AST 201 - Introduction to Astrobiology
Script

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Autumn 2020

1 What is Life?

The definition of Life is not simple. NASA defines life as follows, *"Life is a self-sustaining system capable of Darwinian evolution."*. However, this excludes for instance mules as they are infertile. The definition might depend in which context it is asked. Different smart people came up with various definitions, however they could never agree upon a single definition. It is important that a definition should apply to alien life as well. Reproduction/replication needs to be imperfect to allow for natural selection of those branches of life with beneficial traits, otherwise life would have got stuck at the first replicating organism.

The chicken and egg problem illustrates the problem of the definition of life and species. Which came first? It can be argued that the precursor of the chicken was a mutation that occurred in the genes of its parents during the formation of the egg (a living multicellular progenitor does not mutate into a new species). So the chicken egg came first laid by a bird that was almost, but not quite, a chicken. If natural selection proceeds $\sim$one genetic mutation at a time, when can we speak of a new species? Perhaps the answer is that linguistically, the question "what is life?" is ill defined since language is imprecise and vague.

1.1 Characteristics of life on Earth

Instead of defining we can list 10 common features of **life on Earth**:

- Life is an organised collection of molecules.
- Life is based on six main elements.
- Life requires a liquid (water).
- Life is based on the same types of amino acids.
- Life can metabolise energy from its surroundings.
- Life grows and develops.
- Life can respond to its environment.
- Life contains a genetic code, a blueprint to what it will be and how it functions.
- Life is based on the cell, a container to protect and propagate its genetic code.
- Life can reproduce.

Note that also some non-living things satisfy some of these traits (e.g. Fire, snowflake). In addition, some living things (e.g. seed, bacteria) can undergo a period of dormancy. Are they dead during that time because they are not growing, metabolising or interacting with the environment?

1.2 Physical definition of life

Life is an ordered system of molecules that 'disobeys' the second law of thermodynamics – that entropy always increases. An isolated cell cannot violate the second law of thermodynamics, the only way it can maintain a low-entropy, nonequilibrium state characterised by a high degree of structural organisation is to increase the entropy of its surroundings. A cell releases some of the energy that it obtains from its environment as heat that is transferred to its surroundings, thereby resulting in an increase in the entropy of the universe. The release of energy must be coupled to processes that increase the degree of order within a cell.

Why is there life? There is one essential difference between living things and inanimate clumps of carbon atoms: life tends to be much better at capturing energy from their environment and dissipating that energy as heat. It can be argued that when a group of atoms is driven by an external source of energy and surrounded by a heat bath, it will often gradually restructure itself in order to dissipate increasingly more energy.

2 How life works I

LUCA The last universal common ancestor of all living things (LUCA). The three domains of life, with 'time' branches based on ribosomal RNA sequencing. Eukaryotes (with nucles) are complex cells that can form multicellular creatures. Archaea are single celled organisms which used to be classed with bacteria but have unique features and close connections to Eukaryotes. Procaryotes (no nucleus) are usually single-celled (Archaea, Bacteria).

The cell Cell is a vessel for transporting genetic code. A protoplasm enclosed within a membrane. There is no essential reason for this, it is just an evolved strategy that worked. The cell membrane is built from long organic amphiphilic chains. Note that amphiphilic structures can self-organise into vesicles. *Cholesterol* is found in every cell of your body and in all eukaryotic cells (but not prokaryotes). It is an important biomarker for studying the origin of cell complexity.

Bacteria Their biomass may equal that of all plants and animals put together. Bacteria have been present on Earth for over three billion years and could be considered the most successful branch of life on our planet. The cellular production rate for all prokaryotes on Earth is estimated at $2 \cdot 10^{30}$ cells per year and is highest in the oceans. The large population size and rapid growth of prokaryotes provides an enormous capacity for genetic diversity. Between one and two percent of our body weight consists of bacteria. That's over half of the cells in ones body. The symbiosis of complex living things with bacteria has always been present.

2.1 Composition of life

99% of a human body is (by mass): oxygen (65%), carbon (18%), hydrogen (10%), nitrogen (3%), calcium (1.4%), phosphorous (1.1%). 0.85% is made of the five elements potassium (0.25%), sulphur (0.25%), sodium (0.15%), chlorine (0.15%), magnesium (0.05%). Rest is "trace elements", of which a dozen play an important role in our bodies. i.e. zinc (0.0032%).

Composition of the Earth's crust: 46% oxygen, 27% silicon, 6.3% iron, 5% calcium, 2.9% Mg, 2.3% sodium, ..., (0.18% carbon)

Life is based on carbon as a structural molecule. However carbon is an extremely rare element on earth. (>0.01%). Life consumes a lot of carbon. This life dies and becomes part of the carbon cycle.

Carbon Organic chemistry tells us that carbon is the element on earth that can form the largest amount of different compounds where water is a liquid. Carbon has four valence electrons that can form covalent bonds. Most organic compounds, including amino acids, dissociate above 300C. This provides a strong upper limit to environments that carbon based life can survive.

Carbon alternatives Silicon has four valence electrons and can form four stable bonds with itself and other elements, and long chemical chains known as silane polymers, which are very similar to the hydrocarbons essential to life on Earth. Silicon is more reactive than carbon, which could make it optimal for extremely cold environments. Can form complex one-, two- and three-dimensional polymers in which oxygen atoms form bridges between silicon atoms (silicates). They are both stable and abundant under terrestrial conditions, and have been proposed as a basis for a pre-organic form of evolution on Earth. Any environment with the potential for silicon-based life would have to be very cold, devoid of oxygen and water, but with another compatible solvent, such as liquid methane or a methyl compound to exhibit polymer activity. However, silanes spontaneously burn in the presence of oxygen, so an oxygen atmosphere would be deadly to any silicon-based life, and water as a solvent would be equally deadly for the same reason.

DNA DNA and RNA contain genetic code information in all known living organisms and many viruses. The backbone of DNA and RNA is a succession of sugars (deoxyribose for DNA, ribose for RNA) linked by phosphate bridges. Connected to each sugar molecule, are the purine bases adenine (A) and guanine (G) and the pyrimidine bases cytosine (C), thymine (T) (T in DNA only), and uracil (U) (in RNA only). The code is read by copying stretches of DNA into the related nucleic acid RNA in a process called transcription. Eukaryotic organisms (animals, plants, fungi, and protists) store most of their DNA inside the cell nucleus and some of their DNA in organelles, such as mitochondria or chloroplasts. In contrast, prokaryotes (bacteria and archaea) store their DNA only in the cytoplasm.

Genes Most ($\sim$ 98%) of our DNA is "noncoding". The reasons for a lot of repetition could be that earlier life used a binary code. The genome of two individual humans will differ at the 0.1% level. Our genome is $\sim$95% in common with chimpanzees and $<$ 1% in common to bacteria. Human DNA contains $\sim$20,000 protein encoding sequences, which could hold a far larger number of possible combinations of instructions.

Amino Acids and Proteins There are about 500 known amino acids, half of them occur in nature. All life is based on just 20 of these (some rare cases use 22). Of these, 9 are called "essential2" to humans. This is evidence that all life shares a single common ancestor as all life uses the same set of amino acids. Living cells only use the left handed version of amino acids. Carbohydrates provide similar evidence - life mainly use the right-handed versions of sugars. The codons show us that in most cases the first two letters alone determine the amino acid. This suggests that the current genetic code evolved from an earlier version that used only two-letter "words" rather than three-letter "words."

Replication and Mutations DNA gyrase makes a nick in the double helix and each side separates (unzips) > helicase unwinds the double-stranded DNA > single strand binding proteins temporarily bind to each side and keep them separated > DNA polymerase adds new nucleotides to each strand > nucleotides pair with the complementary nucleotides on the existing stand > subunit of the DNA polymerase proofreads the new DNA > an enzyme called DNA ligase seals up the fragments into a continuous strand > new copies automatically wind up again.
Mutations can occur, simple copying mistakes. The mutation rate in humans (and most organisms) is low, but sufficient to produce the diversity of life on Earth. Self replication is driven by physics & chemistry. There is no rule of nature stating that more complex organisms should form. In terms of survival abilities, populate size and age, bacteria are far more successful.

Evidence for a single common ancestor

- Phylogenetic tree appears to have a root node,
- life on Earth utilises the same amino acids,
- all life on Earth utilises the left handed version of amino acids,
- all life uses DNA for storing information and RNA for copying genes,

- all life on Earth uses the same code table for identifying amino acids,
- some genes are common to all life on Earth,
- all life uses ATP for storing energy.

3 How life works II

Prokaryotes were alone on Earth for at least two billion years before the modern (organelle-containing) eukaryotic cell appears in the fossil record. And metazoans (multi-celled plants and animals) have only existed for some half billion years or so. In terms of their evolutionary history, the mouse and the elephant are virtually identical organisms. By contrast to higher organisms prokaryotes have had the evolutionary time and replication rate, to show great genetic divergence. Unlike metazoans, evolutionary change in prokaryotes is not manifest in morphological variation. Bacteria maintained a very small size and changed relatively little in morphology through billions of years of evolutionary history. Molecular sequencing tells us that they have indeed evolved significantly but that the product of this evolutionary change is invisible– instead of big changes in size or shape, evolutionary change in the prokaryotes focused on metabolic diversity and the genetic capacities to explore and eventually colonise every conceivable environment on Earth, including extreme environments.

3.1 Metabolism

Metabolism has two forms: catabolism, in which the cell breaks down complex molecules to produce energy and anabolism, in which the cell uses energy and reducing power (charged particles), to construct complex molecules and perform other biological functions. The removal of an electron from a molecule, oxidising it, results in a decrease in potential energy in the oxidised compound. The electron is shifted to a second compound, reducing the second compound. The shift of an electron from one compound to another removes some potential energy from the oxidised compound and increases the potential energy of the reduced compound. The transfer of electrons between molecules is important because most of the energy stored in atoms and used to fuel cell functions is in the form of high-energy electrons. In living systems, a small class of compounds functions as electron shuttles: they bind and carry high-energy electrons between compounds in pathways. Many are derived from the B vitamin group and are derivatives of nucleotides.

Storing energy Every living cell uses the same molecule, called ATP, to store and release energy for nearly all its chemical manufacturing. The negative charges on the phosphate groups of ATP repel each other requiring energy to bond them together and releasing energy when these bonds are broken. ATP is primarily produced in mitochondria, which have a own set of DNA that closely resemble bacteria. This provides support for the idea that nucleated complex cells of animals resulted from a symbiosis between prokaryotic cells. Breaking the ATP molecule releases charged particles, protons and electrons, that can do work. That is the stored energy that life utilises. The energy source to construct ATP can be derived from sunlight (photosynthesis) and/or chemical reactions involving inorganic or organic materials.

Metabolic Classification Organisms that grow by fixing carbon are called *autotrophs*, which include *photoautotrophs* (which use sunlight), and *lithoautotrophs* (which use inorganic oxidation). *Heterotrophs* are not themselves capable of carbon fixation but are able to grow by consuming the carbon fixed by *autotrophs*.

Photosynthesis CO_2 is converted into sugars in a process called carbon fixation - an endothermic (requires energy) oxidation-reduction (redox) reaction (transfer of electrons). Plants, algae and cyanobacteria use the Calvin cycle for this process. There are several other known carbon fixation cycles (two found only in bacteria and two found in archaea). General formula: Carbon dioxide + electron donor + light energy → carbohydrate + oxidised electron donor + water. In oxygenic photosynthesis water is the electron donor and, since its hydrolyses releases oxygen. The “light independent” reaction (Calvin cycle) creates sugars (glyceraldehyde linked to a phosphate). Light is absorbed by proteins that contain green chlorophyll pigments. In plants, these proteins are held inside organelles called chloroplasts, which are most abundant in leaf cells while in bacteria they are embedded in the plasma membrane. Most organisms that utilise oxygenic photosynthesis use visible light for the light-dependent reactions, however several microbes use shortwave infrared or far-red radiation. Some types of cyanobacteria growing in near-infrared light have a slightly modified version of chlorophyll.

