactors that play so many roles in life are based on ribose; for example:
  - ATP
  - NAD
  - FAD
  - coenzyme A
  - cyclic AMP
  - GTP
- In the cell, all deoxyribonucleotides are synthesized from ribonucleotide precursors.
- Many bacteria control the transcription and/or translation of certain genes with RNA molecules (Link to "riboswitches") , not protein molecules.

Reproduction?

Perhaps the earliest form of reproduction was a simple fission of the growing aggregate into two parts — each with identical metabolic and genetic systems intact.

The First Cell?

To function, the machinery of life must be separated from its surroundings — some form of extracellular fluid (ECF). This function is provided by the plasma membrane.

Today's plasma membranes are made of a double layer of phospholipids. They are only permeable to small, uncharged molecules like H_2O, CO_2, and O_2. Specialized transmembrane transporters are needed for ions, hydrophilic, and charged organic molecules (e.g., amino acids and nucleotides) to pass into and out of the cell.

However, the same Szostak lab that produced the finding described above reported in the 3 July 2008 issue of **Nature** that fatty acids, fatty alcohols, and monoglycerides — all molecules that can be synthesized under prebiotic conditions — can also form lipid bilayers and these can spontaneously assemble into enclosed vesicles.

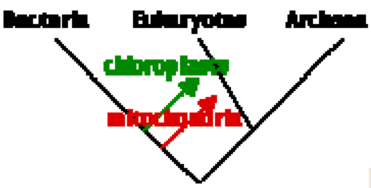
Unlike phospholipid vesicles, these

- admit from the external medium charged molecules like nucleotides
- admit from the external medium hydrophilic molecules like ribose
- grow by self-assembly
- are impermeable to, and thus retain, polymers like oligonucleotides.

These workers loaded their synthetic vesicles with a short single strand of deoxyguanosine (dC) structured to provide a template for its replication. When the vesicles were placed in a medium containing (chemically modified) dG, these nucleotides entered the vesicles and assembled into a strand of Gs complementary to the template strand of Cs.

Here, then, is a simple system that is a plausible model for the creation of the first cells from the primeval "soup" of organic molecules.

The Last Universal Common Ancestor (LUCA)?



The 3 kingdoms of contemporary life — archaea, bacteria, and eukaryotes — all share many similarities of their metabolic and genetic systems [Link]. Presumably these were present in an organism (or organisms) that were ancestral to these groups: the "LUCA". Although there are not enough data at present to describe LUCA, comparative genomics and proteomics reveal a closer relationship between archaea and eukaryotes than either shares with the bacteria. (Except, of course, for the mitochondria and chloroplasts that eukaryotes gained later from bacterial endosymbionts [Link].)

Welcome&Next Search

16 July 2008

We all live on planet Earth

We all live on planet Earth. Earth is full of living organisms .We can see living things all around us. There are plants, animals, birds, insects and tiny microscopic micro-organisms. Have you ever wondered if there is life on any other planet? People have tried to find the answer to this for ages. From the information gathered until now, we have concluded that it is possible that there is life on some distant planets in outer space.

However we do not know about it yet. In our solar system we are the only ones. Our solar system is the Sun and all the bodies that circle around it. That includes the nine planets, their moons, the asteroids and comets. Our Earth is one of those nine planets. The nine planets move around the Sun in definite path's called orbits. Mercury is closest to the sun, then Venus. Next is Earth, Mars, Jupiter, then Saturn, Uranus, Neptune and the farthest one is Pluto.

So why is life only on Earth? The answer is that, none of the other eight planets have conditions suitable for life. Living organisms need liquid water. The first living organisms on Earth were formed in water. Earth is the only planet at the correct distance from the Sun where water can remain in a liquid form.

Mercury and Venus are too hot. There is absolutely no water on those planets. Mars may have had liquid water in the past, but does not have it anymore. All of Mars's water is frozen in its two polar ice caps. Jupiter and Saturn are planets made entirely of gas. Uranus, Neptune and Pluto are too far away from the sun and extremely cold for any life to survive.

Our Earth also has the right size and the right gravity to hold the atmospheric blanket around it. The atmosphere around the Earth contains all the necessary gases in the air and moisture needed by living organisms. This atmospheric blanket also helps to keep Sun's heat energy trapped. This heat is required to keep the Earth's temperature right, to maintain liquid water. Thus earth is the only planet with the right distance from the Sun, right temperature, right size, right gravity, liquid water and all the other components necessary for life. Earth is our only home, the only planet with life. We need to preserve it.

The last common ancestor

When the earth formed some 4.6 billion years ago, it was lifeless and inhospitable to living organisms. One billion years later it was already teeming with prokaryotic life forms, **ancestors to all present living things**.
What would these early progenitors of life be like? If we make the reasonable assumption that the **last common ancestor** of all presently living organisms must have had those characteristics which are now shared by the organisms which constitute the five living kingdoms, then a listing of the common characteristics of living species also describes the minimum characteristics of the last common ancestor.
Harold Horowitz compiled the following list in his book, "Beginnings of Cellular Life" (Yale University Press, 1992)

- All life is cellular.
- All living things are from 50 to over 90% water, the source of protons, hydrogen and oxygen in photosynthesis and the solvent of biomolecules.
- The major elements of covalently bound biomolecules are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur.
- There is a universal set of small molecules: (i.e. sugars, amino acids, nucleotides, fatty acids, phospholipids, vitamins and coenzymes.)
- The principle macromolecules are proteins, lipids, carbohydrates and nucleic acids.
- There is a universal type of membrane structure (i.e. the lipid bilayer).
- The flow of energy in living things involves formation and hydrolysis of phosphate bonds, usually ATP.
- The metabolic reactions of any living species is a subset of a universal network of intermediary metabolism (i.e. glycolysis; the Krebs cycle, the electron transport chain)
- Every replicating cell has a genome made of DNA that stores the genetic information of the cell which is read out in sequences of RNA and translated into protein.
- All growing cells have ribosomes, which are the sites of protein synthesis.
- All living things translate information from nucleotide language through specific activating enzymes and transfer RNAs.
- All replicating biological systems give rise to altered phenotype due to mutated genotypes.
- Reactions that proceed at appreciable rates in all living cells are catalyzed by enzymes.

How did they get there? What mechanism(s) could produce such a complex organism from inanimate matter?
Darwin offered two answers, one public and the other private. In the final chapter of the "*Origin of Species",* he wrote *"the Creator... originally breathed life.... into a few forms or one. ... From so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved". In private correspondence he suggested life could have arisen through chemistry "in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc. present".*

Biologists and paleontologists have defined some basic questions that need to be answered when discussing the origin of life.

(1) Where did the raw materials for life come from?
(2) How did monomers develop?
(3) How did polymers develop?
(4) How did an isolated cell form?

http//www.utdallas.edu/~cirillo/nats/day18htm

Where did the raw materials for life come from?

One of the prerequisites of life is the presence of elements such as H, C, O, N, S, and P among others. Those elements, with the exception of hydrogen, the most abundant element in space, were not yet present in the early universe. The hot chemistry in the very early universe only produced very light elements, predominantly hydrogen and helium and traces of deuterium, tritium, lithium and berillium. All the other chemical elements that are featured in terrestrial biochemistry were formed by nucleosynthesis during the course of stellar evolution.
Carbon, the basis of organic chemistry, is produced by the so-called triple-α process ($3\ {}^{4}He \rightarrow {}^{12}C$) in the cores of stars more massive than half a solar mass. In the cores of evolving, massive (mass >10 solar masses) stars, heavy element nuclear burning produces the most abundant isotopes of sulfur (${}^{32}S$) and phosphorus (${}^{31}P$). In contrast to the primary production of carbon and oxygen, nitrogen is a secondary product, in the sense that its synthesis requires the presence of pre-existing carbon or oxygen from earlier generations of stars.

Proton-proton fusion

$$H^1 + H^1 \rightarrow D^2 + e^+ + \nu \quad 1.44\,Mev$$
$$D^2 + H^1 \rightarrow He^3 + \gamma \quad 5.49\,Mev$$
$$He^3 + He^3 \rightarrow He^4 + 2H^1 \quad 12.85\,Mev$$

During the main phase of its life, the star supports itself and emits energy by means of the nuclear fusion in its central region. Many hydrogen atoms are joined, producing helium nuclei and energy.
Other fusion reactions

At even higher temperatures inside the sun and other aging stars, other nuclei undergo fusion reactions. These reactions occur in layers, with the higher temperature layers closer to the center. Some examples are given in the table below.

Temperature		
~2 x 10^8 °K	~5 x 10^8 °K	~10 x 10^8 °K
He burning occurs $3\ {}^{4}He \longrightarrow {}^{12}C$ ${}^{4}He + {}^{12}C \longrightarrow {}^{16}O$ ${}^{4}He + {}^{16}O \longrightarrow {}^{20}Ne$	C burning occurs ${}^{12}C + {}^{12}C \longrightarrow {}^{24}Mg$ ${}^{12}C + {}^{12}C \longrightarrow {}^{23}Na + {}^{1}H$ ${}^{12}C + {}^{12}C \longrightarrow {}^{20}Ne + {}^{4}He$	myriad reactions occur ${}^{20}Ne \longrightarrow {}^{4}He + {}^{16}O$ ${}^{20}Ne + {}^{4}He \longrightarrow {}^{24}Mg$ ${}^{24}Mg + {}^{4}He \longrightarrow {}^{28}Si$

At the end of their lifetime, stars lose mass either in continuous or explosive events and the heavy elements are distributed into the interstellar medium, which gets gradually enriched in metallicity over time. Supernovae explosions, the final stages of high-mass stars (stars with more than 8 times the solar mass), are responsible for the fast and efficient distribution of elements over space and time. The heavy elements are crucial for the formation of complex molecules essential for life as we know it.
The step from atomic nuclei to molecules begins with the expulsion of nucleosynthetic products into the interstellar medium (ISM) by stellar winds, planetary nebula ejection, and supernova explosions.
After dying stars belch out carbon, some of the carbon atoms combine with hydrogen to form polycyclic aromatic hydrocarbons (PAHs). PAHs, a kind of carbon soot similar to the scorched portions of burnt toast, are the most abundant organic compounds in space, and a primary ingredient of carbonaceous chondrite meteorites. Although PAHs aren't found in living cells, they can be converted into quinones, molecules that are involved in cellular energy processes. For instance, quinones play an essential role in photosynthesis, helping plants turn light into chemical energy.
The transformation of PAHs occurs in interstellar clouds of ice and dust. After floating through space, PAH soot eventually condenses into these "dense molecular clouds." The material in these clouds blocks out some but not all of the harsh radiation of space. The radiation that does filter through modifies the PAHs and other material in the clouds.
Infrared and radio telescope observations of the clouds have detected the PAHs, as well as fatty acids, simple sugars, faint amounts of the amino acids, and over 100 other molecules, including water, carbon monoxide, ammonia, formaldehyde, and hydrogen cyanide.
The clouds have never been sampled directly -- they're too far away -- so to confirm what is occurring chemically in the clouds, a research team led by Max Bernstein and Scott Sandford at the Astrochemistry

Laboratory at NASA's Ames Research Center set up experiments to mimic the cloud conditions. In one experiment, a PAH/water mixture is vapor-deposited onto salt and then bombarded with ultraviolet (UV) radiation. This allows the researchers to observe how the basic PAH skeleton turns into quinones. Irradiating a frozen mixture of water, ammonia, hydrogen cyanide, and methanol (a precursor chemical to formaldehyde) generates the amino acids glycine, alanine and serine, the three most abundant amino acids in living systems. The experiment suggest that UV and other forms of radiation provide the energy needed to break apart chemical bonds in the low temperatures and pressures of the dense clouds. Because the atoms are still locked in ice, the molecules don't fly apart, but instead recombine into more complex structures.

