University of Central Lancashire

Introduction to Astrobiology
AA1059

Available as a *University Certificate*
and a module for *CertHE*, *DipHE* and *BSc in Astronomy*.

Sample Notes

These sample pages from the Course Notes for the module *Introduction to Astrobiology* have been selected to give an indication of the level and approach of the course. They are not designed to be read as a whole, but are intended to give you a flavour of the syllabus, style, diagrams, images, equations, mathematical content and presentation. They are a subset of the colour, navigable on-line version of the learning materials.

- All enrolled students will have access to the Course Notes via the course website.
- All sections of notes will be available in modest colour and basic navigation in html and pdf format suitable for downloading and printing at home.

July 2008

Introduction

Section 1

Astrobiology has taken great strides in the last ten years, moving to become a central part of the scientific enquiry into our origins. Discoveries both on Earth and via astrophysics have moved our understanding on tremendously. We can estimate where in the Universe Earth-like life could survive and develop. But we have also found life in extreme terrestrial environments that suggest much wider possibilities for the initial formation of life and its subsequent development. We will combine our understanding of biology and astrophysics to come to a modern view of astrobiology.

Mankind has always had an inquisitive nature; pondering problems and seeking solutions. Today some of the biggest questions left for us to answer are: *the origin of the universe*, *the origin of life* and also *an explanation of how our brains work*. This course looks at some of the options for the origin and evolution of life in the universe and asks the questions such as whether life is an natural consequence of the universe we inhabit.

There are two possible ways to construct a timeline that charts the development of life in our universe. Firstly we can assume that we have a good understanding of the starting conditions in the early universe and attempt to construct a sequence the events that predict what we observe today Alternatively, we can try to extrapolate back through time from our current position looking for commonality. A hybrid is likely to be the best, with data points checked against current observations. Even then we are left with a determination of the statistical chances of life forming a developing in particular conditions. We cannot say "look here and you will find life" but rather "if you want to find life, you have the best chance looking there".

In this course we will attempt to draw a timeline from the origin of the universe to the present highlighting key evolutionary phases and the missing steps that we can only speculate on due to lack of technology to make appropriate observations. Thus we will consider the origin and evolution of life within the evolution of the universe. Obviously our focus will be on life that is very much simpler than man but why have we introduced the origin of the universe into the puzzle?

The course involves the interplay between astronomy, biology and chemistry. Physics (the law of physics) together with observational data define the starting conditions. However, after this chemistry then biology has an increasingly stronger input but this is not clear cut or precise and there is a statistical selection process that makes it difficult for us to determine what actually happened.

Icons

Throughout the notes a number of icons (graphical symbols) are used to highlight particular sorts of information. The table below indicates the intended meaning of the icons used. These are particularly useful where they direct you from the printed material to a web link via the online material.

ICON KEY
When you see the *Valuable information* icon, this information is especially useful.
When you see the *Test yourself icon*, there is a test of the preceding module material.
When you see the *Worked example* icon, there is an example exercise with solutions.
When you see a *Book reference* icon there is a reference to a text book.
When you see the *Important equation* icon there is an important equation in the text.
When you see the *External link* icon, there is a link in the paragraph to a web-site outside the module material.

Module contents

This module consists of 12 sections of notes covering the fundamentals of Astrobiology. There are associated self-test questions and a set of assessed questions and practical exercises. The sections are:

1. Introduction (this section)
2. Origins of Life
3. Our Solar System
4. Exoplanets
5. Environments in Space
6. Basic Biology
7. Molecular Biology
8. Primordial Soup
9. Alternative Chemistry
10. Human Factors
11. Space Travel
12. Colonizing Space

It is expected that you will work through these sections at a steady rate. The assessed question sheets relate directly to the section content. The practical exercises build on that knowledge base and provide an opportunity to develop scientific skills alongside wider knowledge of the subject.

What is life?

Any definition of life that we introduce will be based on our own experiences but it must be sufficiently basic and universal that we can apply it to a wide range of circumstances not only on the Earth but also much further afield on another planet in the solar system or elsewhere in the universe.