Glycolysis The glucose consumed or generated by organisms is broken down into pyruvate releasing energy to make ATP. The first reaction is shared by all types of respiration, sugar is split into two molecules of pyruvic acid. The pyruvic acid is processed further into end products such as ethyl alcohol or lactic acid. If glycolysis were to continue indefinitely, all of the NAD+ would be used up, and glycolysis would stop. To allow glycolysis to continue, organisms must be able to oxidise NADH back to NAD+. How this is performed depends on which external electron acceptor is available. The glycolysis reaction sequence is oxygen independent, but the by-products of this process may be recycled with or without using atmospheric oxygen. In the absence of oxygen, the pyruvate can do the anaerobic oxidation; in this process, pyruvate is converted to lactate or ethanol in a process called lactic acid/alcoholic fermentation (Occurs in bacteria / single-cell organsims (yeast) or in animals in hypoxic conditions such as overworked muscles). In aerobic organisms, a complex mechanism has been developed to use the oxygen in air as the final electron acceptor. For each glucose molecule we use for energy we breath out 6 CO_2 molecules. Aerobic respiration is a far more efficient (∼13x) energy producer than anaerobic respiration and provides a huge advantage to those organisms that can use it.

Origins The first photosynthetic organisms probably evolved early in the evolutionary history of life and most likely used reducing agents such as hydrogen or hydrogen sulphide, rather than water, as sources of electrons. Anaerobic glycolysis is thought to have been the primary means of energy production in earlier organisms before oxygen was at high concentration in the atmosphere. Cyanobacteria appeared later; the excess oxygen they produced contributed directly to the oxygenation of the Earth. The higher efficiency of aerobic respiration allowed the evolution of more complex life.

3.2 Metabolic pathways

Lithotrophs are organisms that use inorganic substrate (usually of mineral origin) to obtain reducing equivalents for use in biosynthesis or ATP production, via aerobic or anaerobic respiration. Known chemolithotrophs are exclusively microbes; no known multicellular organisms use such compounds as energy sources. However, they can form symbiotic relationships, in which case the lithotrophs are called "prokaryotic symbionts".

Chemolitotrophs The majority of chemolithotrophs are able to fix carbon dioxide (CO_2) through the Calvin cycle. Often this process is highly inefficient which limits the growths of these organisms. In chemolithotrophs, the electron donors are oxidised in the cell, and the electrons are channelled into respiratory chains, ultimately producing ATP. The electron acceptor can be oxygen (in aerobic bacteria), but a variety of other electron acceptors, organic and inorganic, are also used. Chemosytnthesis is the a process that creates organic compounds from carbon dioxide. Plants use energy from sunlight to drive carbon dioxide fixation, since both water and carbon dioxide are low in energy. By contrast, the hydrogen compounds used in chemosynthesis are high in energy, so chemosynthesis can take place in the absence of sunlight (light independent).

Archea Usually anaerobic organisms live in low oxygen environments (difficult to culture in the lab). The membrane lipids of archaea contain fatty acid linked to glycerol molecule by ether bond instead of ester bond as in bacteria and eukaryotes. The cell wall in bacteria is a lipid-bilayer, in archaea it can be a monolayer. Archaea are non-pathogenic. Archaea do not use glycolysis to break down glucose, although it is a similar pathway.

3.3 The extremes of life

Life is based on water as a solvent, therefore a limiting factor should be the range of tempreatures where water is liquid. Moreover, few common elements/molecules are liquid in the range of temperatures that also allow complex biochemical molecules to exist and if so they are usually non-polar.

Thermophiles Life that exists in hot conditions. Main problems to overcome include: solubility of gasses decreases with temperature, denaturing of proteins and nucleic acids, etc. "Black smokers" are hydrothermal vents on the bottom of the oceans. Life exists there where water nearly approaches 400C and no light is available. As these conditions are quite common in our solar system life there is really interesting to study. The chemo-synthesising organisms around hydrothermal vents can support a fairly complex ecosystem including plants and animals, all reliant on the hydrothermal vent as their ultimate source of energy. But some of these life-cycle organisms do rely on photosynthesis indirectly, since they use nutrients that fall to the bottom of the ocean.

Halophiles Haloarchaea require salt concentrations in excess to grow. Visible within salty lakes, salt ponds and some live underground in rock salt deposits. Salty environments causes osmotic stress on microbes. Haloarchaea combat this by retaining compatible solutes such as potassium chloride in their intracellular space to allow them to balance osmotic pressure. They have specialised proteins that have a highly negative surface charge to tolerate high potassium concentrations.

Psychrophiles (Cryophiles) Ice worms live and thrive at temperatures below 0C. They use protein structures called cryoprotectants which are resistant to freezing. In most organisms, ATP levels and usage drops as temperature decreases. For the ice worms, the opposite is true, their metabolism increases.

Radiophiles Deinococcus radiodurans is the most resistant organisms known to radioactivity. This bacterium can also survive cold, dehydration, vacuum and acid and is thus known as a poly-extremophile. It has multiple copies of its DNA code and a built in mechanism to repair the strands if they break.

Gravity and Acceleration Bacteria have benn subjected to conditions in extreme gravity. Some displayed not only survival but also robust cellular growth under these conditions of hyper-acceleration which are usually found only in cosmic environments, such as on very massive stars or in the shock waves of supernovas.

Tardigrades They are perhaps the most complex polyextremophiles. They have been frozen, boiled, exposed to pressure, radiation and vacuum but survived and still reproduced. As its surroundings dries out, the water bear shrinks in a form of cryptobiosis called anhydrobiosis, meaning life without water, the animal can survive just about anything. The abilities of tardigrades to withstand extremes seems to have evolved through natural selection responding to rapidly changing terrestrial micro-environments of damp flora subject to rapid drying and extreme weather. In addition they can reproduce without mating.

Mechanisms of Extremophiles Extremophiles stabilise their DNA by using different proteins. Chaperones are used to refold denautred proteins in thermophiles. Psychrophiles have structures that maximise their flexibility. Also the structure of the cell wall, which differs in bacteria and in archea is important. Many living organisms can withstand extreme environments, but will be in a state of stasis or hibernation. The physical conditions for surviving versus thriving can be rather different.

3.4 Life independent of a star

Panspermia is the hypothesis that life exists throughout the galaxy and is/was distributed by objects in space. Recent results have indicated that there are a number of species that indeed could survive conditions that would require travelling through space.

4 Early life, early Earth

Isotope Analysis Isotopes of a given element have the same number of protons but different numbers of neutrons. Isotopes can be stable or unstable. E.g. Carbon 14 is an unstable isotope of carbon produced when cosmic rays collide with the atmosphere. Its half life is 5730 years. Rocks and minerals contain long-lived radioactive elements that were incorporated into Earth when the solar system formed. They constitute independent clocks that can be used to determine the age of the material.

4.1 Cambrian explosion

The rapid appearance of fossils ∼500 Ma. Charles Darwin discussed the then inexplicable lack of earlier fossils as one of the main difficulties for his theory of descent with slow modification through natural selection. Possible explanations for this event are

- Oxygen increase: Amount of oxygen a creature can take in is proportional to surface area but amount needed to function is proportional to volume.
- Snowball Earth: Earth was nearly or entirely frozen most of the period between 780-630 Ma. Obviously not good for photosynthetic life, mass extinctions. So before this time would have been difficult, and extinctions open up ecosystems for new life.
- Calcium increase: Enhanced tectonic activity - volcanic active midocean ridges caused a surge of calcium concentration in the oceans which is needed for the structural components of animals
- Genetic improvements: development of bodies are controlled by large gene regulatory networks. Has been suggested that a key gene was transferred horizontally from a bacteria to a sponge.

Aquatic fresh water flower is ∼130 my. The first evidence of moss-like plants ∼500 Mya. Footprints of a four limbed fossil ∼400 Mya. Centipede-like animals ∼ 530 Mya.

4.2 Chemical signatures of biological activity

The Ozone layer that shields UV Radiation formed ∼600 Mya allowing first land-based life. Dense, hard structures (e.g. shells or bones) did not appear in the fossil record until ∼500 Mya. How can we identify life prior to this?

1. **biomarkers**: specific molecules that are unambiguous remnants of their biological precursors, i.e. lipids synthesised by life.
2. **isotopic fractionations**: metabolic pathways which prefer one isotope to another, leaving behind a high concentration of the favoured isotope.

Some biomarkers or their remnants are stable over a long period of time and can be signatures for life. Amongst them are, Amino acids and their specific chirality, Lipids in membranes, DNA/RNA leftovers, the ratio of the elements that life is made of, coal/oil which has a unique proportion of atoms.

4.3 Biomarkers

The first Eukaryotic cells Microfossils indicate that ∼ 1.7 Gyr is a reasonably robust earliest date for the appearance of eukaryotes. The earliest unambiguous record of photosynthetic eukaryotic life is 1.1 Gya.

Gabon macrofossils 2.1 Gyr old. Possibly the first multicellulcar life on earth, others suggest that these are pseudofossils of inorganic pyrites.

Prokaryotes Genetic evidence suggests that the earliest life-forms on Earth were prokaryotes. Microscopic fossils in 3.4 billion year old rock, show evidence for bacteria living in an oxygen-free world long ago.

Stromatolites Rocky outcrops made of many thin layers of sedimentary grains that are found in shallow water. Tiny particles of rock are trapped and cemented by microbial mats ∼1mm thick. These are loosely connected prokaryotic cells which thrive together. They trap mineral grains, compounded into layers that can be identified after billions of years. The microbes slowly move upwards to keep on top of the sediments they trap. Takes ∼1000 years to grow 1m high. The layers through the stromatolite reflect growth periods. Stromatolites are a major constituent of the fossil record for life's first 3.5 billion years, peaking about 1.25 billion years ago. They subsequently declined in abundance and diversity. The most widely supported explanation is that stromatolites fell victims to grazing eukaryotic creatures (the Cambrian substrate revolution), implying that sufficiently complex organisms were common over a billion years ago.

Photosynthesis Eukaryotic photosynthesis originated from endosymbiosis of cyanobacterial-like organisms, which ultimately became chloroplasts. By studying the development of the sequences of genes responsible for photosynthesis using molecular clocks it is thought photosynthesis arose 3.4 billion years ago.

4.4 Isotopic fractionation

The separation of different atomic isotopes can occur by natural and biological processes. The physical reason can be related to the different mass of the isotopes (e.g. rainwater is lighter than seawater). Metabolism can separate elemental isotopes, leading to "unnatural" abundance ratios. Most biological pathways discriminate against heavy carbon 13C and become enriched in the lighter stable isotope 12C.
The Isua greenstone belt in Greenland (3.8 billion years old) contains some of the earliest evidence for life due to a carbon 13 isotope deficit.

Early bacteria The oldest identified bacterial fossils are $\sim$3.5 billion years old. This was infered from a large negative sulphur isotopic fractionation that is characteristic of dissimilatory sulphate reduction, which is only formed at low temperatures, by Bacteria. This places an early age limit on the separation of the Archaea–Eukarya lineage from Bacteria.

Early archaea The membranes of archaea do not contain the same lipids that other organisms do; instead, their membranes are formed from isoprene chains. These particular structures are unique to archaeans and have been widely found in rocks 1.6 Gy old. Biological methane has been found in rocks that are 3.4 Gy old. The only source of biological methane is methanogenic archaea that carried out sulphate reduction, so we know that archaea have been around since the very beginnings of life on Earth.

- Oldest potential evidence for life, C isotopes in Zircon crystal 4.1 Gy.
- Convincing and widely accepted evidence for life $\sim$3.5 Gyrs

4.5 Earth 4 billion years ago

Earth was a hot, violent place with dominating volcanic activity. The sky was cloudy and grey, keeping the heat in despite the sun being weaker than today. The water temperature of the oceans was much higher at 40-50 degrees – the temperature of a hot acidic bath – and circulating currents were very strong. Any land masses were small, tectonic activity rapid, and the tidal range was huge.

Oxygenation Photosynthesising cyanobacteria are thought to have begun the rise in oxygen 2.5 Gyrs ago. Oxygen levels plateaued 1.8Gyrs ago and stayed flat until 0.8Gyrs ago. Possibly due to decline of nutrients: Less erosion = less ocean nutrients = less cyanobacteria. A rise in nutrients $\sim$750 million years ago led to increase in bacteria and plankton in the oceans = rise in atmospheric oxygen = increase in oxidative erosion of the continents = more nutrients.