Organic molecules in interstellar space

Astronomers, using infrared spectroscopy, have identified a variety of organic molecules in interstellar space, including

- methane (CH_4),
- methanol (CH_3OH),
- formaldehyde (HCHO),
- cyanoacetylene (HC_3N) (which in spark-discharge experiments is a precursor to the pyrimidine **cytosine**).
- polycyclic aromatic hydrocarbons
- as well as such inorganic building blocks as carbon dioxide (CO_2), carbon monoxide (CO), ammonia (NH_3), hydrogen sulfide (H_2S), and hydrogen cyanide (HCN).

What is a star?

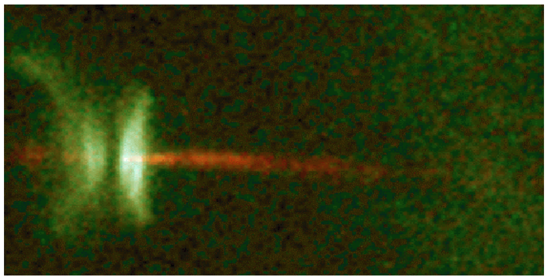
Stars are hot bodies of glowing gas that start their life in ***Nebulae.*** They vary in size, mass and temperature, diameters ranging from 500 smaller to over 1000 larger than that of the Sun. Masses range from a twentieth to over 50 solar masses and surface temperature can range from 3,000 degrees Celsius to over 50,000 degrees Celsius.
The colour of a star is determined by its temperature, the hottest stars are blue and the coolest stars are red. The Sun has a surface temperature of 5,500 degrees Celsius, its colour appears yellow.
The energy produced by the star is by nuclear fusion in the stars core.

Small Stars- The Life of a Star of about one Solar Mass.

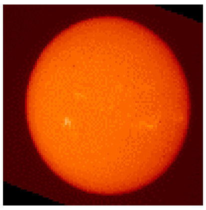
Small stars have a mass up to one and a half times that of the Sun.
Stage 1- Stars are born in a region of high density ***Nebula***, and condenses into a huge globule of gas and dust and contracts under its own gravity.
Stage 2 - A region of condensing matter will begin to heat up and start to glow forming *Protostars.* If a protostar contains enough matter the central temperature reaches 15 million degrees centigrade.
Stage 3 - At this temperature, nuclear reactions in which hydrogen fuses to form helium can start.
Stage 4 - The star begins to release energy, stopping it from contracting even more and causes it to shine. It is now a M*ain Sequence* ***Star.***
Stage 5 - A star of one solar mass remains in main sequence for about 10 billion years, until all of the hydrogen has fused to form helium.
Stage 6 - The helium core now starts to contract further and reactions begin to occur in a shell around the core.
Stage 7 - The core is hot enough for the helium to fuse to form carbon. The outer layers begin to expand, cool and shine less brightly. The expanding star is now called a ***Red Giant.***
Stage 8 - The helium core runs out, and the outer layers drift of away from the core as a gaseous shell, this gas that surrounds the core is called a ***Planetary Nebula***.
Stage 9 - The remaining core (thats 80% of the original star) is now in its final stages. The core becomes a W***hite Dwarf*** the star eventually cools and dims. When it stops shining, the now dead star is called a ***Black Dwarf***.

1 - The Orion Nebula or M42

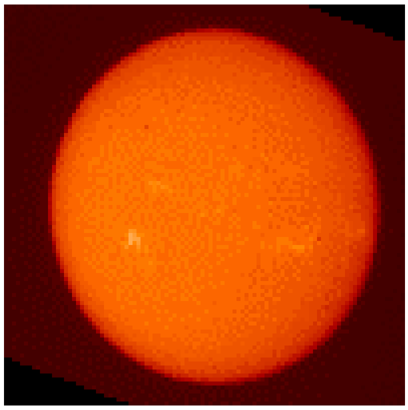
2 – A protostar



4 – The Sun



7 – Red Giant



8 - A Planetary Nebula

Massive Stars - The Life of a Star of about 10 Solar Masses

Massive stars have a mass 3x times that of the Sun. Some are 50x that of the Sun

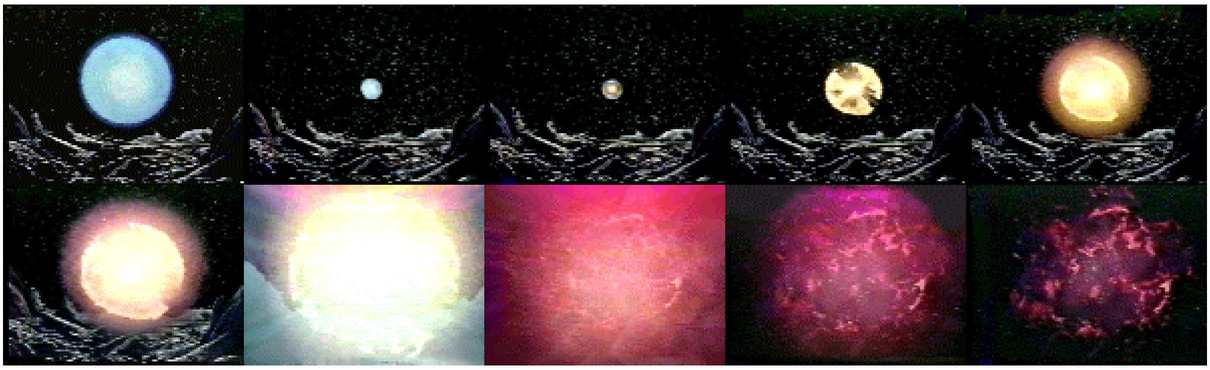
Stage 1 - Massive stars evolve in a similar way to a small stars until it reaches its main sequence stage (see small stars, stages 1-4). The stars shine steadily until the hydrogen has fused to form helium (it takes billions of years in a small star, but only millions in a massive star).

Stage 2 - The massive star then becomes a *Red Supergiant* and starts of with a helium core surrounded by a shell of cooling, expanding gas.

Stage 3 - In the next million years a series of nuclear reactions occur forming different elements in shells around the iron core.

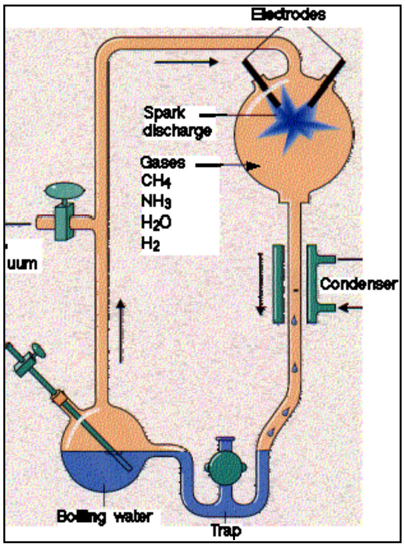
Stage 4 - The core collapses in less than a second, causing an explosion called a ***Supernova***, in which a shock wave blows of the outer layers of the star. (The actual supernova shines brighter than the entire galaxy for a short time).

Stage 5 - Sometimes the core survives the explosion. If the surviving core is between 1.5 - 3 solar masses it contracts to become a a tiny, very dense ***Neutron Star***. If the core is much greater than 3 solar masses, the core contracts to become a ***Black Hole.***



How did monomers develop?

The Miller-Urey experiments in the late 40's and early 50's showed that organic molecules could be formed by inorganic processes under primitive earth conditions. By discharging electric sparks in a large flask containing boiling water, methane, hydrogen and ammonia, conditions presumed to be similar to those of the early earth, they produced amino acids and other organic molecules experimentally. Using variations of their technique, most of the major building blocks of life have been produced: amino acids, sugars, nucleic acid bases and lipids.



Stanley Miller, a graduate student in biochemistry, built the apparatus shown here. He filled it with

- water (H_2O
- methane (CH_4)
- ammonia (NH_3) and
- hydrogen (H_2)
- but no oxygen

He hypothesized that this mixture resembled the atmosphere of the early earth. The mixture was kept circulating by continuously boiling and then condensing the water.

The gases passed through a chamber containing two electrodes with a spark passing between them.

At the end of a week, Miller used paper chromatography to show that the flask n ow contained several amino acids as well as some other organic molecules

Another source of amino acids and other organic molecule is meteorites. The amino acid content of the Murchison meteorite, for example, is surprisingly similar to that formed in the Miller-Urey experiments.

Murchison meteorite contains chains of fatty acids, various types of sugars, all five nucleic acid bases, and more than 70 different amino acids (life uses 20 amino acids, only six of which are in the Murchison meteorite).

The Murchison Meteorite crashed on September 28, 1969, near Murchison, Australia. *Credit: NASA*

Because such carbonaceous meteorites are generally uniform in composition, they are thought to be representative of the initial dust cloud from which the sun and solar system were born. So it seems that nearly everything needed for life was available at the beginning, and meteorites and comets then make fresh deliveries of these materials to the planets over time.

Both by earth-formed and meteorite-delivered processes, the early ocean could have become the thin "organic soup" proposed independently many years earlier by Alexander Oparin and J. B. S. Haldane as the starting place for life.

The first "organisms" presumably consumed these molecules both as building blocks and as sources of energy.

How did polymers develop?

The large molecules necessary to build living cells are:

* Proteins
* Carbohydrates (sugars)
* Lipids (fats)
* Nucleic acids

How polymers — the basis of life itself — could be assembled?

- In solution, hydrolysis of a growing polymer would soon limit the size it could reach.
- Abiotic synthesis produces a mixture of **L** and **D** enantiomers. Each inhibits the polymerization of the other. (So, for example, the presence of **D** amino acids inhibits the polymerization of **L** amino acids (the ones that make up proteins here on earth).

This has led to a theory that early polymers were assembled on solid, mineral surfaces that protected them from degradation, and in the laboratory polypeptides and polynucleotides (RNA molecules) containing about ~50 units have been synthesized on mineral (e.g., clay) surfaces.

An RNA Beginning?

All metabolism depends on enzymes and, until recently, every enzyme has turned out to be a protein. But proteins are synthesized from information encoded in DNA and translated into mRNA. So here is a chicken-and-egg dilemma. The synthesis of DNA and RNA requires proteins. So

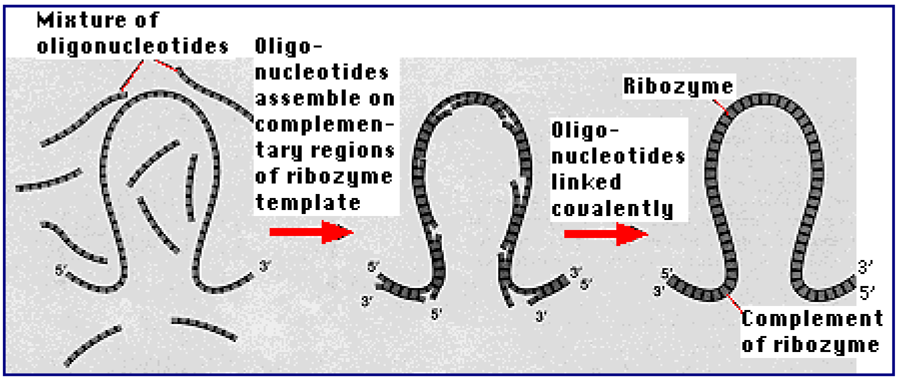
- proteins cannot be made without nucleic acids and
- nucleic acids cannot be made without proteins.

The discovery that certain RNA molecules have enzymatic activity provides a possible solution. These RNA molecules — called ribozymes — incorporate both the features required of life:

- storage of information
- the ability to act as catalysts

While no ribozyme in nature has yet been found that can replicate itself, ribozymes have been synthesized in the laboratory that can catalyze the assembly of short oligonucleotides into exact complements of themselves. The ribozyme serves as both

- the template on which short lengths of RNA ("oligonucleotides" are assembled following the rules of base pairing and
- the catalyst for covalently linking these oligonucleotides.



(The figure is based on the work of Green and Szostak, **Science 258:**1910, 1992.)