The most basic definition of life might be something that is **capable of self replication/duplication that is not always perfect copy**. This latter point means that we can have Darwinian evolution provided that the mistake is heritable, and clearly this gives life the ability to adapt to the local environment. Any defects that are introduced should be passed on to the next generation. Those that help the survival in the current environment will for the time being have a statistical advantage. We will return to this question in Section 2.

Theories on the origin of life

Observational evidence suggests that the Earth is about 4.55×10^9 years old, while the oldest rocks are about 3.8×10^9 yrs old, and for a significant portion of this time there has been life of some form or other. The earliest fossils (cyanobacteria), found in North West Australia, are possibly 3.5×10^9 yrs old. They are still present on the Earth today. Cyanobacteria require water and grow in groups that are large enough to be seen. This is the blue-green algae. They are also probably responsible for generating the oxygen rich atmosphere on Earth.

Until very recently most scientists believed that "early" forms of life began on the Earth. This is very similar to how pre-20th Century astronomers viewed the universe; that the Earth occupies a very special place. Based on our current knowledge we cannot contradict this but the Greeks did propose an alternative.

Panspermia

Panspermia (the seeds of life everywhere) was first proposed by the Greeks, but it failed to gain general acceptance. Today the theory has been revived most recently by Fred Hoyle and Chandra Wickramasinghe. Panspermia was reintroduced to avoid the need to have "spontaneous creation" by suggesting that life originated elsewhere in the universe. This removes the requirement that the Earth has a special place in the universe.

Panspermia does not explain the origin of life, only how it came to be on Earth. Some versions of the theory suggest that life has always existed. There are unanswered questions such as did life start at one place and then spread out or did it start at several places. Even more fundamentally how did these "seeds" of life come into being.

Darwinism

In 1859 Darwin wrote on the subject of "The Origin of Species". He proposed that all life evolved and that natural selection ensures that the observed life was well suited to the environment in which it was found. However, it does not explain the origin of the very first species. This is one of the questions still to be answered.

The principle of **Natural Selection** provides a route from the earliest organisms to the full range of current species. This seems incredible on the face of it, but one has to realize that the process has operated over 3 billion years. As each generation can introduce an advantage that enables individuals to better survive, we can see that this period equates to 120 million human generations; most species have significantly shorter periods between birth and reproduction, tending towards many hundreds each year for the simplest organisms. Thus there have been literally hundreds of billions of opportunities for small advantageous changes to have an effect. Just as many disadvantageous changes would lead to individuals not surviving, but of course such changes are not passed on.

We do not fully understand the detailed progress of evolution, for example if it is a continuous steady progress or if particular changes lead to accelerated development at particular times.

Creationism

An alternative to both Darwinism and Panspermia, Creationism exists in various forms. Some expressions of this idea indicate that all the species that currently exist have always existed in their current form. Other expressions believe life was created as a conscious act of a supreme being or deity, and then evolved to the currently existing state. One advantage of these ideas have is that it actually provides an explanation of how life came into being in the first case. However it is also one that is not readily amenable to scientific exploration. If it is true, then most forms of creationism do not admit even the idea that we can explain it in scientific terms. Thus for the purposes of this course we consider the contemporary scientific understanding we have of how life may have formed and developed according to the best scientific approach.

Origins of Life

Note then that none of the scientific explanations of how life came to be on Earth, or how it came to the form it has today, really examine how life came into existence in the first case. A major attempt was made by Alexander Oparin, who examined the differences between purely physical systems and those that are biological. He set out some basic ideas that define how it might be possible to go from organic chemistry reactions to biological cells that could reproduce. This involved some intermediate structures that could in principle form into cells. Miller & Urey latter carried out experiments in which life's building blocks, including amino acids, were created from a chemical "cocktail" that arguably could have been present on the early Earth.

Origin of the Universe

The most up to date hypothesis on the origin and evolution of the Universe is that it all began with a hot big bang and subsequently expanded out into nothing. As near to the beginning as we can currently attempt to explain (10^{-43} sec) the entire universe was contained within a very small volume and the temperature was extremely high. There were no particles as we know them today and the environment was exactly as described by the relevant theoretical physics. Our current thinking suggests that there may not have been very many options and that our universe is a natural consequence of the hot big bang.