Permian extinction The large drop in oxygen 250 million years ago coincides with the Permian mass extinction. Most likely due to massive amount of volcanism in Siberia. Single-celled algae and bacteria in the oceans recovered much more quickly. The driver of the ongoing population boom appears to have been the massive amounts of carbon dioxide pumped into the atmosphere during the volcanism, which caused the world to warm. The increased amounts of more acidic rain increased weathering of the land surface, which sent more nutrients into the ocean, which fuelled explosions of life such as algae blooms.

Plate tectonics Some plates consist entirely of suboceanic lithosphere with the corresponding overlying oceanic crust, while others contain both continental and oceanic crust underlain by the corresponding lithosphere. Plates grow by volcanic activity at oceanic spreading ridges and are transported away from these ridges by convection currents in the underlying asthenosphere. Plate tectonics is important for life – trapping and recycling carbon and perhaps providing the location for life to begin at hydrothermal vents.

Carbon in the Earth One of the key reasons Earth has an oxygenated atmosphere is that this chemical cycle is slightly imbalanced. For some reason, a small percentage of organic carbon is not broken down by microbes, but instead stays preserved underground for millions of years. If it were perfectly balanced, all the free oxygen in the atmosphere would be used up as quickly as it was created. In order to have oxygen left for us to breathe, some of the organic carbon has to be hidden away where it can't decompose. There are two possible reasons why carbon is left behind. The first, called ”selective preservation” suggests that some molecules of organic carbon may be difficult for microorganisms to break down, so they remain untouched in sediments once all others have decomposed. The second, called the ”mineral protection” hypothesis, states that molecules of organic carbon may instead be forming strong chemical bonds with the minerals around them – so strong that bacteria aren't able to consume them.

Early continents *Cratons* are long lived ancient plates. Less than 10

1. Pangaea: 250Mya, one big continent where all the continents are clustered together
2. Pannotia: 550Mya, a brief supercontinent
3. Rodina: 1 Gya, supercontinent

The “timescale” over which major tectonic activity takes place today is $\sim$500 million years.

Mafic and Felsic rocks *Mafic* (e.g. basalt) and *Felsic* (e.g. granite) rocks are produced from solidified lava, but Felsic rocks form when Mafic rocks are pushed deep into the Earth enriching them with silicon and oxygen. Modern oceanic crust, produced by mantle melting, is basaltic in composition and is continuously recycled into the mantle at subduction zones. Earth's earliest crust was also presumably mafic but eventually evolved into two distinct components: an oceanic crust composed of mafic minerals and a continental crust bearing felsic minerals. The continental crust is recycled and not much is left from 3.5Gyrs ago. Constraining when a felsic crust first developed and how its chemical composition changed through time are important questions because the composition of the crust influences the composition of the atmosphere, controls the flux of biologically important nutrients to the ocean, and is related to the initiation of plate tectonics.

Ancient rocks The oldest rocks known on earth are metamorphosed sedimentary outcrops that are $\sim$4.0Gy old. Sedimentary rocks are a result of erosion of older igneous (solidified magma) rocks that are washed down rivers and are deposited in lakes or oceans, or minerals that precipitate from ocean water settling at the ocean floor. Sedimentary rocks indicate the presence of water on Earth at least 3.8 billion years ago.

4.6 Early earth

Sun and asteroids are 4.56 billion years old, and we think that the solar system planets formed within ∼10-100 million years after the Sun. What was Earth like for the first half billion years?

Late heavy bombardment The moon tells us (there is no erosion on the moon) that there were large number of impacts ∼3.9 Gya. Not clear if this was a single event or rail of a heavier event. It kept the Moon and Earth molten. This hypothesis is debated.

Zircon crystals Zirconium silicate, forms in silicate melts, primary crystallisation product in metamorphic and sedimentary rocks as the magma cools as it rises to the surface. They are too small to see but we can measure the age gradient across the crystals as well as the different atoms and minerals that they contain. The dark separating lines between growth layers indicate the crystals were embedded in different host rocks. They are the oldest objects on earth with an age of ∼4.4 Gyrs. They are extremely hard and durable and can survive conditions that erode, melt or otherwise transform the rock around them. The zircons also contain enough uranium (decays to lead) that they can be precisely dated. The existence of these crystals tells us that some solid rocky material existed 4.4 Gya, otherwise they would never have been able to form in the first place. Even after they are recycled through countless generations of rock, zircon crystals retain hints about the physical and chemical conditions in which they formed. The crystals take millions of years to grow and the age gradient across the crystals occurs in bands/steps. These bands of new growth are separated by intervals of about 50 million years. This suggests that plate tectonics/recycling times were already active and that plate collisions and subductions were happening much faster than today (timescale today ∼500 million years).

Water on early earth The titanium content of zircons can be used as a thermometer to measure the temperature at which they formed. The presence of water lowers the melting point of all rocks. This suggests the presence of water on Earth ∼4.4 billion years ago. The oxygen isotopic composition of zircons also indicate that these ancient crystal formed in the presence of water.

A molten hot earth At the time of its formation, the Earth received increments of heat from several sources, leading to temperatures ∼7000K at the Earths core. This was due to

1. Conversion of the kinetic energy of planetesimals into heat at the time of impact upon the Earth.
2. Decay of naturally occurring radioactive elements which were more abundant 4.6 billion years ago, but which still generate heat in the Earth at the present time.
3. Compression of the Earth as its mass continued to rise.
4. Release of gravitational potential energy by molten iron sinking toward the center of the Earth.
5. Heat generated by the gravitational interaction with the Moon.

Melting of the Earth's interior allowed dense iron to sink to center, forming a core and light, silicate-rich magma to rise to the surface to form a magma ocean. The remaining material between the core and the magma ocean formed the mantle. Eventually, the magma ocean would have cooled to form a layer of basaltic crust such as is present beneath the oceans today. Continental crust would form later. It is probable that the Earth's initial crust was re-melted several times due to impacts with large asteroids. The rocks on the surface have a lower density than average, the crust floats on the molten magma below. Our knowledge of the Earth's interior come from seismic studies & modelling. The surface cools and begins to solidify, a dense atmosphere from outgassing volcanoes encompassed the Earth. Timescales ∼10,000-1,000,000yrs (modelling).

Differentiation of the elements inside the early Earth

1. Differentiation inside the Earth,
2. cooling (phase transitions) on the surface,
3. a "late veneer" of asteroid & comet impacts.

Differentiation either due to gravity or chemical affinities are also important. Elements that tend to bond (and thus sink) with the iron are called siderophiles, and those which bond (and thus float with sulphur or oxygen) are called chalcophiles. Uranium and thorium are very heavy elements, but they are concentrated in the mantle and crust. The ion size and chemical affinities of U and Th prevent them from being incorporated in the dense, tight crystal structures that are stable at the high pressures encountered in the Earth's core. Because they can fit much more easily into the more open crystalline structures of silicate and oxide minerals, they are enriched in the crust and mantle.

5 Abiogenesis I

Life was present on Earth, in a oxygen free atmosphere at least 3.5 billion years ago. There is no standard model for the origin of life. There are many theories which introduce some of the steps to life, but there is no consensus, no complete theory, and all have their problems.

Genomic and fossil evidence General assumption is that the number of differences in the genomes of two living species are proportional to the time since they shared a common ancestor.

- LUCA predated the end of late heavy bombardment > 3.9 Gya
- bacteria and archae, emerged much later < 3.4 Ga
- Great Oxidation Event (2.5Gyrs) significantly predates the origin of modern Cyanobacteria, indicating that oxygenic photosynthesis evolved within the cyanobacterial stem lineage.
- Modern eukaryotes do not constitute a primary lineage of life and emerged late in Earth's history (>1.84 Gya)

- Symbiotic origin of mitochondria at 2.053–1.21 Gya reflects a late origin of the total-group Alphaproteobacteria to which the free living ancestor of mitochondria belonged.

5.1 The minimal genome

The last common ancestor had ∼300 million years to form. The first self-replicating structure might not initially have had any ‘coding’ sequence, presumably it simply autonomously made copies of itself. It is unlikely it had any error control so its evolution would be haphazard – many of the structures would fail to carry on.

Bacteria Pelagibacter ubique has the smallest known genome of 1,389 genes (1,308,759 bp), of which 1354 are protein encoding and 35 are RNA genes. All essential functions are encoded and it has metabolic pathways for constructing all 20 amino acids. Zero junk DNA! Mycoplasma genitalium is a parasitic bacterium which has the smallest known genome. One circular chromosome, 580kb of information, 482 protein encoding genes, 382 of which are essential.

Mycoplasma laboratorium Computer model of a working genome was constructed with one million base pairs. This was used as a blueprint to build the DNA strand in a laboratory. No natural DNA was used. The DNA was inserted into a living yeast cell with no DNA inside. The cell came to life, sustained itself and self-replicated billions of times. Most of the vital genes were involved with cell metabolism (∼50% for DNA and RNA metabolism and protein and amino acid synthesis, ∼20% are for cell structure, shape and division i.e. for membrane and cell wall formation).

Conserved genes Of all the genes in the human genome over half were present in the first animal. Some genes are conserved in all species, including ATPases, genes involved in transcription and translation, as well as genes which are involved in nucleotide biosynthesis and RNA processing. This suggests the conclusion that early organisms possessed means for maintaining its genetic information and a translation system. A set of 355 genes from the Last Common Ancestor (LCA) of all organisms. Moreover, the metabolic pathways suggested that the LCA inhabited an anaerobic hydrothermal vent setting in a geochemically active environment rich in H_2, $C0_2$ and iron. However, the role of lateral or horizontal gene transfer is not fully known – we know that many genes have been passed between species.

5.2 Primodial soup theory

Oparin and Haldane suggested that the early Earth had a chemically reducing atmosphere. This atmosphere, exposed to energy in various forms, produced simple organic compounds (‘monomers’). These compounds accumulated in a concentrated ‘soup’ at various locations such as ocean tide pools. By further transformation, more complex organic polymers - and ultimately life - developed in the soup. It is still the basis of theories of abiogenesis, although focus has changed from the atmosphere and tide pools, to deep ocean vents. Life is constructed primarily from CHNOPS atoms which must have been available.

Miller & Urey experiment Recreate conditions on earth ∼ 4Gya. The experiment used water, methane, ammonia and hydrogen. The liquid water was heated in a sealed environment to induce evaporation, sparks were fired between the electrodes to simulate lightning through the atmosphere and water vapour. The experiments showed that simple organic compounds of building blocks of proteins and other macromolecules can be formed from gases/liquids with the addition of energy. Two percent of the carbon had formed 23 different amino acids which could be identified, with glycine as the most abundant. Sugars were also formed, but no nucleic acids appeared. Both left-handed and right-handed isomers were created in equal mixtures. The oldest genes utilise the same simple amino acids as found in the Miller-Urey experiment.

Nucelobases Abiotically in several ways, but most require either cold or hot conditions, together with wet-dry cycles. Formamide can produce all five nucleobases and other biological molecules when warmed in the presence of various terrestrial minerals. Formamide is common in the Universe, possibly by the reaction of hydrogen cyanide, ammonia and water in cold conditions, or methane and nitrogen and cosmic rays!

Sugars Synthesis of backbone sugars more difficult than that of amino acids and base pairs. The formose reaction requires a concentrated formaldehyde solution and a catalyst, such as calcium carbonate or clay minerals. It results in a mixture of many kinds of sugars, but ribose is present at only a very low level. Why ribose was selected as building block is therefore hard to say. The formose reaction requires a high concentration of formaldehyde which is difficult to produce either in the atmosphere or oceans. Ribose and other sugars might not have been components of the first genetic material, and were preceded by simpler and more stable compounds, such as peptide nucleic acid.

Fatty acids All cells have lipid membranes. Today’s cells are made of phospholipids, which do not naturally grow and divide, nor allow the inwards diffusion of compounds. These are controlled with complex biochemical machinery. Therefore phospholipids are not a good candidate for the first cells since this machinery did not exist. Condensations of fatty acids with glycerol and phosphate has been shown to yield phospholipids. The most widely invoked pathway for the formation of fatty acids in geochemical environments is the Fischer-Tropsch synthesis.