In principal, the minimal functions of life might have begun with RNA and only later did

- proteins take over the catalytic machinery of metabolism and
- DNA take over as the repository of the genetic code.

Several other bits of evidence support this notion of an original "RNA world":

- Many of the cofactors that play so many roles in life are based on ribose; for example: ATP, NAD, FAD, coenzyme A, etc.
- In the cell, all deoxyribonucleotides are synthesized from ribonucleotide precursors.
- Many bacteria control the transcription and/or translation of certain genes with RNA molecules (Link to "riboswitches") , not protein molecules.

How did an isolated cell form?

The First Cell?

To function, the machinery of life must be separated from its surroundings — some form of extracellular fluid (ECF). This function is provided by the plasma membrane.

Today's plasma membranes are made of a double layer of phospholipids. They are only permeable to small, uncharged molecules like H_2O, CO_2, and O_2. Specialized transmembrane transporters are needed for ions, hydrophilic, and charged organic molecules (e.g., amino acids and nucleotides) to pass into and out of the cell.

However, the same Szostak lab that produced the finding described above reported in the 3 July 2008 issue of **Nature** that fatty acids, fatty alcohols, and monoglycerides — all molecules that can be synthesized under prebiotic conditions — can also form lipid bilayers and these can spontaneously assemble into enclosed vesicles.

Unlike phospholipid vesicles, these

- admit from the external medium charged molecules like nucleotides
- admit from the external medium hydrophilic molecules like ribose
- grow by self-assembly
- are impermeable to, and thus retain, polymers like oligonucleotides.

All living things evolved from a common ancestor
Origin of life on Earth: Lecture outline No. 18

The origin of life on earth

The last common ancestor.

When the earth formed some 4.6 billion years ago, it was lifeless and inhospitable to living organisms. One billion years later it was already teeming with prokaryotic life forms, **ancestors to all present living things**. What would these early progenitors of life be like? If we make the reasonable assumption that the **last common ancestor** of all presently living organisms must have had those characteristics which are now shared by the organisms which constitute the five living kingdoms, then a listing of the common characteristics of living species also describes the minimum characteristics of the last common ancestor. Harold Horowitz compiled the following list in his book, "Beginnings of Cellular Life" (Yale University Press, 1992)

- All life is cellular.
- All living things are from 50 to over 90% water, the source of protons, hydrogen and oxygen in photosynthesis and the solvent of biomolecules.
- The major elements of covalently bound biomolecules are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur.
- There is a universal set of small molecules: (i.e. sugars, amino acids, nucleotides, fatty acids, phospholipids, vitamins and coenzymes.)
- The principle macromolecules are proteins, lipids, carbohydrates and nucleic acids.
- There is a universal type of membrane structure (i.e. the lipid bilayer).
- The flow of energy in living things involves formation and hydrolysis of phosphate bonds, usually ATP.
- The metabolic reactions of any living species is a subset of a universal network of intermediary metabolism (i.e. glycolysis; the Krebs cycle, the electron transport chain)
- Every replicating cell has a genome made of DNA that stores the genetic information of the cell which is read out in sequences of RNA and translated into protein.
- All growing cells have ribosomes, which are the sites of protein synthesis.
- All living things translate information from nucleotide language through specific activating enzymes and transfer RNAs.
- All replicating biological systems give rise to altered phenotype due to mutated genotypes.
- Reactions that proceed at appreciable rates in all living cells are catalyzed by enzymes.

How did they get there? What mechanism(s) could produce such a complex organism from inanimate matter? Darwin offered two answers, one public and the other private. In the final chapter of the "*Origin of Species",* he wrote *"the Creator... originally breathed life.... into a few forms or one. ... From so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved". In private correspondence he suggested life could have arisen through chemistry "in some warm little pond, with all sorts of ammonia and phosphoric salts, light, heat, electricity, etc. present".*

Leslie Orgel of the Salk Institute has said that *"For most of the 20th century, origin-of-life research has been trying to flesh out Darwin's private hypothesis - to elucidate how,* *without divine intervention, spontaneous interaction of relatively simple molecules dissolved in lakes and oceans of the prebiotic world could have yielded life's **last common ancestor**."* (Scientific American, October 1994, p. 77).

Biologists and paleontologists have defined five basic questions that need to be answered when discussing the origin of life.

(1) Where did the raw materials for life come from?
(2) How did monomers develop?
(3) How did polymers develop?
(4) How did an isolated cell form?
(5) How did reproduction begin?

The following are only tentative and speculative answers to these questions

1) **Where did the raw materials come from?**

The early earth is presumed to have provided all of the elements and chemicals needed for life to begin.

2) How did monomers form?

The Miller-Urey experiments in the late 40's and early 50's showed that organic molecules could be formed by inorganic processes under primitive earth conditions. By discharging electric sparks in a large flask containing boiling water, methane, hydrogen and ammonia, conditions presumed to be similar to those of the early earth, they produced amino acids and other organic molecules experimentally. Using variations of their technique, most of the major building blocks of life have been produced: amino acids, sugars, nucleic acid bases and lipids.

Another source of amino acids and other organic molecule is meteorites. The amino acid content of the Murchison meteorite, for example, is surprisingly similar to that formed in the Miller-Urey experiments.

Both by earth-formed and meteorite-delivered processes, the early ocean could have become the thin "organic soup" proposed independently many years earlier by Alexander Oparin and J. B. S. Haldane as the starting place for life. The first "organisms" presumably consumed these molecules both as building blocks and as sources of energy. Upon the exhaustion of these early molecules, other strategies had to be develop such as photosynthesis. The first forms of photosynthesis was probably non-oxygenic using inorganic molecules as a source of electrons to reduce carbon dioxide, however, when these sources were exhausted, oxygen generating photosynthesis was developed using water as the electron source. The generation of oxygen had a most dramatic effect on future evolution.

3) How did polymers develop?

Various suggestions about this process exist. Polymerization on clays or the evaporation of amino acid containing water near volcanic vents. Sidney Fox has demonstrated such polymerizations experimentally. Such reactions could have led to the polymerization of amino acids and nucleotides. Others believe that polymerizations occurred in cold environments where the polymers would be more stable.

4) How did an isolated cell form?

Harold Morowitz has proposed that the formation of **closed, membrane vesicles** was an early event in cellular evolution. Lipid molecules *spontaneously* form membrane vesicles or liposomes. ("Beginnings of Cellular Life", 1992, Yale University Press). Consider the following properties of membrane vesicles, which are also the properties of cells.

1) They maintain separate stable phases in an aqueous environment.
2) They maintain different chemical compositions between intra- and extra-cellular compartments.
3) They maintain substantial transbilayer electrical voltages, pH differences, and oxidation potentials (necessary for chemiosmotic processes).
4) They form spontaneously from abiotically formed amphipathic lipid molecules

"What is impressive in simply listing the properties of vesicles is how many cellular features are already present in these simple systems. Strong reasons for assuming the importance of vesicles in biogenesis are their spontaneous formation and the continuity they make with contemporary cells in so many ways".

5) How did reproduction begin?

By what series of chemical reactions did the complex structure and the interdependent system of nucleic acids and proteins come about? Carl Woese, Francis Crick and Leslie Orgel propose that RNA came first. It could self-replicate and possibly serve as enzymes for protein synthesis. In 1983 Thomas Cech and, independently, Sidney Altman discovered ribozymes, that is, the ability of RNA to catalyze its own modifications without the use of protein enzymes. They received the Nobel Prize and the RNA world is now with us. Eventually the RNA it would be replaced by DNA and protein enzymes to take over information storage and enzymatic functions, respectively.

Ribozymes exist and have been modified to carry out some of the important reactions of RNA replication such as stringing up nucleotides and oligonucleotides using ATP. Derived ribozymes can also be made to cleave chemical bonds including peptides. In translation on ribosomes it is probably the rRNA, not the protein, that forms the peptide bonds. Furthermore, ATP and all coenzymes are *ribonucleotides* which some consider are relics of the original RNA World. Thus there is reason to believe that there was an original RNA world which invented protein synthesis and only later was supplanted by DNA.

The extraterrestrial origin of life?

Svante Arrhenius in 1908 proposed the **"panspermia theory"** - that life originated on Earth with the arrival of spores that had drifted through space from some other planetary or solar system. Among those who favor this hypothesis, Francis Crick argues that the overwhelming biochemical and molecular evidence suggests that the last **common ancestor** was already on earth 3.5 to 3.6 billion years ago when the history of life began on earth.

Is the Panspermia idea a viable one? The possibility that life once existed on Mars made much news last year. The evidence is questionable but still a possibility. Is it likely that microbial life came to earth from Mars or some more distant extraterrestrial source? "*Deinococcus radiodurans*, a bacterium highly resistant to radiation**,** would be a good vector for panspermia, said Dr. [Kenneth W.] Minton [of the Uniformed Services University of Health Sciences in Bethesda, MD]. While drifting through interstellar space for many thousands of years, it might acquire a shell of interstellar crud that could protect it [from the intense heat generated] when it entered some planet's atmosphere space".

Final Caveat

Almost all of this section is highly conjectural. Read it with this in mind.

Building Life from Star-Stuff

by Leslie Mullen

Hourglass marking dawn since nebula, an exploded star peering back through time.
Credit: Hubble

Life on Earth was made possible by the death of stars. Atoms like carbon and oxygen were expelled in the last few dying gasps of stars after their final supplies of hydrogen fuel were used up.

How this star-stuff came together to form life is still a mystery, but scientists know that certain atomic combinations were necessary. Water - two hydrogen atoms linked to one oxygen atom -was vital to the development of life on Earth, and so NASA missions now search for water on other worlds in the hopes of finding life elsewhere. Organic molecules built mostly of carbon atoms are also thought to be important, since all life on Earth is carbon-based.

The most popular theories of the origin of life say the necessary chemistry occurred at hydrothermal vents on the ocean floor or in some sunlit shallow pool. However, discoveries in the past few years have shown that many of the basic materials for life form in the cold depths of space, where life as we know it is not possible.

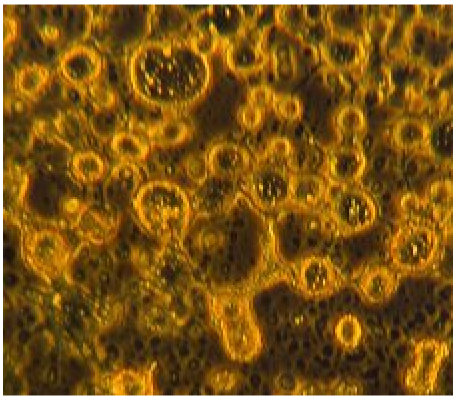
After dying stars belch out carbon, some of the carbon atoms combine with hydrogen to form polycyclic aromatic hydrocarbons (PAHs). PAHs -- a kind of carbon soot similar to the scorched portions of burnt toast -- are the most abundant organic compounds in space, and a primary ingredient of carbonaceous chondrite meteorites. Although PAHs aren't found in living cells, they can be converted into quinones, molecules that are involved in cellular energy processes. For instance, quinones play an essential role in photosynthesis, helping plants turn light into chemical energy.

The transformation of PAHs occurs in interstellar clouds of ice and dust. After floating through space, PAH soot eventually condenses into these "dense molecular clouds." The material in these clouds blocks out some but not all of the harsh radiation of space. The radiation that does filter through modifies the PAHs and other material in the clouds.

Infrared and radio telescope observations of the clouds have detected the PAHs, as well as fatty acids, simple sugars, faint amounts of the amino acid glycine, and over 100 other molecules, including water, carbon monoxide, ammonia, formaldehyde, and hydrogen cyanide.

The clouds have never been sampled directly -- they're too far away -- so to confirm what is occurring chemically in the clouds, a research team led by Max Bernstein and Scott Sandford at the Astrochemistry Laboratory at NASA's Ames Research Center set up experiments to mimic the cloud conditions.