As the universe expanded it had to cool (by the laws of physics) and gradually the particles that are present in the Universe today began to form. Surprisingly, it seems to be inescapable that the Universe is dominated by hydrogen and helium. The hot big bang model predicts that the universe will be mainly hydrogen with about 25% helium by mass and very few other chemical elements. This is because the neutron is slightly heavier than the proton, and so more difficult to create. There were very few other chemical elements at this stage. This was the first stage in the chemical evolution of the Universe and it was complete within a few minutes of the big bang. After this point the temperature is too low to allow nucleosynthesis outside of stars. However, life - as we know it on Earth - requires carbon, nitrogen and oxygen. These elements are all created at the centres of stars, and returned via a variety of mass loss processes.

Other components of the universe are the fundamental forces. The gravitational force caused matter to start clumping and stars and galaxies formed. Early generations of stars were responsible for the production of chemical elements heavier than hydrogen and helium. These are all required before we can have organic chemistry on a grand scale.

Current knowledge indicates that the universe is about 13.7 billion years old. The **first stars** were massive (over 100 times that of the Sun, and so much more massive than most stars that formed subsequently or those in existence now) and formed entirely of hydrogen and helium, living for only a **few million years**. Subsequent star formation was modified by the small fraction of heavier elements, changing the range of star masses and the nucleosynthesis that resulted, but also enabling the formation of planets. All this combined to create the conditions for life to come into existence. The result of this nucleosynthesis is all the elements we know of today, except for a small number that we have synthesized most notably plutonium. These are most concisely summarized in the Periodic Table (Table 1.1) which also presents the standard chemical symbols for all the known elements.

One of the remaining big questions of Cosmology is the formation, properties and evolution of these first stars. While we know what must have gone into forming them, and we can observe today the products, we are only just becoming able to observe this period in the Universe's history and begin to understand the detailed processes involved. This is beyond the scope of this module in astrobiology, but is a scientific question on the same level as "what is the origin of life".

Table 1.1. The Periodic Table. Here we see all the elements currently known, with the associated chemical symbols and nucleon numbers.

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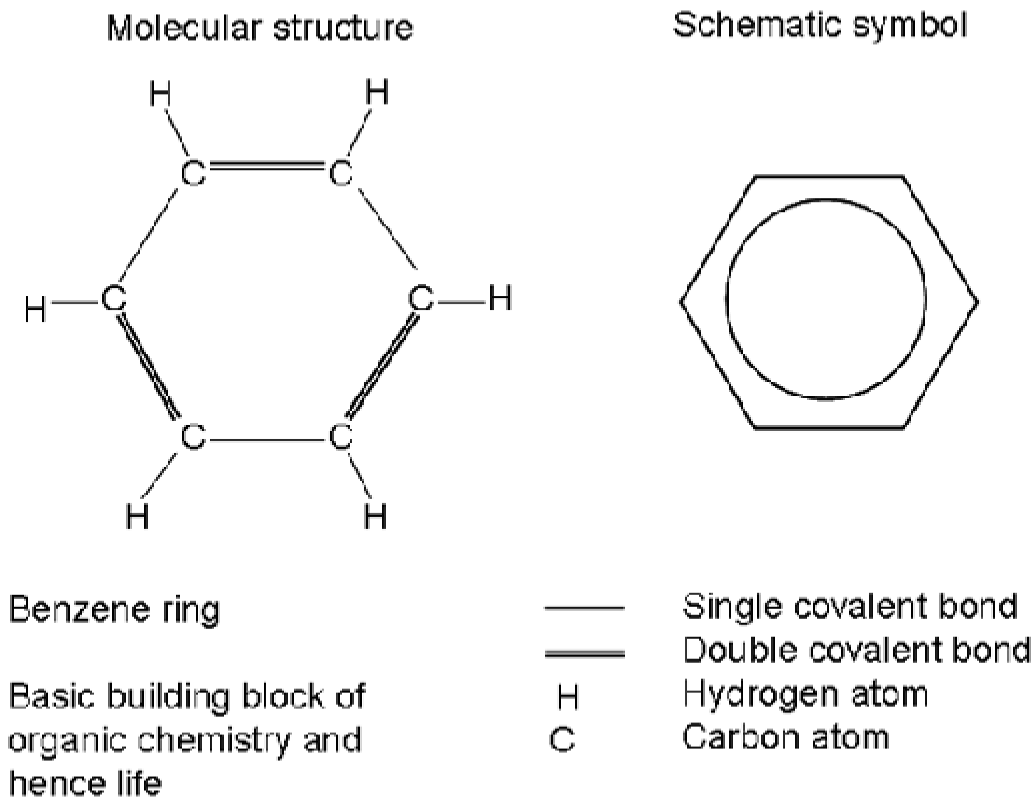
Chemistry