Nitrogen N_2 inert and tightly bound. The nature and relative abundance of nitrogen compounds formed through abiotic processes depends on the oxidation state of the atmosphere. A reducing atmosphere rich in hydrogen and methane generates hydrogen cyanide and glycolonitrile as major N-containing compounds.In contrast, if the primitive atmosphere was more neutral, composed of carbon dioxide and N_2, the main form of fixed nitrogen is nitric oxide. The most important geochemical process of NO production could have been lightning or cosmic rays. The NO could then be converted to nitrate and nitrite through a series of photochemical and aqueous phase reactions. Finally, these nitrogen oxides can be reduced to ammonia through interactions with metals such as iron or iron sulphides. A significant fraction of the nitrogen on Earth could have originally been dissolved in the early magma ocean. Recent research suggests that that the oxygen fugacity of the Hadean crust was low. Therefore, at underwater geothermal fields, the release of nitrogen could have provided an ample and continuous supply of NH_4 during the Hadean era.

Phosphorous fixation Phosphorous commonly occurs as oxidised orthophosphate PO 3– within igneous and metamorphic rocks. Mechanisms of abiotic formation of phosphite is reduction of phosphate from the action of lightning or within geothermal pools. If geothermal environments on the Hadean Earth were reducing enough for the occurrence of high concentrations of methane and Hydrogen phosphate reduction at localized reductive sites could have been a significant source of reduced P at the time of the origin of life.

5.3 Atmosphere & tide pools

The original idea of Oparin and Haldane. Organic molecules rained to Earth and became concentrated via evaporation of water in ocean tide pools. Earth's original atmosphere is now thought to have had a different composition from the gas used in the Miller–Urey experiment rather a neutral than the reducing composition they adopted. A reducing atmosphere is one in which oxidation is prevented by removal of oxygen and other oxidising gases or vapours, and which may contain actively reducing gases such as hydrogen, carbon monoxide and gases that would be oxidised by any free oxygen. The early atmosphere was hot and probably enriched in CO_2. Probably the pressure was also higher as more carbon was in the atmosphere. In a reducing atmosphere, if carbon is in a reduced state in the form of methane a large diversity of amino acids are synthesised in a rather efficient way. If our atmosphere was a source of molecules for the building blocks of life then the key questions would be whether or not $H_2CO"$ (formaldehyde) and HCN (hydrogen cyanide) could form. These are key ingredients for amino and nucleic acids. Hydrogen cyanide is more difficult since Nitrogen needs breaking into $N + N$ needs reducing to $CO + O$. This can occur with the energy from lightning discharges, although the N and C atoms are more likely to combine with O atoms rather with each other unless the C:O ratio is larger than unity.

5.4 Hydrothermal vents

The synthesis of organic compounds at the bottom of the ocean in hydrothermal vents is another source of prebiotic molecules. Where oceanic plates drift apart, sea water circulating through the ocean crust is heated up, and it dissolves and exchanges chemicals with the rock. It reenters the ocean from black smokers at a high temperature, enriched in gas, ions, and minerals. Catalytic clays and minerals interact with the aqueous reducing environment, when exhausted from the vent, the dramatic drop in temperature, from 350C to about 2C, favours chemical reactions and polymerisation. It was suggested that the rapidity of the evolution of life is dictated by the rate of recirculating water through midocean submarine vents. Complete recirculation takes around a million years, thus any organic compounds produced by then would be altered or destroyed by temperatures exceeding 300°C. Life may have had to emerge quickly: chemical reactions happen quickly or not at all; if any reaction takes a millennium to complete then the chances are all the reagents will simply dissipate or break down in the meantime, unless they are replenished by other faster reactions.

5.5 Comets and asteroids

Astronomical observations have given evidence that organic chemistry is very active in interstellar molecular clouds, as much in the gaseous phase as in the solid phase. Gaseous mixtures consisting of simple volatile compounds, which have been detected in interstellar environments, are introduced into a cryostat. These molecules then condense and form an icy mixture. If exposed to irradiations or to thermal cycles, chemical reactions between these simple compounds lead to the formation of much more elaborated organic structures. A great number of organic molecules have been detected in meteorites. Diamino acids (chains of amino acids), different polymers, sugars, purines and pyrimidines have been found in meteorites.

Enantiomeric excess Compounds found on meteorites suggest that the chirality of life derives from abiogenic synthesis, since amino acids from meteorites show a left-handed bias, whereas sugars show a predominantly right-handed bias, the same as found in living organisms!

6 Abiogenesis II

What came first: replication, metabolism, the cell?

6.1 Cell

The lipid world theory postulates that the first self-replicating object was lipid- like. Phospholipids form lipid bilayers in water while under agitation—the same structure as in cell membranes. These structures may expand and under excessive expansion may undergo spontaneous splitting which preserves the same size and composition of lipids in the two progenies. In this theory the molecular composition of the lipid bodies is the preliminary way for information storage, and evolution led to the appearance of polymer entities such as RNA.

6.2 Metabolism

The 'iron–sulphur world' came first - a theory of the evolution of prebiotic chemical pathways as the starting point in the evolution of life. It is a theory that traces today's biochemistry back to ancestral reactions that provide alternative pathways to the synthesis of organic building blocks from simple minerals and gases. The source of energy are sulphides of iron and other minerals. The energy released from redox reactions of these substances is available for the synthesis of organic molecules. Self sustaining network of chemical reactions forms, Chemical networks become enclosed in membranes. However, where does genetic replication fit in?

Carbon fixation Carbon fixation is really hard and you have to drive the reaction with a catalyst (much research on this for taking CO2 from the atmosphere). There are only six known pathways of carbon fixation across all life. One of these, the acetyl CoA pathway, is found in both archaea (methanogens) and bacteria (acetogens). It is the only exergonic pathway of carbon fixation, drawing on just H_2 and CO_2 as substrates to drive both carbon and energy metabolism.

Modern Metabolism In most present-day life forms on Earth, the citric acid cycle operates to break organic molecules down into carbon dioxide and water, using oxygen to produce energy for the cell—in effect, "burning" those molecules as fuel (Oxidative mode). The cycle can also operate in the opposite direction, taking in energy (in the form of high- energy electrons) and building up larger molecules from smaller ones. (Reductive mode). In the oxidative mode, the input is an organic molecule, and the output is chemical energy, carbon dioxide and water. In the reductive mode, the input is chemical energy, carbon dioxide and water, and the output is a more complex organic molecule.

6.3 Replication

DNA does not have catalytic ability and can not replicate on its own, it needs proteins to do this. Proposing that RNA was the original code carrier and replicator. A folded RNA molecule can catalyse chemical reactions just like a protein enzyme (the RNA world hypothesis). RNA spontaneously forms and functions both as an enzyme for self-replication, to catalyse chemical reactions and as a carrier of information. Later, DNA took over its genetic role leaving other key roles for the RNA. Evidence for this is given by: RNA that work as enzymes, RNA viruses, fundamental parts of every cell require RNA, RNA can fold into a shape that gives the catalytic ability to accurately copy itself and other strands of RNA.

RNA vs. DNA DNA is stable in alkaline conditions. DNA has smaller grooves where potentially damaging enzymes can attach. RNA is not stable in alkaline conditions. However, RNA has larger grooves, which makes it easier to be attacked by enzymes. DNA can be damaged by exposure to UV rays. RNA strands are more resistant to damage by UV radiation (4Gya sun was intense and no ozone layer that blocked UV). RNA it is not as robust as DNA.

Viruses Viruses carry genetic information, reproduce and evolve through natural selection. However, they do not host or carry instructions for a metabolism to facilitate replication, they take over living cells for that purpose. RNA viruses have smaller genome sizes than DNA viruses: RNA has a higher error rate when replicating. RNA viruses replicate in the cell's cytoplasm, and they use their own RNA replicase enzymes to create copies of their genomes. The largest known virus genomes contain over a million base pairs, has similar size to bacteria. Pandoravirus discovered in 2013 is reported to contain 2556 protein-coding sequences, of which only 6% have recognisable relationships with genes from other known organisms. Is this evidence for a 4th domain of life? 2500 of its genes have no counterparts in life. Origin of viruses is not known: they may have originated from cells, reducing their number of genes as they adapted to taking over the functions of existing cells around them. They may have evolved from pieces of DNA or RNA that were 'lost' from the genes of a larger organism. Some argue that viruses originated first, or simultaneously, with the first cell-based life. Phyologenetic studies suggest that viruses are indeed as old as life. Interestingly, there is no gene shared by all viruses.

Lateral (horizontal) gene transfer Viruses are an important natural means of transferring genes between different species, which increases genetic diversity and drives evolution. (It is thought that $\sim 10\%$ of our genetic code has come from viruses.) Cells can uptake and express foreign genetic material. At the extreme is symbiosis – complete cellular structures are used, such as mitochondria, or the chloroplasts in plants arose from ingested cyanobacteria.

6.4 RNA World

Spiegelman's monster Spiegelman (1965) introduced RNA from a simple virus into a solution which contained the RNA replication enzyme, some free nucleotides, and some salts. In this environment, the RNA started to replicate. A mixture containing no RNA at all but only RNA bases and a replicase (an enzyme that catalyses the replication of RNA, also called a polymerase) can, under the right conditions, spontaneously generate self-replicating RNA. Thus, it is likely that the proto-ribosome had to be composed of short fragments of RNA that jointly formed one functional complex.

Breakthrough organism The initiation of genetically encoded protein synthesis was most likely the key step in the development of any more-advanced life. This event is considered so important that the first creature that produced proteins has been named 'the breakthrough organism'. Because protein synthesis did not exist prior to this time, the assembly or function of a primitive translation machinery by a protein could not have depended on any specific proteins. Thus, the early translation reactions had to be catalysed by the existing RNAs alone. This is theoretically feasible because in all the present-day life forms, the formation of the peptide bonds between amino acids is specifically mediated by one RNA component of the ribosomes. Some sequences of RNA bases may attract specific amino-acids to the RNA. Small chains of amino acids could link together forming a protein. That protein may offer some advantage, such as a way of protecting the RNA or by facilitating the creation of copies of the RNA. If the RNA and the enzyme are isolated from the outside environment inside a pre-cell, then only the molecules in this particular pre-cell will benefit from the new enzyme, perhaps speeding up the evolution.

6.5 Location of the RNA world

The polymerisation of nucleotides needs to take place in an aqueous environment because the nucleotides are water-soluble and liquid water is needed to carry them into the reaction site. However, water efficiently reacts with the RNA polymers to hydrolyse the phosphodiester bonds, which can break them apart (faster if temperature is higher). The phosphate groups forming the phosphodiester bonds carry a negative charge the total charge of the polymer is highly negative. For stable assembly, the negative charges of the phosphates need to be neutralised by an adequate level of soluble cations. Because of the difficulty in producing large amounts of ribose, alternative solutions have been suggested, such as a pre-RNA world. This could be based, for example, on peptide analogues of nucleic acids, which are called ‘peptide nucleic acids’ (PNAs) in which the sugar would be replaced by amino acids

Clay beds in ocean tide pools The ocean water would have brought in the precursors for the reactions, and these might have been bound, by hydrogen bonding or ionic forces, to the cationic minerals in the clay and sand. Small drying ponds might have provided the concentration mechanism for the compounds, and the subsurface layers of sand might have provided protection against UV radiation, as well as size-based fractionation and concentration by chromatographic filtration. Binding to the clay surfaces significantly stabilises the ready-made RNA polymers, which otherwise would be very easily degraded by hydrolysis.

First cells Experiments have demonstrated that RNA, along with other organic molecules, could easily have become confined within naturally forming microscopic enclosures often called ‘pre-cells’ (or vesicles). Pre-cells can be formed naturally in at least two different ways: by cooling a warm-water solution of amino acids so that they form bonds among themselves to make an enclosed spherical structure or by mixing lipids with water. In some cases, they can also grow until they reach an unstable size, at which point they split to form ‘daughter’ spheres. Moreover, experiments show that lipid pre-cells can form on the surface of the same clay minerals that help assemble RNA molecules, sometimes with RNA inside them!