In one experiment, a PAH/water mixture is vapor-deposited onto salt and then bombarded with ultraviolet (UV) radiation. This allows the researchers to observe how the basic PAH skeleton turns into quinones. Irradiating a frozen mixture of water, ammonia, hydrogen cyanide, and methanol (a precursor chemical to formaldehyde) generates the amino acids glycine, alanine and serine -- the three most abundant amino acids in living systems.



Scientists have created primitive organic cell-like structures, or vesicles.

Because UV is not the only type of radiation in space, the researchers also have used a Van de Graaff generator to bombard the PAHs with mega-electron volt (MeV) protons, which have similar energies to cosmic rays. The MeV results for the PAHs were similar although not identical to the UV bombardment. A MeV study for the amino acids has not yet been conducted.

These experiments suggest that UV and other forms of radiation provide the energy needed to break apart chemical bonds in the low temperatures and pressures of the dense clouds. Because the atoms are still locked in ice, the molecules don't fly apart, but instead recombine into more complex structures.

In another experiment led by Jason Dworkin, a frozen mixture of water, methanol, ammonia and carbon monoxide was subjected to UV radiation. This combination yielded organic material that formed bubbles when immersed in water. These bubbles are reminiscent of cell membranes that enclose and concentrate the chemistry of life, separating it from the outside world.

The bubbles produced in this experiment were between 10 to 40 micrometers, or about the size of red blood cells. Remarkably, the bubbles fluoresced, or glowed, when exposed to UV light. Absorbing UV and converting it into visible light in this way could provide energy to a primitive cell. If such bubbles played a role in the origin of life, the fluorescence could have been a precursor to photosynthesis.

Fluorescence also could act as sunscreen, diffusing any damage that otherwise would be inflicted by UV radiation. Such a protective function would have been vital for life on the early Earth, since the ozone layer, which blocks out the sun's most destructive UV rays, did not form until after photosynthetic life began to produce oxygen.

From space clouds to the seeds of life

Dense molecular clouds in space eventually gravitationally collapse to form new stars. Some of the leftover dust later clumps together to form asteroids and comets, and some of these asteroids clump together to form planetary cores. On our planet, life then arose from whatever basic materials were at hand.

The large molecules necessary to build living cells are:

* Proteins
* Carbohydrates (sugars)
* Lipids (fats)
* Nucleic acids

Meteorites have been found to contain amino acids (the building blocks of proteins), sugars, fatty acids (the building blocks of lipids), and nucleic acid bases. The Murchison meteorite, for instance, contains chains of fatty acids, various types of sugars, all five nucleic acid bases, and more than 70 different amino acids (life uses 20 amino acids, only six of which are in the Murchison meteorite).

The Murchison Meteorite crashed on September 28, 1969, near Murchison, Australia. The meteorite contains minerals, water, and complex organic molecules such as amino acids. *Credit: NASA*

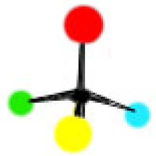
Because such carbonaceous meteorites are generally uniform in composition, they are thought to be representative of the initial dust cloud from which the sun and solar system were born. So it seems that nearly everything needed for life was available at the beginning, and meteorites and comets then make fresh deliveries of these materials to the planets over time.

If this is true, and if molecular dust clouds are chemically similar throughout the galaxy, then the ingredients for life should be widespread.

The downside of the abiotic production of the ingredients for life is that none of them can be used as "biomarkers," indicators that life exists in a particular environment.

Max Bernstein points to the Alan Hills meteorite 84001 as an example of biomarkers that didn't provide proof of life. In 1996, Dave McKay of NASA's Johnson Space Center and his colleagues announced there were four possible biomarkers within this martian meteorite. ALH84001 had carbon globules containing PAHs, a mineral distribution suggestive of biological chemistry, magnetite crystals resembling those produced by bacteria, and bacteria-like shapes. While each alone was not thought to be evidence for life, the four in conjunction seemed compelling.

After the McKay announcement, subsequent studies found that each of these so-called biomarkers also could be produced by non-living means. Most scientists therefore are now inclined to believe that the meteorite does not contain fossilized alien life.



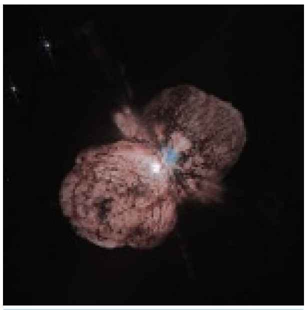
When a molecule comes in two mirror-image forms, it is termed chiral. The majority of amino acids are chiral molecules (shown above). Proteins on Earth are composed of left-handed amino acids, allowing a chain of them to fold up nicely into a compact protein. When scientists synthesize amino acids from nonchiral precursors, the result is a "racemic" mixture - equal numbers of right- and left-handed forms.
Credit: Bernhard Rupp

"As soon as they had the result, people went gunning for them because that's the way it works," says Bernstein. "Our chances of not making an error when we come up with a biomarker on Mars or on Europa will be much better if we've already done the equivalent of what those guys did after McKay, et al., published their article."

Bernstein says that by simulating conditions on other planets, scientists can figure out what should be happening there chemically and geologically. Then, when we visit a planet, we can see how closely reality matches the predictions. If there's anything on the planet that we didn't expect to find, that could be an indication that life processes have altered the picture.

"What you have on Mars or on Europa is material that's been delivered," says Bernstein. "Plus, you have whatever has formed subsequently from whatever conditions are present. So (to look for life), you need to look at the molecules that are there, and keep in mind the chemistry that may have happened over time."

Bernstein thinks chirality, or a molecule's "handedness," could be a biomarker on other worlds. Biological molecules often come in two forms that, while chemically identical, have opposite shapes: a "left-handed" one, and its mirror image, a "right-handed" one. A molecule's handedness is due to how the atoms bond. While handedness is evenly dispersed throughout nature, in most cases living systems on Earth have left-handed amino acids and right-handed sugars. If molecules on other planets show a different preference in handedness, says Bernstein, that could be an indication of alien life.



Spectacular gas remnants from exploding star.
Image Credit: Hubble

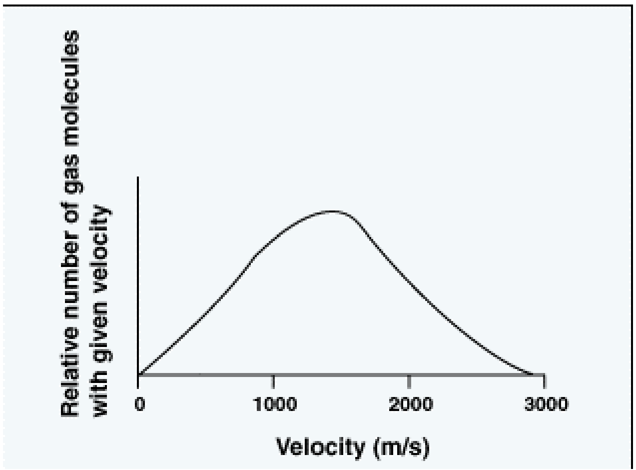
"If you went to Mars or Europa and you saw a bias the same as ours, with sugars or amino acids having our chirality, then people would simply suspect it was contamination," says Bernstein. "But if you saw an amino acid with a bias towards the right, or if you saw a sugar that had a bias towards the left -- in other words, not our form -- that would be really compelling."

However, Bernstein notes that the chiral forms found in meteorites reflect what is seen on Earth: meteorites contain left-handed amino acids and right-handed sugars. If meteorites represent the template for life on Earth, then life elsewhere in the solar system also may reflect that same bias in handedness. Thus, something more than chirality may be needed for proof of life. Bernstein says that finding chains of molecules, "such as a couple of amino acids linked together," also could be evidence for life, "because in meteorites we tend to just see single molecules."

Fusion Chemistry - A Closer Look

The composition of the sun can be described in several ways. By modern estimates, the composition by mass is: 71% H, 27% He, and 2% other heavier elements. By number of atoms of a given type, the sun's composition is: 91% H, 9% He, and 0.1% other heavier elements. Hydrogen can mean either H atoms or H_2 molecules and context is needed to make the meaning of the word clear. In the sun's core neither hydrogen molecules nor neutral hydrogen atoms with one proton in the nucleus and one orbital electron are present. The violent, hot environment of the sun's center rips atoms apart into their constituent pieces: protons, electrons, and other bare atomic nuclei. Hydrogen in the sun's core is **ionized**, a bare proton, represented by the symbol p^+. It is these protons that fuse together with the release of energy.

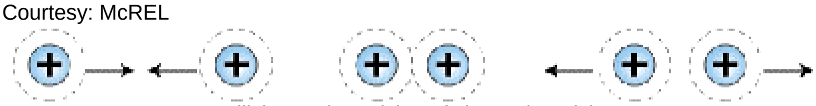
What keeps the sun from exploding when all of those hydrogen nuclei (protons) collide and fuse together? How has the sun managed to ration its supply of hydrogen nuclei in such a way as to preserve most of them for millions of years? The answer to these questions is that the core, like the rest of the sun, can be regarded as a gaseous body and analyzed according to the principles of the Kinetic Molecular Theory of Gases, which is well understood by researchers.



Velocity distribution of particles
Courtesy: McREL

In this model the temperature of a moving gas particle is directly proportional to its velocity squared. Also, according to this model there is a bell-shaped statistical distribution of particle velocities in a sample of a gas, as shown here, where the x-axis might represent either particle velocity or particle temperature.

It should be clear that in a sample of gas a few particles are almost motionless, while a few other particles are moving at extraordinarily high velocities. In other words some particles are cold (slow moving) and others are extraordinarily hot (extremely fast moving). However, as indicated by the shape of the curve, the largest portion of particles has a specific velocity that corresponds to the average temperature of the sample. So in the sun's core, even at its average "low" temperature, there are present a relatively few extraordinarily hot protons that are moving with much higher velocities than the "average" proton.



Collision and repulsion of charged particles
Courtesy: McREL

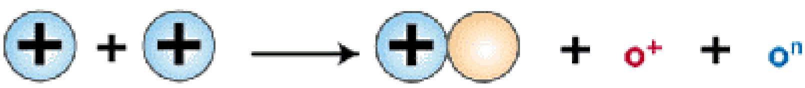
Typically, the motion of particles of like charges is random, resulting in collisions and repulsions. It almost seems as if there were a barrier of some kind around each particle, causing repulsion when they approach each other. Only a few super-high-speed protons have enough kinetic energy to tunnel through the electrostatic repulsion barrier and fuse together, initiating the chain of events that ultimately provides the energy from the sun's core. The average proton simply does not have enough energy to tunnel through the barrier and fuse with a collision partner. In other words the vast majority of collisions do not lead to a fusion event.

Proton-proton fusion

In the mid-1930s, after the discovery of the neutron in 1932 and the construction of machines that could accelerate particles, **fusion reactions** were demonstrated in earth-bound laboratories and the essential correctness of the theoretical predictions regarding fusion in the sun was established. It is now estimated that at core temperatures, only one proton in 100 million is hot enough to fuse during a collision. Put another way, the reaction rate is so very slow that a specific proton would require 14,000 billion years to find a suitably "hot" partner with which to collide in a successful fusion event. Since the sun is only about 4.5 billion years old, most of its protons have not yet found a fusion partner.