Once we have the heavier elements it is the object of chemistry to describe how they interact with each other. While nucleosynthesis within stars is governed by interactions between nucleons (protons and neutrons) to build heavier elements out of hydrogen and helium, chemistry is governed by interactions between atoms and ions to form molecules. In fact it is the electrons that are the real mediators of chemical reactions. Atoms consist of a compact nucleus of tightly bound neutrons and protons, and a much more weakly bound "cloud" of electrons. They can lose (or gain) electrons to form negatively (or positively) charged ions, and share electrons to form molecules. In terrestrial chemistry reactions tend to be rapid due to the density of reactants; in astrochemistry very different conditions hold and molecules can exist in space that would rapidly be destroyed or combine to form different molecules on Earth. For example OH (hydroxyl - one oxygen bound to one hydrogen) does not occur in terrestrial chemistry (although the positively charged hydroxyl radical OH^+ does). In astronomy we see it in many places, such as OH masers around cool stars. In organic chemistry the presence of OH in a molecule is what gives alcohol its chemical properties - and hence this is what astronomers mean when they claim to be observing alcohol in space!

From the point of view of astrobiology, the first time chemical reactions become directly important is as they create the molecules that go into minerals and form cool rocky and gaseous bodies on which life as we know it can survive and develop. There are traditionally two branches of chemistry: organic and inorganic. The first consists of reactions between molecules that are crucial to life systems, while the second is concerned with all the other reactions. This does not mean that the presence of organic chemistry means that life will be present. Rather for life to be present we must have organic chemistry. Organic molecules are seen by astronomers in space, but it does not follow that life is present.

All the key molecules of life that we will encounter in Section 2 (amino acids, sugars, nucleotides and lipids) are the products of organic chemistry. The building block of these molecules is the benzene ring, illustrated in Fig. 1.1 alongside the symbolic representation. An interesting aspect of this molecule is that the six carbon atoms share their electrons, which is why it can survive as a unit through various interactions and occur multiply in more complex molecules.

Figure 1.1. Standard chemical representation of benzene ring. Left: The arrangement of carbon and hydrogen atoms with covalent bonds. Right: Schematic representation of the benzene ring.



Chemical bonding

Atoms and molecules bond together through electron interaction. Two types of bond can operate:

1. Covalent bonding
2. Ionic bonding

In **covalent bonds** the atoms share electrons, and this is a lower energy state than the individual atoms can achieve alone. This is the guiding principle that governs chemical reactions, a tendency to move towards the lowest energy state. An atom can form bonds according to the number of electrons it has in its highest energy state. Thus hydrogen, with only one electron, can only form a single bond. Oxygen on the other hand becomes more stable if it can add to its complement of six electrons. This leads to the form of the most basic molecule of life, water or H_2O - that is two hydrogen atoms bonded to a single oxygen atom. In this molecule there is a single covalent bond between each hydrogen atom and the oxygen atom, and each bond shares a pair of electrons - one from a hydrogen, one from the oxygen atom.