Problems Problems with the RNA world hypothesis are: RNA is too complex a molecule to have arisen prebiotically, RNA is inherently unstable, catalysis is a relatively rare property of long RNA sequences only, the catalytic repertoire of RNA is too limited.

6.6 Alkaline hydrothermal vents

Located on the seafloor of the mid-Atlantic ocean, where reactions between seawater and upper mantle peridotite produce methane and hydrogen-rich fluids that are highly alkaline (pH 9 to 11), with temperatures ranging from ¡40° to 90 °C. There is a field of about 30 chimneys made of calcium carbonate 30 to 60 meters tall, with a number of smaller chimneys. The vents release methane and hydrogen into the surrounding water; they do not produce significant amounts of carbon dioxide, hydrogen sulphide or metals, which are the major outputs of volcanic black smoker vents. Oxygen isotope data and radiocarbon ages document at least 30,000 years of hydrothermal activity driven by serpentinisation reactions at Lost City, two orders of magnitude older than known black smoker vents.

1. Water percolated down into newly formed rock under the seafloor, where it reacted with minerals such as olivine, producing a warm alkaline fluid rich in hydrogen, sulphides and other chemicals – a process called serpentinisation. This hot fluid emerged and formed alkaline hydrothermal vents.
2. Unlike today’s seas, the early ocean was acidic and rich in dissolved iron. When upwelling hydrothermal fluids reacted with this primordial seawater, they produced carbonate rocks riddled with tiny pores and a “foam” of iron- sulphur bubbles. Alkaline fluids bubbling into an acidic ocean form catalytic mineral ’cells’ with a proton gradient across their inorganic membranes
3. Inside the iron-sulphur bubbles, hydrogen reacted with carbon dioxide, forming simple organic molecules such as methane, formate and acetate. Some of these reactions were catalysed by the iron-sulphur minerals. Similar iron-sulphur catalysts are still found at the heart of many proteins today.
4. The electrochemical gradient between the alkaline vent fluid and the acidic seawater leads to the spontaneous formation of acetyl phosphate and pyrophospate, which act just like adenosine triphosphate or ATP, the chemical that powers living cells. These molecules drove the formation of amino acids and nucleotides.
5. Thermal currents and diffusion within the vent pores concentrated larger molecules like nucleotides, driving the formation of RNA and DNA – and providing an ideal setting for their evolution into the world of DNA and proteins. Evolution got under way, with sets of molecules capable of producing more of themselves starting to dominate.
6. Fatty molecules coated the iron-sulphur froth and spontaneously formed cell-like bubbles. Some of these bubbles would have enclosed self-replicating sets of molecules – the first organic cells. The earliest protocells may have been elusive entities, though, often dissolving and reforming as they circulated within the vents.
7. The evolution of an enzyme called pyrophosphatase, which catalyses the production of pyrophosphate, allowed the protocells to extract more energy from the gradient between the alkaline vent fluid and the acidic ocean. This ancient enzyme is still found in many bacteria and archaea, the first two branches on the tree of life.
8. Some protocells started using ATP as well as acetyl phosphate and pyrophosphate. The production of ATP using energy from the electrochemical gradient is perfected with the evolution of the enzyme ATP synthase, found within all life today.
9. Protocells further away from the main vent axis, where the natural electrochemical gradient is weaker, started to generate their own gradient by pumping protons across their membranes, using the energy released when carbon dioxide reacts with hydrogen. This reaction yields only a small amount of energy, not enough to make ATP. By repeating the reaction and storing the energy in the form of an electrochemical gradient, however, protocells “saved up” enough energy for ATP production.

10. Once protocells could generate their own electrochemical gradient, they were no longer tied to the vents and become free-living organisms in the ocean. Possibly, cells left the vents on two separate occasions, with one exodus giving rise to bacteria and the other to archaea.

7 Habitability - Lessons from Earth I

Here are some of the main factors often quoted to determine the classic 'habitability' of a planet life similar to us may be happy, based on conditions and life known on Earth.

1. a safe place in our galaxy (no nearby supernova, stellar collisions)
2. presence of a long lived star (life takes time to evolve)
3. a nearby gas giant planet (clears out dangerous asteroids)
4. a terrestrial planet on a stable orbit (chaotic temperature variations bad)
5. an atmosphere (with oxygen & ozone, to cycle elements, to protect against meteroids & high energy radiation/cosmic rays)
6. presence of liquid water on or near the surface (life needs a liquid)
7. a large moon to stabilise the planet's spin axis and temperature
8. active plate tectonics to recycle the biological elements that life needs
9. magnetosphere screening from solar radiation harmful for biological systems & to protect out atmosphere from being removed

7.1 Liquid water

The habitable zone It is determined by the location of a planet at which water can exist in liquid form. This can be a narrow but uncertain distance from the star, because of the dependence on the strength of the greenhouse effect which depends on multiple factors. Inner edge: The outer most point where a runaway greenhouse effect would evaporate all water from the planet. As the oceans evaporate, water vapour penetrates into the stratosphere and is photo-dissociated by UV radiation. The hydrogen then escapes the atmosphere due to its low molecular weight. Outer edge: Usually called the 'maximum greenhouse limit' - this is where a cloud-free pure CO_2 atmosphere leads to a surface temperature T=273 K. The habitable zone changes over time since stars evolve.

The faint young Sun paradox When the Sun formed its luminosity was 2/3rds of today. On an absolute scale, Kelvins, that was 90K colder (-75C) on Earth than today's mean temperature of 15C (288K)! But there is evidence of liquid water on Earth 4 Gyrs ago. Today, a blackbody radiator at the distance of the Earth today should be -19C. Our temeprature is due to the greenhouse effcect and has only varied by a few defrees over the past 500 million years.

The greenhouse effect Visible light from the Sun passes through the atmosphere – most of the Sun's energy is in visible light and the atmosphere is transparent at these wavelengths. Sunlight is absorbed by the ground/oceans. The land/oceans radiate the heat in infra-red wavelengths. Water vapour and greenhouse gases reflect this longer wavelength light, effectively trapping the heat. Despite its rare fraction in the atmosphere CO_2 is an important greenhouse gas mainly due to it longlivety in the atmosphere. Water vapour is the most abundant heat-trapping gas, but has a short cycle. The main positive feedback in global warming is the tendency of warming to increase the amount of water vapour in the atmosphere, which in turn leads to further warming. The main negative feedback comes from heat radiated into space, described by the 'Stefan–Boltzmann law': the amount of heat radiated from the Earth into space changes with the fourth power of the temperature of Earth's surface and atmosphere. Clouds also influence the effect on the climate. They reflect radiation back to earth (warming) but also reflect radiation back to space (cooling).

Ice Ice melts into open water and exposes land. Both are on average less reflective than ice and thus absorb more solar radiation. This causes more warming, which in turn causes more melting, and this cycle continues and vice versa if there is global cooling.

7.2 Global cycles, tectonic activity & feedback loops

Recycling the elements that life is made of is essential. Otherwise all elements would simply accumulate on the bottom of the sea.

Carbon On geological timescales the CO_2 content of the atmosphere is controlled by the balance between weathering, subduction and volcanic output. The primary source of CO_2 into the atmosphere is volcanic outgassing. Most of this outgassing is of carbon stored in the lithosphere when the Earth was formed.

Plate tectonics Play a large part in the cycles of elements and the atmospheric composition on Earth. If a planet is too small and too cold it can not sustain active plate tectonics as the crust becomes too thick.

7.2.1 Carbon cycle

Life is an intricate part of the carbon cycle. The reverse process is respiration: we eat carbohydrates and use oxygen to gain energy releasing carbon as a waste product. Any fixed carbon not respired by animals, fungi, or microbes goes into sediments and turns into sedimentary rocks/oil etc. CO_2 is also consumed by the weathering process. Water reacts with CO_2 to from carbonic acid. It is absorbed by the oceans and reacts with calcium and magnesium. The long term carbon cycle is sensitive to feedback mechanisms that act to regulate the temperature on Earth. If there is more CO_2 released the earth gets warmer but in turn chemical processes also run faster which is a negative feedback process. The same is also true in the other direction.

Feedback loops from life The *Gaia* hypothesis for the evolution of the Earth postulates that the presence of life has provided mechanisms to regulate the climate. A test postulates that if a planet had no life, it should have an atmosphere close to the chemical equilibrium state, as determined by chemistry, physics & geology. If the planet held life, the metabolic activities of life-forms would result in an atmosphere far from the equilibrium state. i.e. contain molecules that should not exist via non-biological processes.

Daisyworld Two kinds of daisies coloured either black or white, and the only environmental condition that affects growth rate is temperature. The temperature is modified by the varying amounts of radiation absorbed by the daisies in the presence of an evolving star. The black daisies absorb sunlight, radiating infra-red thermal radiation which warms the planet. The white daises reflect most of the sunlight back into space and thus prevent warming of the planets surface. When the sun was young, the equatorial regions were just barely warm enough to exceed the temperature threshold for daisy growth. Black daisies would have prospered and become dominant over the white daisies and the planet would increasingly be dominated by black daisies, further raising the surface temperatures (positive feedback). Temperatures rise above the optimum, the further expansion of daisies would slow down because of smaller seed production (negative feedback). White daisies would become more abundant as temperatures rise, they can keep cool when it gets too warm for black daisies. Eventually even a planet covered with white daisies will not be able to cope with the incoming heat any more and all the daisies die.

Feedback from life If photosynthesis decreases, there is less plant/algae growth, all of the O_2 would combine with reactive minerals and organic matter, CO_2 would build up in the atmosphere in exact proportion to the lack of carbon burial. Temperatures rise again. If photosynthesis increases, more plant growth, O_2 increases, CO_2 fixed and greenhouse effect lowered. Effects of long-term distribution of plants will also effect atmospheric CO_2, life is critical to chemical balance of our atmosphere.

7.2.2 Other cycles

Sulphur Sulphur is assimilated by bacteria and plants as SO_4 for use and reduction to sulphide. Animals and bacteria can remove the sulphide group from proteins as a source of S during decomposition. Volcanic gases then contain SO_2 and H_2S. These processes complete the sulphur cycle.

Nitrogen Most of the Earth's nitrogen is stored in the atmosphere. It must be converted from the relatively inert state into forms that are usable by life.

Phosphorous The phosphorous cycle does not involve the atmosphere, but moves between the lithosphere, hydrosphere and biosphere. This is because phosphorus and phosphorus-based compounds are usually solids at the typical ranges of temperature and pressure found on Earth. The major long-term transfers in the global cycle are driven by tectonic movements in geologic time.

Oxygen Linked to the carbon cycle via CO_2. Movement of oxygen between the lithosphere (where most of the oxygen is held $\sim$ 99.5 %), atmosphere and biosphere. Lithospheric oxygen is very tightly bound into oxides (ferric and silicate mainly). Its main source for biological activity is from volcanic CO_2 which is converted by photosynthesis. Oxygen was present 3 Gya. That's more than 600 My before the first "Great Oxidation Event". Three billion years ago, some microbes had evolved the ability to carry out photosynthesis. Once the atmosphere was enriched with oxygen, a protecting ozone layer could form perhaps allowing life based on DNA to inhabit the land.

Cyanobacteria Cyanobacteria are a phylum of bacteria that obtain their energy through photosynthesis. Photoautotrophic, oxygen-producing cyanobacteria (or ancestors) created the conditions in the planet's early oceans & later the atmosphere. According to endosymbiotic theory, the chloroplasts found in plants and eukaryotic algae evolved from prokaryotic cyanobacterial ancestors via endosymbiosis between separate single celled organisms. Many cyanobacteria even display the circadian rhythms that were once thought to exist only in eukaryotic cells.