How does **proton-proton fusion** work? First, two exceedingly "hot" protons (hydrogen ions without electrons) collide. This violent event results in the fusion of the two nuclei and the formation of a deuteron, a positron, and a neutrino. This event can be written conveniently in equation form, where superscripts attached to elemental symbols represent mass number and charge:

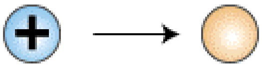
$${}^{1}H + {}^{1}H \longrightarrow {}^{2}D + {}^{o}e^{+} + \ _{c}$$



Formation of Deuterium
Courtesy: McREL

The symbols $^oe^+$ and $_c$ represent a **positron** and a **neutrino**, respectively. The **deuteron**, ^2D, differs from a regular hydrogen nucleus in that it contains a neutron in addition to a proton. In this reaction one of the protons has been changed into a neutron, with the formation of a new nucleus containing one proton and one neutron. The key transformation can be written:

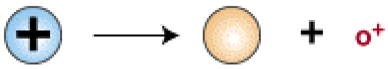
$$^1p^+ \longrightarrow {}^1n^0$$



Proton becomes neutron
Courtesy: McREL

This equation cannot be correct as written, because it does not account for the charge of the proton. On the left side of the equation is a positive charge and on the right side there is no charge. Note that the mass number is conserved. What is indicated is the creation of a particle having a mass of zero and a charge of plus one on the right side of the equation. Thus we are introduced to the positron, $^oe^+$, which is a positively charged electron: a particle of **antimatter**. More correctly, this equation becomes:

$$^1p^+ \longrightarrow {}^1n^o + {}^oe^+$$



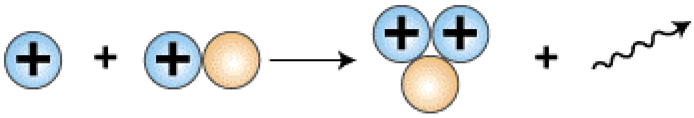
Proton becomes neutron and positron
Courtesy: McREL

Now charge and mass number are conserved. However, in natural reactions, momentum is also conserved. If a positron speeds away, there must be something that flies out in the opposite direction, since it has been determined that the positron momentum is not balanced by recoil of the proton. A neutrino, answering this requirement, is also emitted. The neutrino is represented by the symbol $_c$.

The next step in the so-called proton-proton cycle that fuels the sun is the collision of another proton with the deuteron that is formed, producing a **helium nucleus** containing 2 protons and one neutron, symbolized as ^3He.

$$^1H + {}^2D \longrightarrow {}^3He +$$

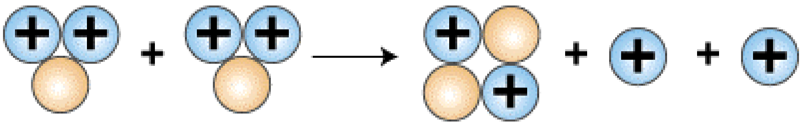
The symbol represents a **gamma ray photon**, which is required to balance the energy on both sides of the equation.



Release of gamma ray photon
Courtesy: McREL

Finally, as the last step, two helium-3 nuclei collide to form helium-4, ^4He, and two protons.

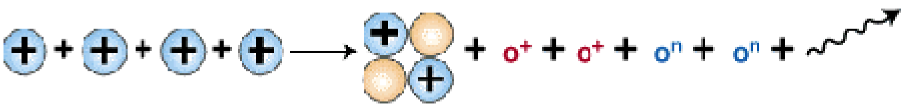
$$^3He + {}^3He \longrightarrow {}^4He + 2\,{}^1H$$



Formation of helium nucleus
Courtesy: McREL

The overall net reaction becomes:

$$4\,{}^1H \longrightarrow {}^4He + 2\,{}^oe^+ + 2\quad c + 2$$

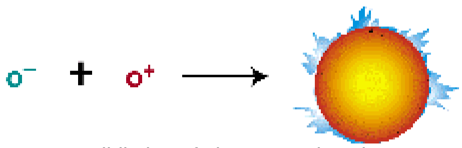


Solar hydrogen fusion yields helium and energy
Courtesy: McREL

The only energy production mentioned in the equation above is the gamma rays, which are the original source of the sun's radiated energy. They must eventually work their way out of the core.

The hydrogen nuclei (protons) at the sun's core are hydrogen atoms from which electrons have been ripped away (ionized nuclei). The hot, rapidly moving protons are mixed with an immense number of loose electrons. The positrons formed in the first equation nearly instantaneously encounter their sub-atomic anti-partners¾the electrons, instantly annihilating each other and producing a flash of pure energy in the form of gamma ray photons.

$$^{o}e^{+} + {}^{o}e^{-} \longrightarrow \text{ENERGY}$$



Annihilation of electron and positron
Courtesy: McREL

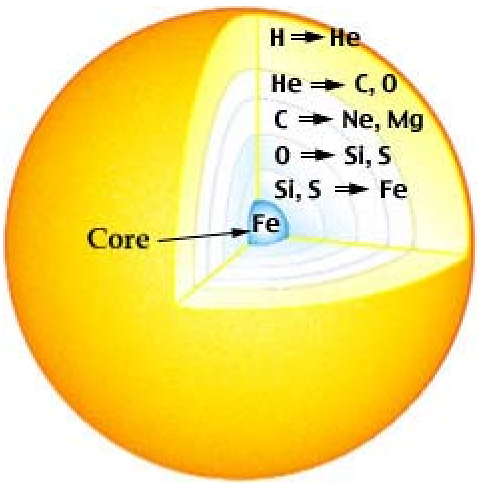
The positron and the electron both have mass (albeit small). Their combined masses are destroyed completely and turned into energy, according to the Einstein relationship $E= mc^2$. Detailed calculations actually show that mass is lost and converted to energy in each of the nuclear reaction steps and these collective mass losses account for the total energy output of the sun.

The scenario outlined above is called the proton-proton chain. It is the most important process for producing the sun's energy, although it is not the only set of reactions that occur.

Other fusion reactions

At even higher temperatures inside the sun and other aging stars, other nuclei undergo fusion reactions. These reactions occur in layers, with the higher temperature layers closer to the center. Some examples are given in the table below.

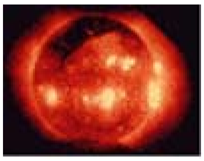
Temperature		
~2 x 10^8 °K	~5 x 10^8 °K	~10 x 10^8 °K
He burning occurs 3 $^{4}He \longrightarrow {}^{12}C$ + $^{4}He + {}^{12}C \longrightarrow {}^{16}O$ + $^{4}He + {}^{16}O \longrightarrow {}^{20}Ne$ + $^{4}He + {}^{20}Ne \longrightarrow {}^{24}Mg$ +	C burning occurs $^{12}C + {}^{12}C \longrightarrow {}^{24}Mg$ + $^{12}C + {}^{12}C \longrightarrow {}^{23}Na + {}^{1}H$ $^{12}C + {}^{12}C \longrightarrow {}^{20}Ne + {}^{4}He$	myriad reactions occur $^{20}Ne \longrightarrow {}^{4}He + {}^{16}O$ $^{20}Ne + {}^{4}He \longrightarrow {}^{24}Mg$ + 2 $^{20}Ne \longrightarrow {}^{16}O + {}^{24}Mg$ + $^{24}Mg + {}^{4}He \longrightarrow {}^{28}Si$ + $^{44}Ca + {}^{4}He \longrightarrow {}^{48}Ti$ +



Nuclear Reaction Layers in an Aging Star
Courtesy: McREL

Reaction rates

It takes a given proton 14,000 million years to find a "hot" partner. How does the sun's prodigious energy production arise from the proton-proton chain when the reaction rate is so low? The answer is that there are a stupendous number of protons available in the sun. Based on the sun's luminosity and the energy released per proton-proton chain event, the number of core reactions occurring every second is calculated to be about 9 x 10^{37}. The sun's mass is being consumed at the astounding rate of 4.4 x 10^9 kg per second.



Courtesy: NASA

This mind-boggling number might seem alarming at first glance. Is the sun in danger of running out of hydrogen? No, absolutely not. Presently the mass of the sun is almost 2×10^{30} kg. In other words, the sun still has a lot of hydrogen to work with. In fact, over the 4.5 billion years that the sun has shone, only about 0.03% of its mass has been consumed. The sun is in the middle of its life cycle, and will be heating and lighting the planets for billions of years to come.

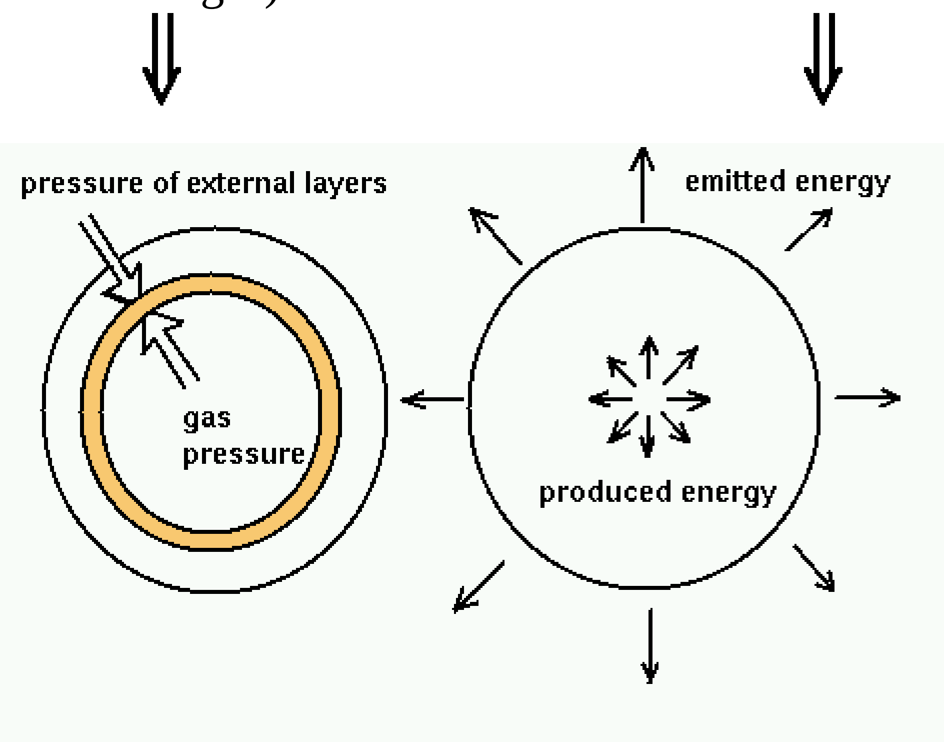
Fusion chemistry as described above forms the basis of the Standard Solar Model, an explanation of the sun's composition and functioning used by Genesis scientists in their design of solar wind collection devices. The results of the analysis of the samples of solar wind collected in the Genesis sample return capsule will test the effectiveness of this model in explaining the formation of the solar system.

How do stars age?

During the main phase of its life, the star supports itself and emits energy by means of the nuclear fusion in its central region. Many hydrogen atoms are joined in groups of four, producing helium nuclei and energy.
The energy produced in the nucleus is used to support the weight of the layers of gas surrounding the nucleus itself and is emitted as radiation. In other words, two kinds of equilibria are maintained inside the star: an **hydrostatic equilibrium** and a **thermal balance**.

The hydrostatic equilibrium is the one that is established between the gravitational force (which would lead the star to collapsing upon itself) and the energy produced in the nucleus (which, on the other hand, tends to push outwards the upper layers of the gas).

The thermal balance consists in the equality between the energy lost each second by the star (that is the energy emitted as light) and that produced each second through the nuclear fusion reactions.

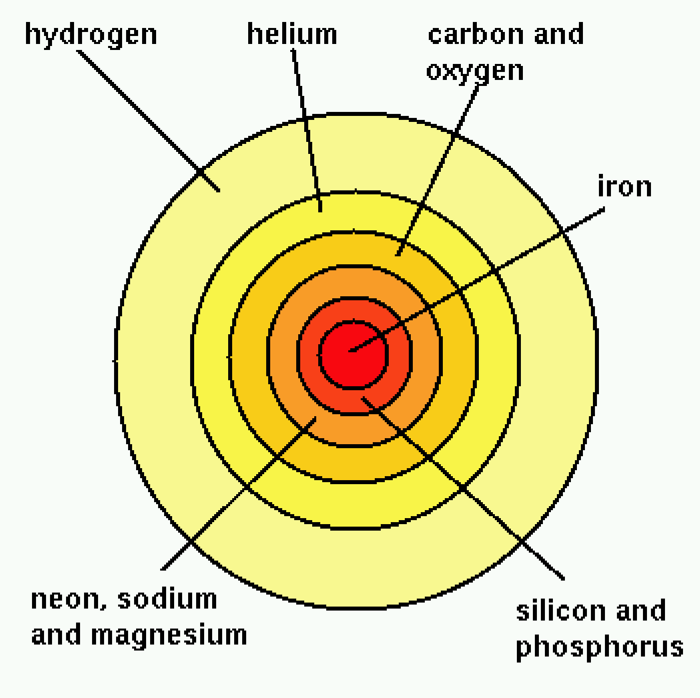


If the star did not produce enough energy in order to support its weight, then it would collapse upon itself under the pushing of its own gravitational force. If, instead, too much energy were produced, the star should expand to disperse it, or even explode! The star spends, in this state of equilibrium, most of its life, even if sometimes some stars go through instability phases: in that case they become variable stars.