It is also possible for two atoms to share four electrons, forming a double covalent bond. This is what happens in a **benzene ring**. Carbon has up to four electrons available for bonding, and in benzene each carbon atom forms a single covalent bond with a hydrogen atom, a single covalent bond with carbon atom and a (stronger) double covalent bond with a second carbon atom. In fact the situation is somewhat more complex, as in this configuration some of the carbon electrons delocalize, effectively bonding the entire carbon ring together covalently. The schematic representation of benzene (a circle in a hexagon - Fig 1.1) alludes to this understanding benzene bonding, with the circle representing the delocalized electrons and the hexagon the six carbon atoms.This establishes the stable ring structure, and subsequent interactions to build larger molecules with different chemical properties progress via the substitution for hydrogen of other elements and molecules.

In **ionic bonds**, the two atoms actually exchange an electron, or alternatively come together as oppositely charged ions. In this case it is the attraction of the opposite charges that leads to bonding. This form of bond predominantly occurs in inorganic chemistry, and so is of little direct relevance to astrobiology.

Biology

As we will see further in Section 2, life is built on basic organic molecules. However the step from the "primordial soup" to living organisms is not an obvious one. This is one of the big questions of science that spans all disciplines: **The origin of life**. One of the prime aims of astrobiology is to develop answers to this question.

There is a fundamental difference between purely physical systems and biological systems. Physical systems naturally tend to the lowest energy state and generally try to achieve an equilibrium state. For example when riding a bicycle, one is constantly correcting an unstable situation - stop peddling and the bicycle will attempt to enter a stable state, that is lying on the floor. By contrast biological systems are working constantly to maintain non-equilibrium conditions, from which they can derive energy and make use of the consequences of numerous chemical and physical processes. Biological cells are effectively the "rider" of the "bicycle" of physics and chemistry.

While we cannot yet demonstrate how the first life came into being, once it exists the use of energy resources is actually much less efficient than in purely physical systems. However all the properties of life mean that it is self-perpetuating, and so can continue to exist in the face of this handicap. In addition biological systems are the only means by which energy can be trapped and transported against the general trend towards equilibrium. Shine sunlight on a rock and it will heat; remove the light and it will cool with essentially no effect or net energy capture. Shine sunlight on a plant on the other hand, and photosynthesis will act to trap the energy and make use of it. Ultimately the energy will return to purely physical systems, but this is the basis of the energy input for the vast majority of the biosphere - that is almost all the plants and animals. The energy captured by Earth's plant life exceeds the total generated by humanity, even at our current level of development. This is an aspect of the arguments for the need to terra form in extraterrestrial colonization, as we will see in Section 12.

Here we are studying astrobiology. Why then are we discussing **life on Earth**? At the moment this is the only life system that we know of, and it is likely to remain the only life system that we can study in detail even if the ongoing searches for Earth-like extra-solar planets find a candidate where life can be shown to exist. So then the question becomes: Is Earth a good representation of life in the Universe? We do not know. From a astrophysical stand point we have good reason to believe that stars form in essentially the same fashion. Following on from this we can assume that planetary systems will all go through similar processes. Finally it seems logical that Earth-like planets exist beyond the solar system. This is all based in broadly well-understood physical and chemical processes. To go beyond that to life existing on these planets means spanning the boundary between pure chemistry and biological systems. Only when we understand how that boundary is crossed will be able to say for certain that life exists beyond the Earth. Conversely as soon as we observe life beyond the Earth, we can immediately say that spanning the boundary is not only possible (which we know from the existence of life on Earth) but also probable (for it to have happened more than once in similar situations).

Life - where and when?

In Section 2 we will look in much more detail at the form life takes and possible definitions of life. However it is useful to look at purely physical constraints we can place on when and where life can exist. A very useful concept is the one of **habitable zones**.

Planetary systems

The search for planets and life beyond the solar system is based around the idea that certain basic conditions are required: broadly liquid water, a thick atmosphere and a tolerable radiation level. We will see in Section 2 that life is somewhat more hardy and diverse than our casual knowledge of Earth might suggest. Nonetheless we can place limits on where in a planetary system life could survive and develop.