7.2.3 Banded iron

Banded iron layers were formed in sea water as the result of oxygen (released by photosynthetic cyanobacteria) combining with dissolved iron in Earth's oceans to form insoluble iron oxides, which precipitated out, forming a thin layer on the substrate, which may have been anoxic mud (shale/chert). The Earth's primitive atmosphere had little or no free oxygen. Since there wasn't any oxygen to combine with it at the surface, the iron entered the ocean as iron ions which dissolves in the water and can be transported over long distances making the oceans iron rich. At the same time, primitive photosynthetic blue/green algae was beginning to proliferate in the near surface waters and produce oxygen that would combine with the iron to form iron oxides. These 'solid particles' are insoluble and would precipitate to the ocean floor, cleansing the algae's environment. At one point the iron fraction dropped and oxygen content of the sea water rose to toxic levels. This eventually resulted in large-scale extinction of the algae population followed by an accumulation of an iron poor layer of silica on the sea floor. As time passed and algae populations re-established themselves, a new iron-rich layer began to accumulate.

Cyanobacteria and extinction events At first, most of the oxygen produced by cyanobacteria was absorbed through the oxidization of surface and ocean iron and the decomposition of life forms. However, as the population of the cyanobacteria continued to grow, these oxygen sinks became saturated. As oxygen "polluted" the methane rich atmosphere, and methane bonded with oxygen to form carbon dioxide and water, a different, thinner atmosphere emerged, and Earth began to lose heat. Thus began the an Ice Age. This led to a mass extinction of most life forms, which were anaerobic, as oxygen was toxic to them. Cyanobacteria may have been responsible for one of the most significant extinction events in Earth's history.

Iron Iron is an essential element for the growth and development of almost all living organisms, and acquiring iron is crucial for the development of any pathogen. Prokaryotic life in the oceans today are part of a global 'iron cycle' and there is a continuous competition for this limited resource. Iron is essential for both the pathogen and the host and complex mechanisms have evolved that illustrate the longstanding battle between pathogens and hosts for iron acquisition. The host has developed mechanisms to withhold iron from the microorganisms, thus preventing their growth, while the microorganisms have the capacity to adapt to the iron restricted environment by several strategies.

8 Habitability - Lessons from Earth II

Protection from the solar wind The Sun's magnetic field is generated by the convective motion of conductive plasma. These are localised patches which rise up through the Sun, reaching the photosphere, causing sunspots, coronal loops and flares. The Earth's magnetic field deflects the solar wind, preventing the evaporation of our atmosphere and radiation damage from high energy particles.

Earth's magnetic field The Earth's magnetic field is caused by electric currents in the rotating convective liquid outer core. The magnetic field requires planets to be rapidly rotating and to have a liquid metal core.

Solar flares Sunspots are regions on the sun that are cooler and have stronger magnetic field than their surrounding. When sunspots merge together their separate magnetic fields explosively realign into a new configuration. It is thought that this process, called 'magnetic reconnection', accelerates charged particles producing a burst of light, UV and X-ray radiation. This is called a solar flare. When this blast of plasma reaches the Earth, it creates electrical currents in the ionosphere and causes Earth's magnetic field to fluctuate widely. Without a magnetic field, the solar wind can strip planets of their atmospheres.

8.1 Earth's orbit, the moon and glacial periods

The interglacial periods are due to the Moon, Jupiter and Saturn. The levels of CO_2 and the temperature correlate pretty well together but in the pre-industrial revolution time carbon dioxide was not causal for the temperature increase. The eccentricity of Earth is variable due to the gravitational influence from Jupiter and Saturn, resulting in a 25 % variation in incident solar flux. Another point is Earth's obliquity precesses on a 26,000yr timescale and oscillates between 22.1 and 24.5 degrees on a 41,000yr timescale. (Mainly due to our Moon.) This varying amount of solar radiation on Earth causes the Milankovitch cycles and with that causes glacial periods. The third point is axial precession that makes seasonal contrasts more extreme in one hemisphere and less extreme in the other. If you add these signals you get a mixed signal that corresponds quite nicely to the Temperature cycles.

How does this now correspond to the carbon dioxide measurements and why are the temperatures underestimated with the Milankovitch cycles? In the case of warming, the lag between temperature and CO_2 is explained as follows: as ocean temperatures rise, oceans release CO_2 into the atmosphere. In turn, this amplifies the warming trend, leading to yet more CO_2 being released. Thus, increasing CO_2 levels become both the cause and effect of further warming. This positive feedback is necessary to trigger the shifts between glacials and interglacials as the effect of orbital changes is too weak to cause such variation.

The problem is though yet a bit more complex. CO_2 is less soluble in warmer water, reduction in salinity by melting ice caps would have partly counteracted this effect. A reduction in biological activity may have played a bigger role. Changes in factors such as winds, ice cover and salinity would have cut productivity, leading to a rise in CO_2.

8.2 Effects of our moon on climate

The obliquity of the Earth has not changed by more than a few degrees over billions of years. This is thanks to the stabilising gravitational torque from our relatively massive Moon. Without our Moon, the Earth would spin chaotically and the ocean's could freeze and thaw on short timescales. The dramatic temperature changes would not be a good environment for plants and land creatures and to evolve.

The tides Water piles up where the moon is the strongest - the distance to the moon is the shortest. When the moon moves, friction force is built up and the tides are happening. The Earth and Moon have lost spin angular momentum thanks to the tidal bulges and energy dissipation. The Moon is now tidally locked to the Earth and has drifted away into its current position.

The future In ~ 10 billion years the Earth-Moon system will be fully tidally locked when our day becomes about two months long and the Moon can only be seen from one side of the Earth. The tides will become much smaller and due to the Sun only as the Moon will be twice as far away.

The past When the Moon is moving away from the Earth it must have been much closer in the past. At this time the Earth was spinning about much faster and the ocean tides were far larger (scales as cube of distance to the Moon). The question arises then, whether life began 4 billion years ago in an ocean tide pool.

Origins of the Moon Earth and Moon have almost identical compositions. The Moon is thought to have formed from a giant impact between a Mars sized planet called 'Theia' and the proto-Earth. But since the composition is so similar another theory arose, namely that it might been two equal mass planets that mixed perfectly.

9 Planet formation

The interstellar medium is the gas between stars. Most molecules can be found in the disc and not in the interstellar medium.

We are made of elements that were synthesised during the big bang, partly from explosions of massive stars, the mergers and explosions of dead stars and from the winds of dying stars like our sun. All these elements become mixed and end up in the gaseous interstellar medium. Gas clouds can collapse, after reaching a critical mass and form new stars. The intensity of light from the sun shows many dips → where the photosphere absorbs light.

Elements found in the sun are very similar to elements found in the interstellar medium. In earths crust there are rarer elements which settle into the Earth's core. How can it thus be, that rare-earth elements like gold accumulate to nuggets? One hypothesis is synergistic gold-copper detoxificaiton of microbials which would lead to formation of nuggets.

- Hydrogen formed 3 minutes after the big bang, after the temperature had dropped.
- Carbon is produced in the planetary nebula end stages of stars.
- Oxygen is formed in massive stars - When the supernova happens, elements heavier than Iron are formed.
- After the end of fusion, the core turns into a white dwarf and elements such as Zinc form when two remnants merge and explode.

9.1 Formation of stars

Turbulent motions cause nebulas like the Orion nebula to collapse. This is a competition between gravity, temperature/pressure, radiation and magnetic fields. Planets like Jupiter have too high of a temperature to form a star → Jupiter is a failed star.

9.2 Protoplanetary disks

The original cloud is large and diffuse and its rotation is imperceptibly slow. Then the cloud begins to collapse. Because of conservation of energy the cloud heats up as it collapses. Because of the conservation of angular momentum the rotation speeds up. Collisions between particles flatten the cloud into a disk. The result is a spinning, flattened disk, with mass and temperature being concentrated near the centre.

Planets then form within these protoplanetary disks as the gas in the disks grows hierarchically into planets.

9.3 Formation of terrestrial planets

- From dust to km-size planetesimals
- From planetesimals to Moon-sized objects (embryos)
- From embryos to terrestrial planets and cores of giants
- accretion of gas on early massive cores to form gas giants
- Can also form gas giant planets via gravitational instability.

dust to rocky terrestrial planets

- Coagulation: Dust particles interact, sticking together to form larger and larger particles
- Runaway growth: The larger a particle becomes, the faster it grows as it has a larger surface area.
- Oligarchic growth: The largest planetesimals grow faster, and the larger they become the more dominant their gravitational attraction becomes, allowing a small number to grow to planetary masses.
- Giant impacts: The late stages of terrestrial rocky planet formation occurs with giant impacts between proto-planetary objects.
- After 100 million years the planet's are in place, the rate of impacts slows down because less objects are left.

As gravity increases with mass, rocky objects larger than ~ 1000 km become spherical. One interesting point is that Jupiter with its mass 'clears out' a lot of the dangerous asteroids from the inner solar system.

9.4 How Earth obtained carbon, water, gold...

One would think that the elemental composition of the planets should be the same as the Sun but the rocky planets clearly have very different chemical compositions from the Sun. The Sun is a gian gas ball of mainly hydrogen & helium, whilst the Earth is mainly made of iron & oxygen. One reason for this is that the temperature is stratified along the proto-planetary disk so that different compounds will condense at different temperatures/distances. This means that hte growth is faster at larger distances from the Sun → Jupiter is further away than Mercury from the Sun. Elements that end up on Earth, condensed from the hot gaseous disk to form solid compounds. The ice line is 3A.U. (i.e. water only forms well beyond the Earth's location and even beyond Mars). One interesting point that follows from this is that the ratio of water and carbon on Earth were not present in this area of the proto-planetary disk. Asteroids have the same carbon and water composition → even life could have formed there. In fact, so much water is delivered from the outer to inner region that we predict many worlds could be water worlds. It was long thought that water originated from comets but the deuterium fraction in water was found to be much higher in comets than on Earth implying that Earth's water came from a different source.

9.5 Asteroids, meteorites and impacts

Meteor's or "shooting stars" are usually small grains of dust from comets broken off their parent bodies 10's to 100's of million years ago. Our atmosphere burns up any space rocks smaller than a few metres across.

Meteorits classification

- Chondirtes: contain small round particles, composed of silicate minerals that appear to have been melted in space.
- achondrites: no chondrules, crust material of more massive asteroids.
- iron: nickel-iron, cores of more massive asteroids that were once molten.
- pallasites: stony iron.

The rotations and spins can be explained in terms of giant impacts → the spin comes from the last large impact in fact.

9.6 Planet formation - gas giants/ice giants

Core accretion model

1. Coagulation of dust: from sub-micron to few hundreds of meters
2. Run-away growth of largest bodies to $\sim$ 100 km size
3. Self-regulated-oligarchic growth (clearing neighbourhood)
4. Formation of rocky core
5. Rocky core accretes gas to form a gas giant planet.

Core accretion model for gaseous planets: first a rocky 'terrestrial planet' forms. Then this accretes gas from the proto-planetary disk.

10 Worlds beyond our Solar System

Definition of a planet

- it is in orbit around the Sun
- it has sufficient mass so that gravity has formed a sphere
- it has cleared the neighbourhood around its orbit

dwarf planets only satisfy the first two components.

10.1 Difficulties in finding planets

There are several difficulties but one is that detection depends on the albedo. A star is far easier to be visualised than a planet. Our eye can only resolve objects that are one millimetre across at a distance of about three metres. That translates to 200 kilometres on the surface of the moon. Any object like the Death Star would only become really obvious once it reached the distance of our Moon. A telescope like HST has a CCD camera which is far more sensitive than our eye, it could spot the Earth at 100 light years away. The problem is though that the telescope only sees a tiny patch instead of the entire nightsky, you would have to make several million images to cover the entire sky. That is the reason why we haven't found all dwarf planets in our solar system yet → there is a lot of space to search for.

Exoplanets are not too faint too see, the problem is much more in diffraction. This is a quantum mechanical effect that results in photons of light scattering off the edges of any obstacle or opening. This causes any source of light to appear slightly fuzzy.There is no way how to overcome this physical limitation and construct a perfectly parallel light beam. Diffraction limits as well the resolution of our eyes and our telescopes. If we e.g. shine a laser pointer of about 200 arcseconds to the moon, it would have a diameter of 400 km across. A larger lense can focus the light into a narrower beam, meaning that larger telescopes can resolve smaller objects. Diffraction causes light of a star to be spread out over the neighbouring dozen or more pixels. Since stars are brighter than a planet, this causes light from the planet to be overwhelmed by the light from the star.