The star is not eternal: after a longer or shorter time, it exhausts the hydrogen in the nucleus. This can happen after some tens of million years or tens of billion years, according to the mass of the star.

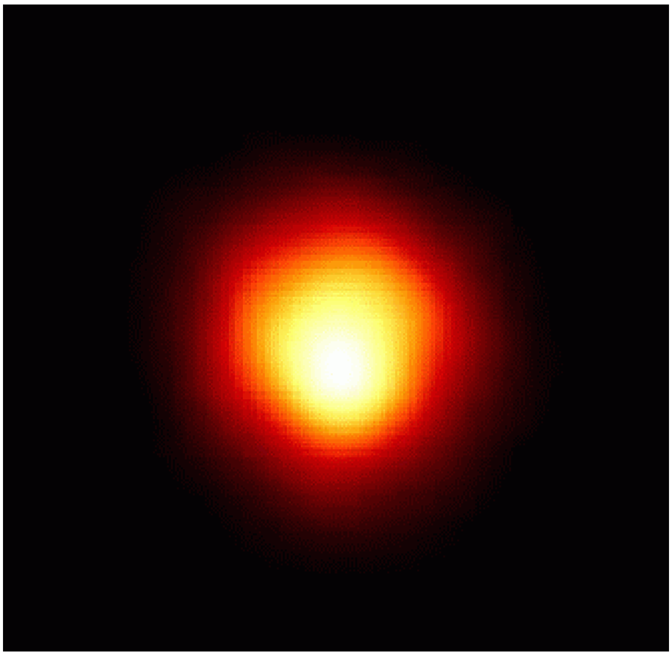
This moment marks the beginning of its "old age" and the end of a relatively quiet life. The equilibrium that, up to that moment, had supported the star finishes and it must experience a series of violent changes. The following phases will be much shorter than the one that just passed.

The star is now rich in helium and poor in hydrogen. The nuclear fusion reactions get slower due to the lack of fuel and the star is not able to support its weight anymore. Its nucleus begins then to contract, and this way its temperature increases. Do you remember the experiment that you made with the gas?



Even the region surrounding the nucleus heats up, and the nuclear reactions that stopped in the nucleus here start again. In order to give out the heat produced by the new reactions, the external layers inflate enormously and cool out: the star becomes a **red giant**.

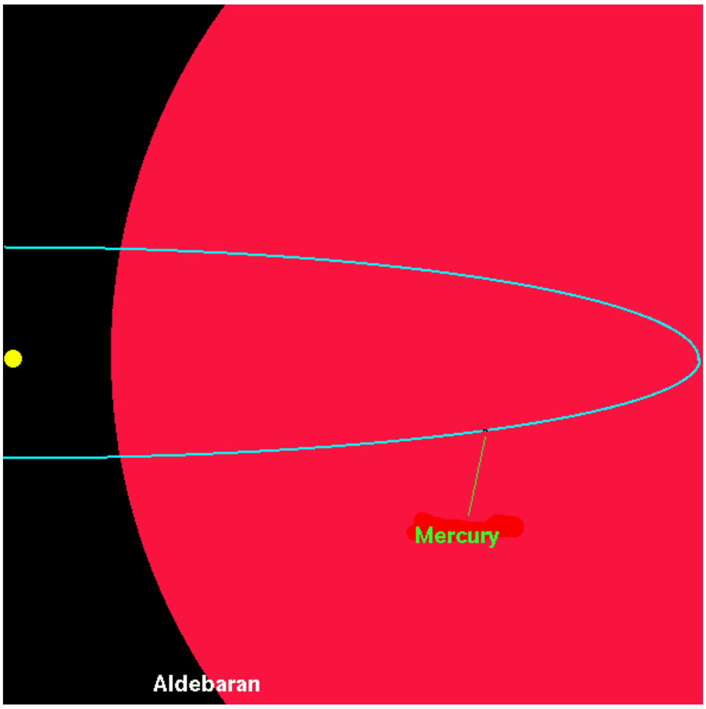
The radius of the star increases up to 1,000 times the initial one. The surface that emits the radiation becomes very large, so the star is up to one hundred thousand times brighter than before. The surface temperature of the star goes down to 3,000-4,000 degrees: at that temperature, it emits red light.
The stars that are passing through this phase, are among the brightest in the sky.



The red giant Betelgeuse, in the Orion constellation. This star is as large as 500 times the Sun. If it were in its place, it would fill all the space out to the orbit of Mars, and farther. (courtesy STScI)

During the red giant phase and the following ones, the relations between mass, radius, and luminosity do not hold anymore. In fact, the equilibrium of the star has changed. A red giant is much brighter than an equal mass star burning hydrogen.

Below you can see how big the red giants are: one could say that the name "giants" is well deserved!

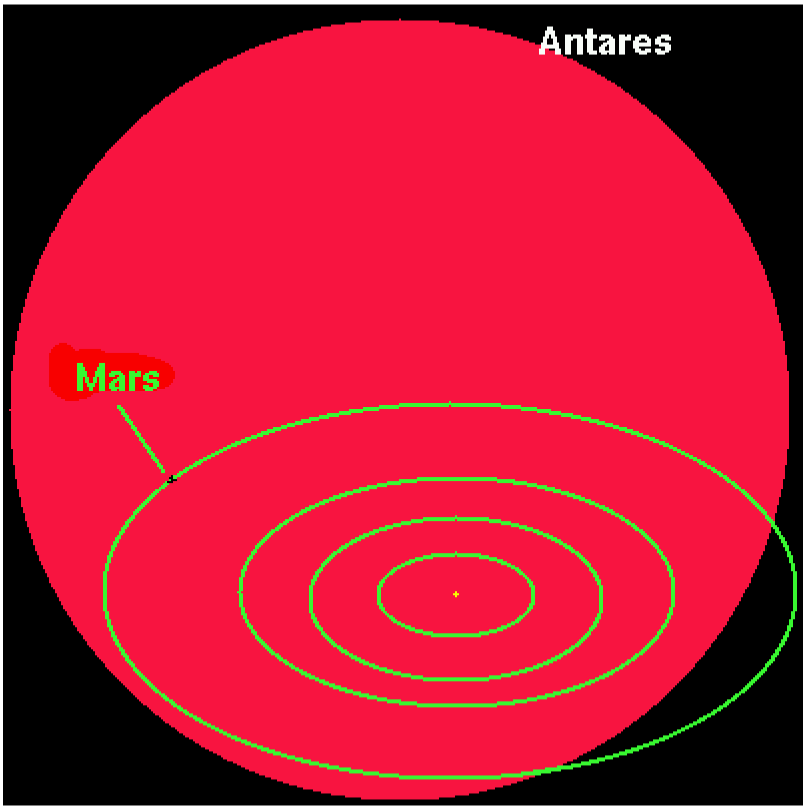


The dimensions of **Aldebaran** (a red giant star in the Taurus constellation) compared to the Sun and the orbit of Mercury.
Click below to enlarge the image.

Larger image

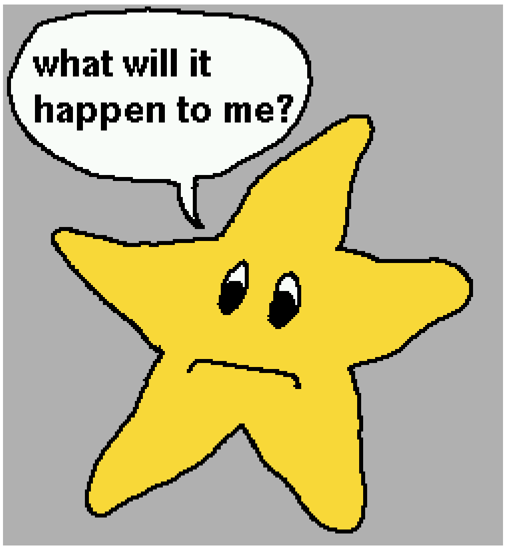
The dimensions of the red giant **Antares** (in the Scorpio constellation) compared to those of the inner Solar System (out to Mars).
Click below to enlarge the image.

Larger image



As we said, the nucleus of the star keeps contracting, heating up to a temperature of 100 million degrees. At this point the speed of

the helium atoms, abundantly present, has increased because of the temperature increase. They begin bouncing with great violence, great enough that they are joined in groups of three and form carbon nuclei.
The star has found another central source of energy so it goes again into an equilibrium state. Slowly the surface heats up and contracts; the star becomes much less bright and now it is not emitting most of its radiation as red light.



The following evolution is not the same for every star. This time, every star follows a different evolution according to its mass.

Roughly one can distinguish between low mass stars (that is with masses going from one tenth to about two times that of the Sun) and high mass stars (with masses from 2 to 100 times that of the Sun).

The Life and Death of Stars

WHERE ARE STARS BORN?

Astronomers believe that molecular clouds, dense clouds of gas located primarily in the spiral arms of galaxies are the birthplace of stars. Dense regions in the clouds collapse and form "protostars". Initially, the gravitational energy of the collapsing star is the source of its energy. Once the star contracts enough that its central core can burn hydrogen to helium, it becomes a "main sequence" star.

Image of "Star Birth" Clouds in M16:

PRC95-44b Hubble Wide Field Image
Text link to the HST press release describing this image

MAIN SEQUENCE STARS

Main sequence stars are stars, like our Sun, that fuse hydrogen atoms together to make helium atoms in their cores. For a given chemical composition and stellar age, a stars' luminosity, the total energy radiated by the star per unit time, depends only on its mass. Stars that are ten times more massive than the Sun are over a thousand times more luminous than the Sun. However, we should not be too embarrassed by the Sun's low luminosity: it is ten times brighter than a star half its mass. The more massive a main sequence star, the brighter and bluer it is. For example, Sirius, the dog star, located to the lower left of the constellation Orion, is more massive than the Sun, and is noticeably bluer. On the other hand, Proxima Centauri, our nearest neighbor, is less massive than the Sun, and is thus redder and less luminous.

Since stars have a limited supply of hydrogen in their cores, they have a limited lifetime as main sequence stars. This lifetime is proportional to $f M / L$, where f is the fraction of the total mass of the star, M, available for nuclear burning in the core and L is the average luminosity of the star during its main sequence lifetime. Because of the strong dependence of luminosity on mass, stellar lifetimes depend sensitively on mass. Thus, it is fortunate that our Sun is not more massive than it is since high mass stars rapidly exhaust their core hydrogen supply. Once a star exhausts its core hydrogen supply, the star becomes redder, larger, and more luminous: it becomes a red giant star. This relationship between mass and lifetime enables astronomers to put a lower limit on the age of the universe.

DEATH OF AN "ORDINARY" STAR

After a low mass star like the Sun exhausts the supply of hydrogen in its core, there is no longer any source of heat to support the core against gravity. Hydrogen burning continues in a shell around the core and the star evolves into a red giant. When the Sun becomes a red giant, its atmosphere will envelope the Earth and our planet will be consumed in a fiery death.