The first condition is the presence of liquid water. We know that this suggests surface temperatures between 273 and 373 K. For any given size and luminosity of star we can determine where this will be by applying the inverse square law. However it is modified by other conditions, the primary one being the presence of a thick atmosphere.

The early Earth had a thick carbon dioxide atmosphere, derived from volcanic out-gassing or infalling comets. This raised the temperature of the surface, but also established the conditions for anaerobic life to develop (that is life that does not need oxygen). This life eventually converted the atmosphere to the oxygen-rich form we have today. This also acts to maintain a higher temperature than would otherwise be the case. It also provides a shield against radiation from the Sun, reducing the damage to biological systems due to the impact of high-energy photons and particles.

Combined this leads to a region around the Sun that could support an Earth-like planet with indigenous life. It so happens that the Earth sits in that zone 150 million km from our nearest star; a slightly different formation history would have placed it at a different distance, and a very different history would have left it in a state similar to one of its neighbours Venus or Mars. The applicability of these considerations to astrobiology are obvious.

We note briefly here that stars are evolving objects. The Sun is consuming hydrogen in its core at a prodigious rate. Fortunately it is so massive that it will continue roughly its current state for another 5 billion years, about half of its entire lifetime. Over the first 5 billion years it has got steadily brighter, and this will continue in the future. This has lead to an understanding of a natural "thermostat" involving the Earth's atmosphere and lithosphere (rocky crust) which has maintained habitable conditions since the first life appeared. This is a further aspect of planetary development that bears further study, and we will return to this when we consider extra-terrestrial colonization.

Galaxies

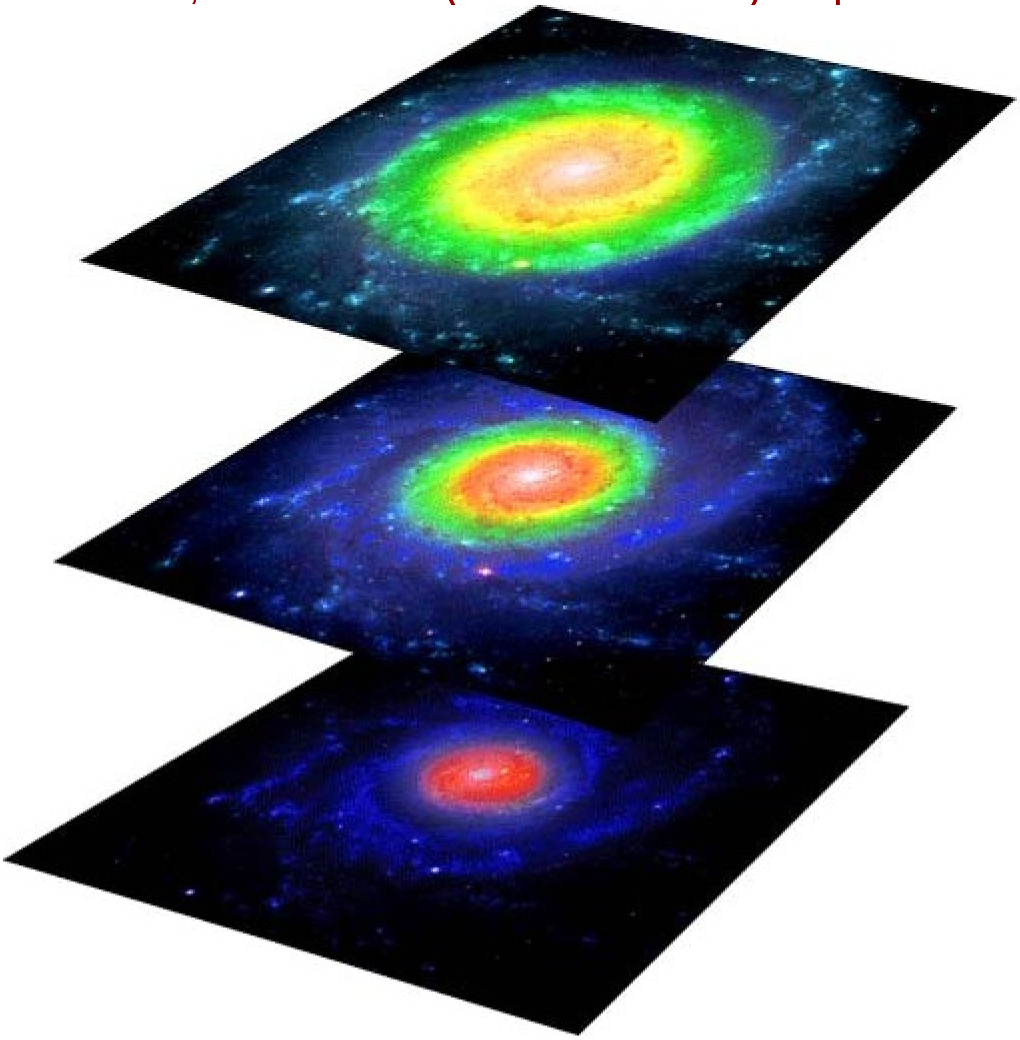
A similar range of considerations can be made with regard to habitable regions within galaxies. The basic assumptions are:

- Life requires elements heavier than hydrogen and helium, both to form living systems and to provide a host for those systems.
- Life will be destroyed by excessive quantities of high energy radiation, particularly X-rays, gamma rays and cosmic rays.

With these two assumptions and some knowledge of how galaxies form and evolve we can make broad predictions about where life can exist. The first thing to realize is that gas is concentrated towards the centres of galaxies, but the mass density is also increased in spiral arms or where two galaxies come together. Where mass density exceeds a critical value, stars and so planetary systems can form. The most massive stars rapidly become supernovae, which emit tremendous amounts of high energy radiation. Thus from this we can see that the regions with the most massive stars are most hostile to life.

On the other hand the massive stars are the factories in which the heavy elements required for life are created. Thus the most likely places for life to come into being are where massive stars have been in the past. We can combine these two facts to determine a **galactic habitable zone**. The shape and development of this zone will depend on the form of the galaxy and how it interacts with other galaxies. For a solitary galaxy Fig 1.2 illustrates the predicted development. As time goes on the habitable zone moves outwards. The inner regions are uninhabitable because of the excessive radiation from supernovae. The outer regions on the other hand are depleted in heavy elements because star formation is slow in these more rarified regions. In addition regions with a large fraction of heavy elements form a preponderance of gas giant planets (such as Jupiter and Saturn) which act to prevent the formation of rocky planets (such as the Earth).