The airy disk is the central bright circular region of the pattern produced by light diffracted when passing through a small circular aperture.

The above points are as well the reasons why we can not see the moons of Jupiter with our own eyes → the light of Jupiter spreads too much in its diffraction pattern.

10.2 How to find planets orbiting other stars

10.2.1 Radial velocity technique

When a planet orbits a star, it causes the star to wobble back and forth since planet and star are orbiting their common centre of mass. If a star (like the Sun) is pulled by several planets, this can give rise to a very complex pattern of motion.This means that the velocity of the light that leaves from the stars on its trajectory changes with the doppler shift. This causes a slight blue shift of the light when the star is approching us and a slight red shift when the star is leaving us. With this technique it is easier to detect more massive planets which are closer to their star since the wobble amplitude increases.

Via this technique the first extrasolar planet, 51 Pegasi was detected by Mayor & Queloz. The orbital period, planet mass, orbital eccentricity and the number of planets in the system can be recorded. 51 Pegasi was a very small radius around its star and will not survive long that close to its sun. If the velocity curves are not symmetric, the orbits of the planets is eccentric. A multi-planet system will lead to a complex signal.

10.2.2 Direct imaging

Hot-Jupiters emit strongly in the infrared wavelengths. There, the contrast between star and planet is much higher. IR emissions was the first light to be detected from a planet outside of our solar system. Such Hot-Jupiters could actually already begin fusion (so become a star) if they have a mass of 13x Jupiter.

10.2.3 Transit technique

Is a good technique for edge-on planet systems where a passing planet dimms the starlight as it passes in front of it. Via the timing of the transit light curve, several properties of the planet can be measured. This techniques has some disadvantages as the starlight can as well be variable e.g. due to repeating sunspots. The changes in intensity are though only quite small.

10.2.4 Gravitational microlensing

The Einstein ring is the characteristic bending angle of light and when a distant object lies exactly behind a foreground mass it appears as a ring. Analogous to a glass lens, the foreground object curves more light into view which magnifies and brightens the distant object. Can be used across the galaxy whereas the other methods are limited to study only nearby probes. The weakness is the probability of getting the right geometry which is very low.

10.2.5 Pulsar timing technique

A dead star can collapse into a neutron star, who's rotation is so regular as an atomic clock. The detection technique for planets is the same as with the doppler effect. The question is a bit how the planets got there after a massive star explosion. What is quite sure, no life could survive a nearby supernova explosion. Perhaps these planets formed from the supernova debris.

Most planets nowadays have been discovered using the transit method via Kepler telescope that was active until 2018.

11 Life in our Solar System I

11.1 Mercury

Mercury is in a 3:2 resonance with the sun, meaning that int rotates 3 times when completing 2 orbits. Mercury has no significant atmosphere and a very hot dayside temperature (430 C) and a very cold nightside temperature of -170C. Mercury possess frozen water on the ice caps but the determinants are bad for life on mercury as it is outside the habitable zone. Even though life could exist without an atmosphere but it couldn't survive without a liquid. Today we are interested what are the tectonic activities of Mercury and how it comes about that such a small planet has an intrinsic magnetic field while Venus, Mars and the Moon don't have any.

11.2 Venus

When looking at the surface of Venus one sees that there are not many craters - asteroids burn when passing through the atmosphere. Venus is at the edge of the habitable zone. The atmosphere looks yellowish because of the SO_2. Venus rotates (backwards) every 243 Earthdays. This might be due to tidal breaking if Venus once ahd an ocean or an atmosphere. The surface temperature is very high with 460C and has a thick atmosphere of CO_2. Venus has approx. the same total mass of carbon as the Earth, but nearly all carbon on Venus is in the atmosphere and on earth, nearly all is in the crust. One assumes, that carbon has been delivered together with water by asteroids, but Venus has no water anymore today. If we consider the D/H ratio on Earth and on Venus we find, that it is 100x higher in the atmosphere of Venus. Since H is lighter than D, Venus must have lost $\sim 99.9\%$ of its H. Since most H is available in water we can calculate back and find that Venus onve had as much water as Earth. One theory is, that Venus had an environment like the earth but without life -

- Without life there is no oxygen and no biological sink
- Without oxygen there is no ozone layer - water is not protected from UV - broken up into H and O
- H moves then to the top of the atmosphere and escapes

Venus is not thought to have plate tectonics today but there is supposed to be volcanic activity. As well the SO_2 in the atmosphere is thought to be due to volcanic activity which has been emitting the carbon of Venus's interior into the atmosphere. This can be inferred through ring-like structures on Venus that are formed when hot material from deep inside the planet rises through the mantle and erupts through the crust.

On the planet Earth the carbon has been removed by dissolving in rainwater and then being subducted to the mantle.

Runaway Greenhouse-effect

- More water evaporates because of dissocation by UV
- Leads to less surface water to absorb CO_2
- More release of carbon via volcanoes
- As the greenhouses build up, the temperature increases further
- once all water is evaporated, the plate tectonics halt , all the CO_2 is in the atmosphere $\rightarrow$ max greenhouse effect temperature is achieved.

Photosynthesis could have prevented this from happening, but maybe life on Venus did not develop in time or perhaps life never developed photosynthesis on Venus.
In the zone of 48-55 km the atmosphere of Venus the temperature and pressures are similar to sea level on Earth which lead to the suggestion of hydrogen floaters which live in this zone. Since a Venus day is very long, little turbulences are proposed that could drag life into hotter/colder atmospheric heights. One difficulty with this theory is the high level of SO_2 leading to acid rain $\rightarrow$ hydrogen based life would dissolve unless it evolved protection mechanisms. There was PH_3 found in the atmosphere of Venus and there is no abiotic way known to produce this compound. This finding has though not been confirmed.

11.3 Earth & its moon

The moon has no atmosphere and is cold $\rightarrow$ no life proposed

11.4 Mars

Mars sols are a bit longer than on earth (24.7h) and a mars year is 668 Earth days. The temperatures range from -130C - 30C. 4 Gyrs Mars was at the edge of the habitable zone, if the atmosphere was thicker then, a greenhouse effect would have allowed oceans of water and rain. The erosions are debated to be either made of lava flows or of water.

Water on Mars Due to low pressure, there cannot exist liquid water on Mars today. Martian soil is $\sim 2\%$ water. As the atmospheric pressure dropped water could evaporate more easily and be lost into space and so the temperature droped until all remaining water froze.

Small planets cool down faster than large planets Amount of heat stored is proportional to the volume (cube) and the rate of heat loss increases with the surface are (squared). Therefore, larger planets lose their hate more slowly than small planets.

How did Mars lose its atmosphere? Could be due to the cooling of the interior of Mars which lead to the loss of the protecting magnetic field. Then solar winds blow the atmosphere constantly away. Another theory states that a giant impact could have reached the entre of mars disrupting its core and ending the magnetic field. This is supported by the fact that the north seems very smooth whereas the south is heavily cratered.

Mars had once very strong volcanic activity, the largest volcano is three times higher than Mt. Everest. Mars has a very rigid crust rather than a more flexible plate structure of the Earth.

One point that states against water on Mars is that we find olivine on the surface of Mars that transforms into serpentine in the presence of water $\rightarrow$ the olivine on the surface has not been transformed, suggesting that there wasn o water over most of the history of Mars.

Search for life on Mars A rover found in 2007 large deposits of silicate which suggest this area to be a terrestiral analogue for ancient Martian hot springs. On earth these silicate deposits are produced by microbes. Radar mapping found evidence for a subglacial lake on Mars, 1.5 km below the southern pole. As the temperature is -10C - -30C it is suggested that the lake is rather salty. A similar enviroment on Earth (lake Vostok) was shown to support life.

Methane was found in the atmosphere of Mars. There are two known ways to produce it, either biological or geothermal, which would be a promising environment to find life on present-day Mars.

Oxygen was found to show significant seasonal and year-to-year variability, suggesting an unknown atmospheric or surface process at work. A habitat of similar conditions on Earth is the Atacama Desert where life has been actually found. The Viking landers took some Martian soil, nutrients and water was added and in the resulting gas CO_2 was measured.

Mars meteorites have been measured. We know that these are from Mars, because Mars' meteorites have a different oxygen isotope ratio. There are isotopes that can only be produced when experiencing cosmic rays outside of Earth's atmosphere.

12 Life in our Solar System II

Space travel The design of rockets hasn't much changed since the 1940s, 90% of the rockets mass is fuel. This kind of travel is to slow for interstellar voyages. Electric/Ion thruster are there to accelerate ions for momentum - used since the 60's for manoeuvres. Nuclear pulses are likely to reach $\sim 10\%$ of the speed of light. Fusion drive would be more efficient than fission but is far away to be produced practically. Laser propelled light sails can reach $\sim 90\%$ speed of light. Teleportation is proven to work but the data rate for transmission would make it slower than walking. Warp drives are as well theoretically possible but need negative matter for travel. Wormholes are theoretically possible but need a black6 and a white hole (the latter has not been discovered yet).

12.1 Jupiter & its moons

Jupiter has an atmosphere made of molecular hydrogen and a core of metallic hydrogen (conducts e-). Jupiter possesses a very strong magnetic field which is due to the metallic hydrogen and its fast rotation. At a depth of 100 km there is a temperature of 300 K and a pressure of 10 atm, similar to the earths atmosphere. The temperature and the pressure increase massively with increasing depth. Since Jupiter only has a solid surface at its centre there is no place for life made of molecules. Neither could life exist in the atmosphere as there are strong vertical circulations which would bring any molecules quickly into regions of high pressure and temperature. One thing we can say for nearly certain is that there won't be any life on the gaseous planets but the moons of Jupiter and Saturn show candidates.

Availability & energy Life must have access to electron donors/acceptors. There are several variants to sustain life via electron acceptors/donors:

1. Autotrophs use inorganic compounds as reduced iron - requires some sort of geochemical disequilibrium where the donors/acceptors are continuously produced and are available for life like via volcanism, plate tectonics etc.
2. Heterotrophs use organic carbon as a source of energy
3. Photoautotrophs use sunlight as a source of energy and drive electrons from water.

The existence of complex multicellular life on earth is dependent on the sun and photosynthesis. It doesn't need to be light it can be high energy particles from radioactive decay, hydrothermal and gravity.

Gravitational tides are due to the formation of a tidal bulge which enables the exchange of energy and angular momentum. This results in tidal damping (decrease of obliquity - so becomes more circular), tidal locking (planet acquires a permanent night and day side) as well as tidal heating (time-varying deformation of the planet results in internal frictional heating). This concept is especially interesting for planets in the habitable zone of red dwarf stars - these are much closer and experience way stronger gravitational forces. This happens as well for the moons of Jupiter which would otherwise be completely frozen and show no volcanic activity.

All four gallilean moons of Jupiter are tidally locked, the question remains how there can be still volcanic activity on Io if it is tidally locked. This is due to Io's orbit being slightly elliptical resulting in a change in speed around Jupiter. Since the turning of the planet must happen at a constant speed but the orbit is elliptical the moon doesn't keep the exact same side facing Jupiter → little jiggle forces cause the tidal heating.

Tidal heating could help planets enter the habitable zone if they are at the outer edge (like Mars) or make it even more difficult on the inner edge (like Venus). Another negative aspect of tides is that they synchronise the spin of the planet resulting thus in a stopping of the core spinning and thus the protective magnetic field.

12.1.1 Europa

Is composed mainly of silicate rock with a possible iron core and a water ice surface. The smoothness of the surface imply a liquid ocean beneath the ice. The ocean is kept warm by Jupiter's gravitational tides and radioactive decays from the interior. The reddish streaks on Europa's surface may be rich in salts such as magnesium sulphate or NaCl deposited from evaporating water. The ice crust is 10-30 km thick. The presence of a liquid ocean beneath is supported by the presence of a weak magnetic field which requires a layer of electrically conductive material such as a salty ocean as well as the presence of auroras that reflect the splitting of water.

Europa is not the only moon believed to have liquid water but the only one where the water layer is thought to be in contact with silicate. Ganymede and Callisto are thought to have a water layer encased between layers of ice. Volcanism at the silicate-water interface on Europa however might provide similar conditions as on Earths deep-sea hydrothermal vents. This happens via convection in Europa's silicate layer.