Meanwhile, the core of the star collapses under gravity's pull until it reaches a high enough density to start burning helium to carbon. The helium burning phase will last about 100 million years, until the helium is exhausted in the core and the star becomes a red supergiant. At this stage, the Sun will have an outer envelope extending out towards Jupiter. During this brief phase of its existence, which lasts only a few tens of thousands of years, the Sun will lose mass in a powerful wind. Eventually, the Sun will lose all of the mass in its envelope and leave behind a hot core of carbon embedded in a nebula of expelled gas. Radiation from this hot core will ionize the nebula, producing a striking "planetary nebula", much like the nebulae seen around the remnants of other stars. The carbon core will eventually cool and become a white dwarf, the dense dim remnant of a once bright star.

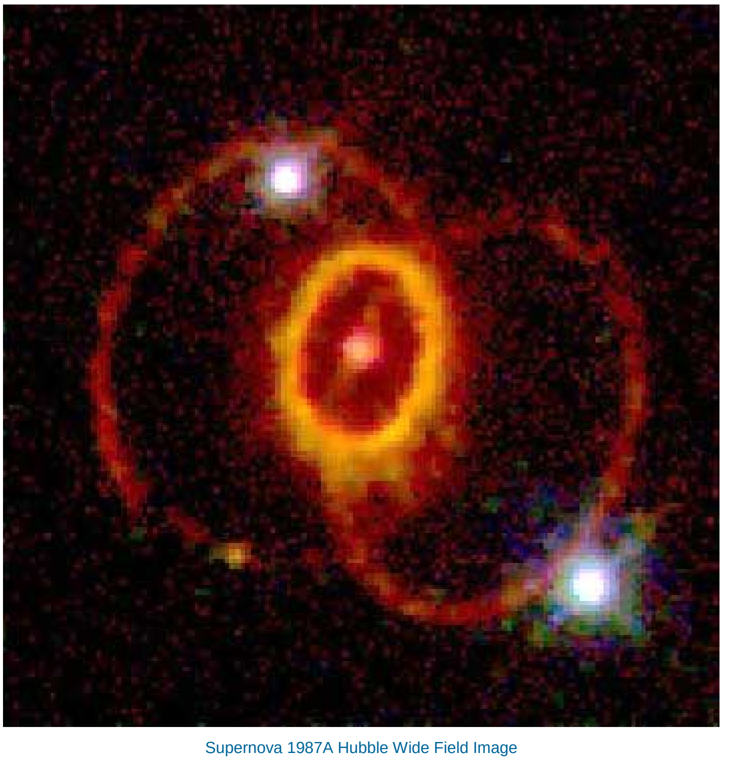
Image of a Planetary Nebula:

NGC 6543 Hubble Wide Field Image
Text Link to the HST press release describing this image

DEATH OF A MASSIVE STAR

Massive stars burn brighter and perish more dramatically than most. When a star ten times more massive than Sun exhaust the helium in the core, the nuclear burning cycle continues. The carbon core contracts further and reaches high enough temperature to burn carbon to oxygen, neon, silicon, sulfur and finally to iron. Iron is the most stable form of nuclear matter and there is no energy to be gained by burning it to any heavier element. Without any source of heat to balance the gravity, the iron core collapses until it reaches nuclear densities. This high density core resists further collapse causing the infalling matter to "bounce" off the core. This sudden core bounce (which includes the release of energetic neutrinos from the core) produces a supernova explosion. For one brilliant month, a single star burns brighter than a whole galaxy of a billion stars. Supernova explosions inject carbon, oxygen, silicon and other heavy elements up to iron into interstellar space. They are also the site where most of the elements heavier than iron are produced. This heavy element enriched gas will be incorporated into future generations of stars and planets. Without supernova, the fiery death of massive stars, there would be no carbon, oxygen or other elements that make life possible.

Image of a Supernova Remnant:



Supernova 1987A Hubble Wide Field Image
Text Link to the HST press release describing this image

The fate of the hot neutron core depends upon the mass of the progenitor star. If the progenitor mass is around ten times the mass of the Sun, the neutron star core will cool to form a neutron star. Neutron stars are potentially detectable as "pulsars", powerful beacons of radio emission. If the progenitor mass is larger, then the resultant core is so heavy that not even nuclear forces can resist the pull of gravity and the core collapses to form a black hole.

Learn more about the late stages of stellar evolution from the Chandra mission's web pages:

- White Dwarfs
- Neutron Stars
- Black Holes
- Supernovae

STARS, LIFE AND CHEMISTRY

Does the Universe need life ?

Only Earth supports life

Earth is full of living organisms

In our solar system we are the only ones.

So why is life present only on Earth?

The Earth, an exceptional planet

Moon

Mars

Earth

Earth is the only planet at the correct distance from the Sun where water can remain in a liquid form

Living organisms need liquid water.

The first living organisms on Earth were formed in water

Only Earth supports life

Our Earth also has the right size and the right gravity to hold the atmospheric blanket around it.
The atmosphere around the Earth contains all the necessary gases in the air and moisture needed by living organisms. This atmospheric blanket also helps to keep Sun's heat energy trapped. This heat is required to keep the Earth's temperature right, to maintain liquid water.
Thus Earth is the only planet with the right distance from the Sun, right temperature, right size, right gravity, liquid water and all the other components necessary for life.
Earth is our only home, the only planet with life.
We need to preserve it.

The last common ancestor

When the Earth formed some 4.6 billion years ago, it was lifeless and inhospitable to living organisms. One billion years later it was already teeming with prokaryotic life forms, ancestors to all present living things.

The last common ancestor of all presently living organisms must have had those characteristics which are now shared by the organisms which constitute the five living kingdoms

Biologists and paleontologists have defined some basic questions that need to be answered when discussing the origin of life:

(1) Where did the raw materials for life come from?
The major elements of covalently bound biomolecules are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur.

(2) How did monomers develop?
There is a universal set of small molecules: sugars, amino acids, nucleotides, fatty acids, etc.

(3) How did polymers develop?
The principle macromolecules are proteins, lipids, carbohydrates and nucleic acids

(4) How did an isolated cell form?
All life is cellular, with a universal type of membrane structure

Where did the raw materials for life come from?

One of the prerequisites of life is the presence of elements such as H, C, O, N, S, and P among others. Those elements, with the exception of hydrogen, the most abundant element in space, were not yet present in the early universe. The hot chemistry in the very early universe only produced very light elements, predominantly hydrogen and helium and traces of deuterium, tritium, lithium and berillium. All the other chemical elements that are featured in terrestrial biochemistry were formed by nucleosynthesis during the course of stellar evolution.

The step from atomic nuclei to molecules begins with the expulsion of nucleosynthetic products into the interstellar medium (ISM) by stellar winds, planetary nebula ejection, and supernova explosions.
After dying stars belch out carbon, some of the carbon atoms combined with hydrogen to form organic compounds

Where were stars born?

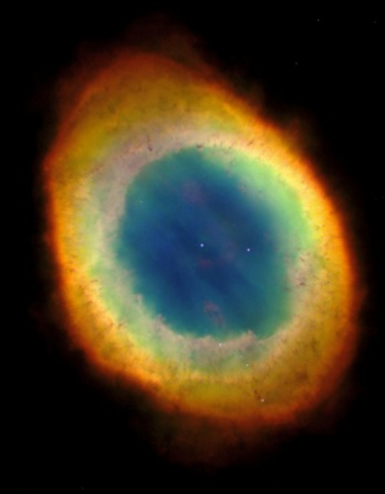
Dense clouds of gas located primarily in the spiral arms of galaxies are the birthplace of stars.
Dense regions in the clouds collapse and form "protostars". The gravitational energy of the collapsing star is the source of its energy. Once the star contracts enough its central core can burn hydrogen to helium, it becomes a star

The Orion cloud is one of the most intense regions of stellar formation visible in our galaxy

horsehead nebula and flame nebula
nebulosa testa di cavallo e nebulosa fiamma

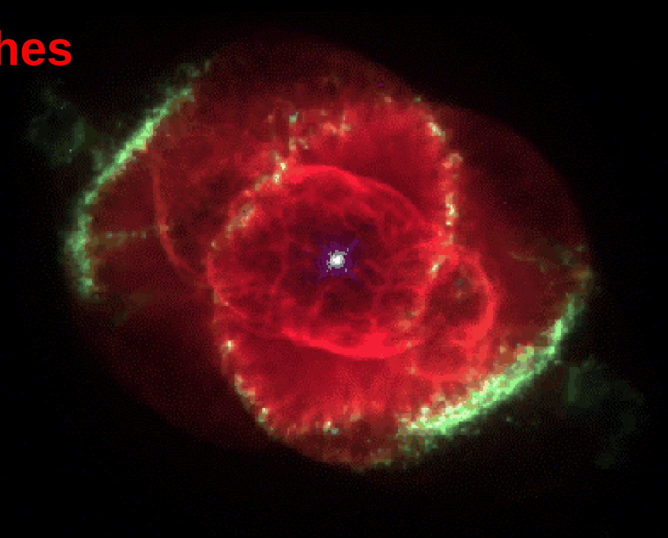
What happens when a star dies?

The star's white-hot-ashes



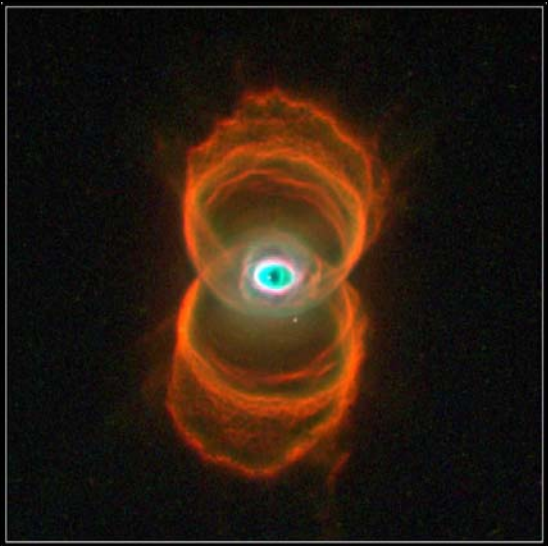
Ring Nebula

A **planetary nebula** is an emission nebula consisting of a glowing shell of gas and plasma formed by certain types of stars when they die.



NGC 6543

Planetary nebulae are important objects in astronomy because they play a crucial role in the chemical evolution of the galaxy, returning material to the interstellar medium which has been enriched in heavy elements and other products of nucleosynthesis (such as carbon, nitrogen, oxygen and calcium).



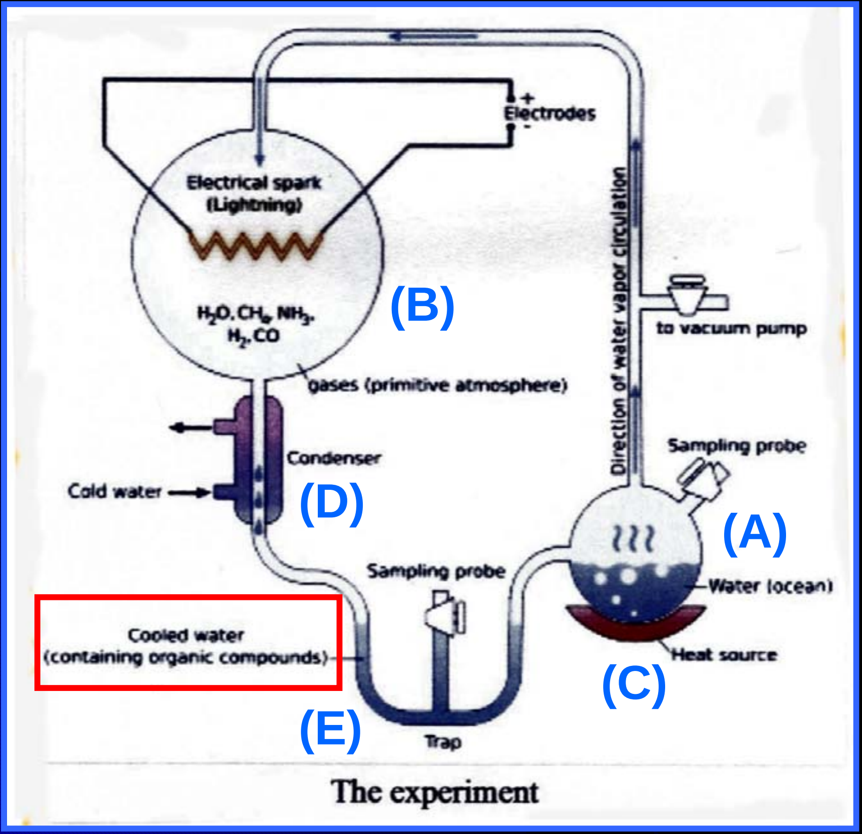
MyCn18

How did monomers develop?

The Miller–Urey experiment

The Miller–Urey experiment was an experiment that simulated hypothetical conditions thought at the time to be present on the early Earth

Specifically the experiment tested that conditions on the primitive Earth favored chemical reactions that synthesized organic compound from inorganic precursors



The experiment

The experiment used water, methane, ammonia, and hydrogen. The chemicals were all sealed inside a sterile array of glass tubes and flasks connected in a loop, with one flask half-full of liquid water (A) and another flask containing a pair of electrodes (B). The liquid water was heated (C) to induce evaporation, sparks were fired between the electrodes to simulate lighthing through the atmosphere and water vapor, and then the atmosphere was cooled (D) again so that the water could condense (E) and trickle back into the first flask in a continuous cycle.

At the end of one week of continuous operation, Miller and Urey observed that as <u>much as 10–15% of the carbon within the system was now in the form of organic compounds</u>. Two percent of the carbon had formed <u>amino acids, sugars, lipids</u>, and some of the building blocks for nucleic acids.

How did polymers develop?

The large molecules necessary to build living cells are:

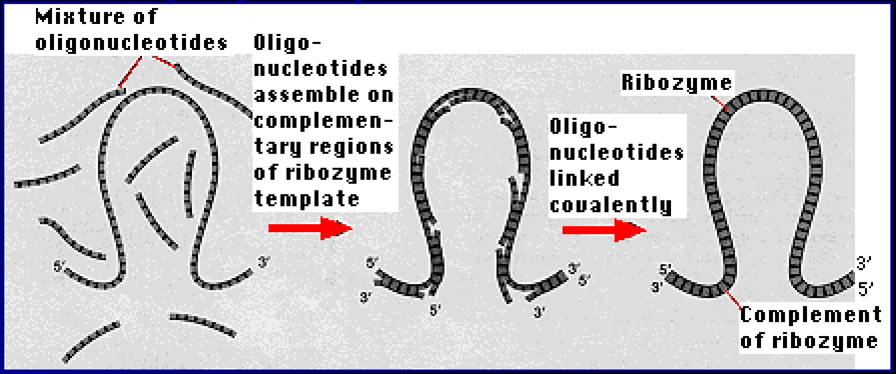
- Proteins
- Carbohydrates (sugars)
- Lipids (fats)
- Nucleic acids

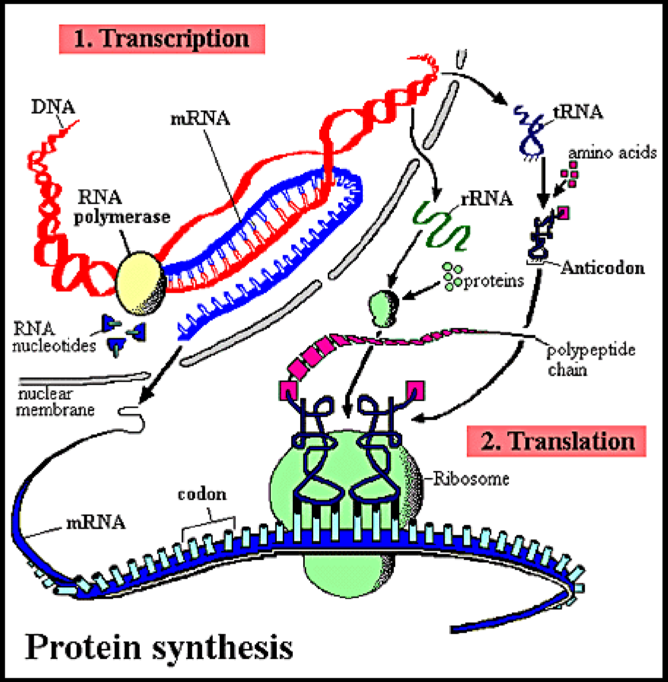
All metabolism depends on enzymes and, until recently, every enzyme has turned out to be a protein. But proteins are synthesized from information encoded in DNA and translated into mRNA. So here is a chicken-and-egg dilemma. The synthesis of DNA and RNA requires proteins. So

- proteins cannot be made without nucleic acids and
- nucleic acids cannot be made without proteins.

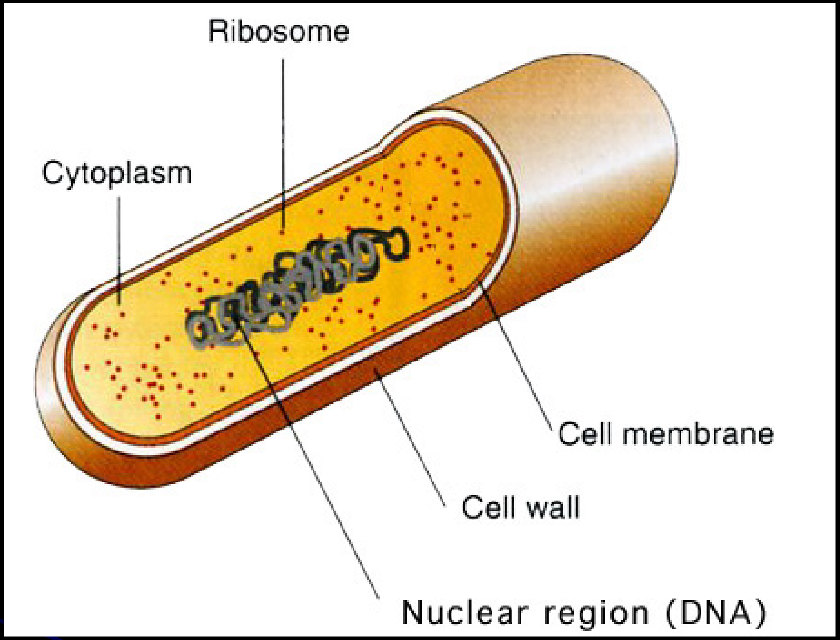
The discovery that certain RNA molecules have enzymatic activity provides a possible solution. These RNA molecules, called ribozymes, incorporate both the features required of life:

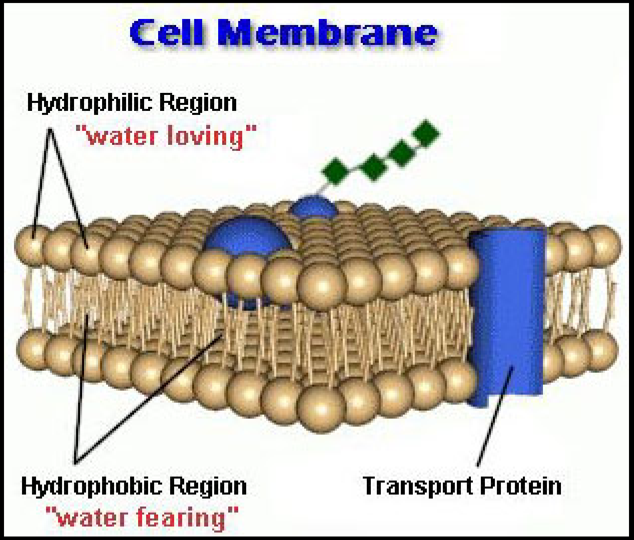
- storage of information
- the ability to act as catalysts





How did an isolated cell form?



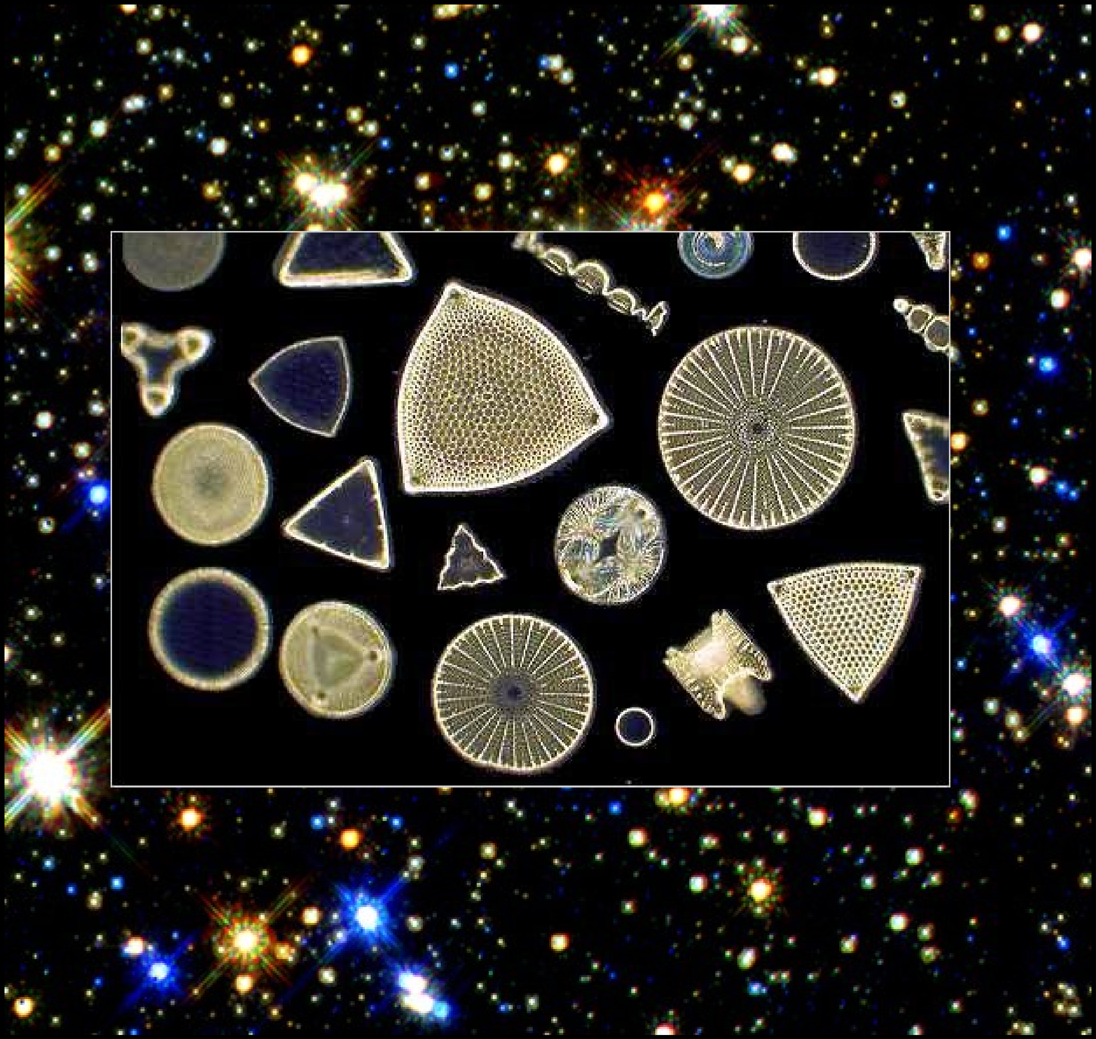


Today's plasma membranes are made of a double layer (bilayer) of phospholipids

A possible solution

Fatty acids, fatty alcohols , and monoglycerides, all molecules that can be synthesized under prebiotic conditions, can also form lipid bilayers and these can spontaneously assemble into enclosed vesicles.

There is a Universe in a drop of water!



Thanks for your attention