All major ingredients for life are theoretically present on Europa, liquid water, inorganic and organic carbon and chemical energy sources. The surface of Europa is subject to strong ionising radiation but the ice crust is supposed to be protective against it. Europa has as well some oxygen as seen in the thin molecular oxygen atmosphere. This happens via radiation splitting water into free oxygen.

12.2 Saturn & its moons

As described before, life on a gaseous planet like Saturn is highly unlikely. The moons of Saturn may host life. Dione and Rhea may have oceans of water but they have thick cratered surface layers. Enceladus is a moon which is very similar to Europa and has as well surface ice. With satellites it was found that there are streaks of warm regions which probably due to warm water percolating up - Cassini found this and discovered that Enceladus definitely has liquid water under its surface. Cryovolcanoes at the sout pole of Enceladus shoot large jets of water vapour via the energy of Saturn's tides. Cassini could evaluated these jets via Mass-spec and detected mainly water, nitrogen, methane, carbon dioxide and simple and complex hydrocarbons. Interesting is foremost the existance of amines (the building blocks of amino acids).

Titan is the only satellite in the solar system with an atmosphere. Titan is warmed by hte tides of Saturn and other energy sources leading to the formation of organic compounds, such as UV solar radiation and high energy electrons from Saturns magnetosphere. Methane can condense in the atmosphere of Titan whereas hydrogen can not. This means that Methane on Titan seems to play the role of water on Earth. The density of Titan indicates an internal structure of water/ammonia ices mixed with silicates. Several possible metabolic processes have been postulated for the hypothetical subsurface oceanic life on Titan, such as nitrate/nitrite reduction or nitrate/dinitrogen reduction

Ammonia based life Ammonia is liquid between $-78C$ to $-33C$. Since chemical reaction take place more slowly at such temperatures, ammonia based life would probably metabolise very slowly. Various water related compounds have ammonia analogues. Ammonia has though as well some issues, as the hydrogen bonds between ammonia molecules are weaker causing ammonia's heat of vaporization to be half that of water. Since ammonia burns in the presence of oxygen the life would have to be non aerobic.

Methane based life has been suggested to host life on Titan. It could have Silicon as a structural atom. Silicon has many chemical properties that are similar to those of carbon, however silicon is not stable with water. Creatures in such a life would inhale hydrogen and exhale methane having metabolised the hydrogen into acetylene. If such a life would exist, there would be a measurable disturbance in the hydrogen to acetylene ratio. Indeed, there is a higher concentration of hydrogen in the upper layers of the atmosphere, suggesting a downward flow and a disappearance of hydrogen at Titan's surface. There was as well a suggestion of low levels of acetylene on Titan's surface. There are comparable life forms that might exist on Titan as well on earth.

Titan will become far more habitable since the ice melts when the Sun becomes a red giant, a phase of lengths that are comparable to those when life arose on earth.

12.3 The remote outer solar system

Neptun & Uranus Both planets are quite similar, having comparable masses and their atmosphere's being made up mainly of H and He, water ice and traces of hydrocarbons and methanes. Temperatures and pressures are hostile for life. The possible solid surface would be at extreme temperatures/pressures.

Neptune's moon Triton could maintain a subsurface ocean of ammonia/water.

Pluto has a very thin atmosphere consisting of nitrogen and methane and carbon monoxide. Pluto and CHaron show long cracks/tectonic features that are a a natural outcome of a refreezing subsurface ocean i.e. Pluto is slowly expanding as its subsurface ocean freezes.

Our solar system is surrounded by the Kuipers belt and situated in the Oort cloud, where comets come from. There are several dwarf planets that have a strangely elliptical radius, indicating a massive unseen planet, called planet 9 that is thought to be responsible for this synchronisation.

13 The search for life out there

Number of worlds with life in our galaxy

$$N_{life} = n_* \cdot f_p \cdot n_e \cdot f_l$$

n_* is the number of suitable stars
f_p is the fraction of long lived stars with planets
n_e is the number of habitable worlds
f_l is the fraction of worlds on which life evolves

13.1 Atmosphere and Biosignatures

A small fraction of light passes through the planets atmosphere during transit. The transmitted spectrum depends on the absorption and through the variation of the planet's observed radius at different wavelengths we can infer the atmospheric composition.

Phase curve Starlight is reflected from the surface of the planet during its orbit. Like this we can study its albedo and properties of the atmosphere (T and presence of clouds). we can do that by subtracting the light of the star from the transition diagram. Different to a transition diagram a phase curve preserves the change in brightness of the planet over the entire orbit. The temperature is measured by comparingflux values at different wavelengths. With this technique water was measured in exoplanets in the habitable zone.

Biosignatures Oxygen in the atmosphere would indicate the presence of life - free oxygen in the absence of life is absorbed by oceans and rocks. Venus and Mars don't have ozone or water in their atmosphere. Another biosignature is N_2O but this is harder to detect. There are abiotic sources for N_2O but their quantity is much smaller. Methyl chloride results from burning of vegetation - again a sign of life since rocks do not burn. Chlorofluorocarbons would be a sign of an advanced civilisation as it is a pollutant.

13.2 Signals from intelligent Life

Radio telescopes would be sensitive enough to detect transmission broadcasts from alien civilisations. This has been done in the context of the SETI program

Drake equation estimates the number of civilisations in the galaxy that we could communicate with.

$$N_{contact} = R_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot t$$

R_* average star-formation rate
f_p fraction of stars with planets - probably 1
n_e number of habitable places in those systems - probably ~ 5
f_l fraction of those places on which life evolves - unknown
f_i fraction of f_l becomes intelligent
f_c fraction of f_i that transmits detectable signals
t is the length of time they broadcast

most factors can't be estimated, only the number of habitable planets can be approximated. In astrobiology one interesting question is the probability of life occuring by abiogenesis. This can not be estimated though since we don't know how life started or what different pathways are there. Another difficulty is to incorporate all effects of natural selection - how likely is it that eyes evolve e.g.?
One thing is though logical, if from a single cellular organism a multi-cellular human can arise, then why not from a replicating molecule to a unicellular organism. The odds become though very small if we make it a 10% chance of evolving - 1 in 10 million.

Which wavelengths would aliens use? Wavelengths shorter than gamma rays take too much energy too produce and very long wavelengths contain too little energy to be detected. Using the radio frequencies is very suitable since they can be transmitted isotropically in all directions or focused into a powerful beam. Information can as well be easily encoded into electromagnetic waves by modulating the amplitude and the frequency. Another good reason for radio frequencies is tha infrared, ultraviolet and anything higher gets blocked by the atmosphere. Photons at the optical and radio wavelenghts can pass straight through. One question remains at which frequency we should search. One problem is the pollution of our planet - that would be a case for a radio telescope on the far side of the moon $\rightarrow$ would block out the earths radio frequencies. Photons are emittedin a narrow wavelength range called the bandwidth. The smaller the bandwidth, the more energy is transmitted and the more information can be encoded. The only real chance of detecting alien life in this way is if the aliens wanted to be detected, meaning that they focussed at the nearby star to announce their presence. This has been done by Arecibo (massive radio telescope on earth).

Radio leakage Radio leakage began in the 1930s with the first radio emissions but with the advances of technology we became a digital society and radio leakage decreased as a consequence. Another thing is that they might use different kinds of means for communication such as gravitational waves.

Interpretation of communication would be very difficult since aliens might use a different kind of logic. To interpret something like this one would need a kind of rosetta stone, so a medium that contains text or pattern common to both languages. In fact it would be already difficult to detect a form of communication as such and not just as noise.

A solution to the Fermi Paradox is that the search-space is n-dimensional and finding something in it is like finding a needle in an n-dimensional haystack. An analogy is to always look at a bathtub of water from the ocean, this would most unlikely contain intelligent life. If we did in fact find alien societies there are guidlines for communication but this has been broken several times.

A dyson sphere is a theoretical object used to capture the maximum amount of light from a dimming star.

Movement of our solar system is that the solar systems in the galaxy are not fixed but move. This means that at some point in time there were solar systems with habitable planets quite near by our solar system. At this point there was no intelligent life but aliens could have detected biomarkers such as our oxygenated atmosphere.

Lagrange points are points where the gravitational waves have a saddle point meaning that there is neither attraction nor repulsion. These points would be optimal for spying stations of aliens.

14 Alien anatomy and the future of life

When thinking about alien anatomy we are often thinking about similar bilateral life forms as on earth. This might have some reasoning behind it as we can see in convergent evolution (dolphins and sharks being very similar, despite being only distantly related). The opposite of this process is divergent evolution (as happening in adaptive radiation). Evolution on life shares some astonishing characteristics in nearly all craniota, like for instance pharyngeal arch. This is an example of continuous evolution. Most animals on earth are bilaterians that have descended from a common wormlike ancestor. The fundament of this life form is a gut cavity that runs from mouth to anus and a nerve cord with a ganglion for each segment. The first ganglion is enlarged - a form of brain. There are though as well exceptions to this rule like the fidler crab which is asymmetric.

Metallic skeletons would be much stronger than bone but it takes much more energy to bond metals like aluminium or iron than carbon. This energy barrier could be overcome in principle thermodynamically. Bones are continually repaired but this should in principle be possible for metal as well. A growing process could look something like shells growing that are periodically discarded. There are even examples on earth of molluscs that have evolved to have teeth made from iron and calcium biominerals.

There are even examples of nymphs that evolved to have cogs and wheels or spookfish that have mirror eyes and copepods with dual lens telescope eyes. This shows that quite some things are possible already on earth.

Limitations due to gravity . The maximum size of creatures is constrained by the strength of the gravity on the respective planet. Creatures living in oceans or which are flat have no constraints but terrestrial animals do. The volume of a creature increases cubic to size, whereas the bone strength only square of the diameter. This means that diameter doesn't increase fast enough and at one point the bone will break. Possibly the largest animal that walked on earth was the *Argentinosaurus* where we only have one fossil - only one in 100 million animals becomes fossilised.

Kleiber's law An animal needs to lift it's mass and overcome the potential energy = mass x gravity x height. This is achieved by ATP whose production is proportional to the number of cells. This would mean that large animals can move as small ones. This is not the case and was described in kleibers law, stating that large animals generate less energy for their size than small ones. There are at least two possible reasons

1. Larger creatures have more volume taken up by structural components.
2. Large organisms have to avoid overheating.

Since the energy is not proportional to mass at some point a large creature is not going to have enough energy to move. According to kleibers law the *Argentinosaurus* could not have moved more than 100 steps in a day.

Another problem to max size is the circulatory system that has to have larger pressure if creatures become larger. Trees don't have that problem, there the limiting factor is the max height of a column of liquid.

Maximum size for flight Amount of vertical lift increases as the square of the speed, meaning that a creature that can run or spring fast enough can overcome gravity and get airborne. It doesn't matter whether creatures fly low or high in the atmosphere as drag forces compensate for air density. The limit for lift-off is $\sim$ 100 kilograms as Kleibers law does again set a limit to the potential available energy. *sidenote: the same applies to rockets - 95% of mass in a rocket is fuel whereas in a 10xEarth it would be 99 %.*

14.1 Life next to a red dwarf star

75% of stars in our galaxy are red dwarf stars. Since those radiate less brightly a planet must be closer than in our system. The strong gravitational field would thus cause the would cause tidal locking - always the same side of the planet will face the light. (the pericenter the planets rotates slower than it orbits but at apocenter it rotates faster. This means that the tidal bulge is not aligned with the orbit and there is a net torque that tends to bring the planet into synchronous rotation.)

One consequence would be that on tidally locked planets there is a narrow ring of land that separates night and day. This would bring constant winds from day to night side such that the night side is warmed. This as a consequence could lead to total freezing of all the water if the atmosphere was too thin. Such a planet would rise questions about life rythmn since there wouldn't be any day and night etc.

Disclaimer
Most of the information of this summary was taken from the lecture slides of Prof. Ben Moore. Some little clarifications were taken from searches in the internet. The authors don't claim that this is their intellectual property. It is solely to be used for studying for the UZH course "AST 201"