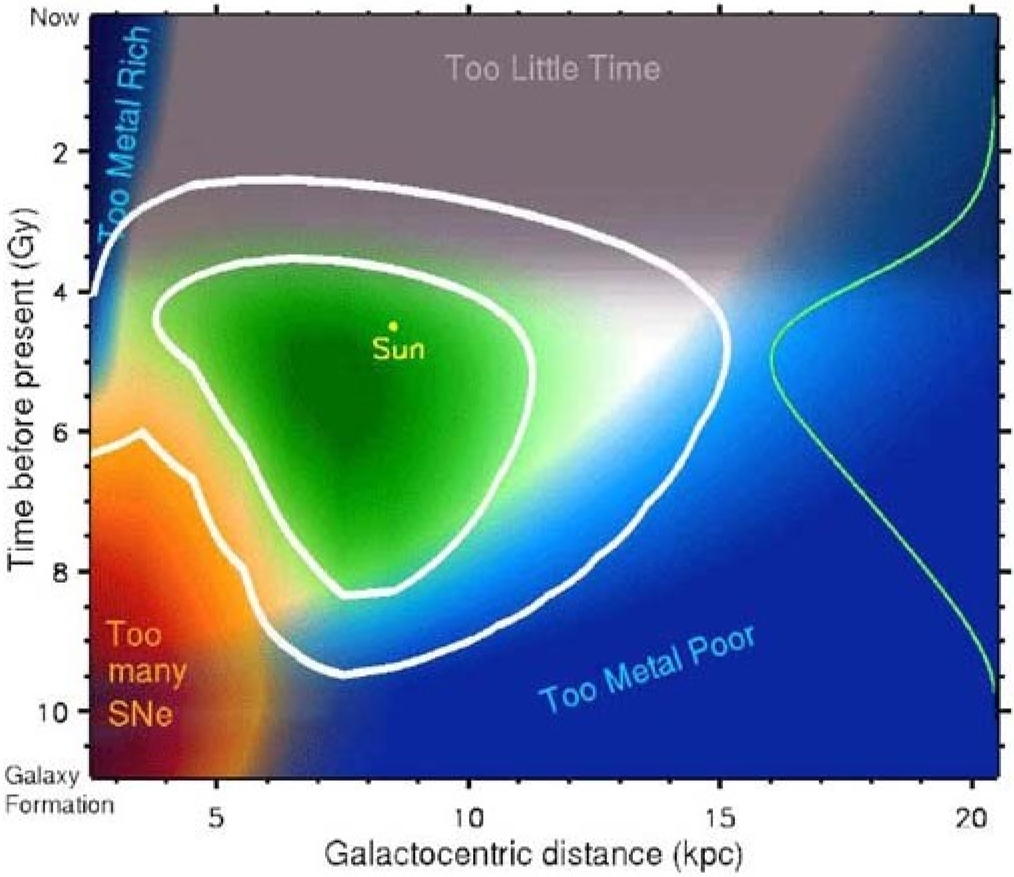
Figure 1.2. Development of a galaxy's habitable zone - earliest times at bottom, recent times at top. Green is habitable, blue are regions of insufficient heavy elements, red to orange excessive radiation. From Lineweaver, Fenner & Gibson (Science 2004 vol. 303) with permission.



In fact Fig 1.2 represents a much more complex model that can determine both the time period and position of the habitable zone. A more useful representation is shown in Fig 1.3, where we plot time before the present against distance from the galaxy centre and show by means of contours and colour coding the different regimes where life is more or less likely to be present.

At early times massive stars in the inner region render the region too hostile to support life, but the outer regions do not yet have the heavy elements to support life or planets. At intermediate times a balance is reached in a narrow band, where planets can form and the potential for life exists. At later times this band expands, the inner regions become relatively less hostile and the uninhabitable regions are pushed to the least dense outer reaches.

Figure 1.3. The change in habitability in time and distance from the galactic centre. Green are habitable, red and orange suffer too much radiation while other regions have the wrong fraction of heavy elements or have simply not had time to form planets or life. From Lineweaver, Fenner & Gibson (Science 2004 vol. 303).



One should realize that while these models made use of real quantities and applied a real physical understanding to the factors involved, our knowledge of the processes of planet formation and the development of life limits what we can conclude. The term we would use is that we have a **qualitative understanding** of what governs habitability in the Galaxy. However because that understanding is based on some very real physical processes, any improvements in our knowledge of the steps to life-bearing systems will immediately impact on where we can place the habitable zones in galaxies. Another way to put this is that we can calculate where planets such as the Earth could support life as we find on Earth, but we do not yet understand how likely it is that life will come into being in the first place.

The big questions

From this we can see that there are big questions we can ask that relate to the study of Astrobiology. These include:

1. How did the Universe and its contents form?
2. How has the Universe developed since its formation?
3. How do planets form?
4. How does life first begin?
5. How does life develop once it comes into existence?
6. What are the prospects for life in the Universe?

7. What impact might this have on the future of humanity?

As these are very big questions, this module cannot possibly answer them all. In the following Sections we will primarily address questions 4, 5 and 6 and touch on 7. The other questions are left for other modules.

Summary

- The Universe formed about 15 billion years ago in the big bang, creating hydrogen, helium and small amounts of lithium.
- The first stars were massive and short lived. They created the first heavier elements from which life would ultimately form.
- The stars around us, including the Sun, are from a later generation of star formation, and their lives were different from the first stars due to the presence of heavy elements.
- The heavy elements created in stars are required for the life that we know about.
- It is generally assumed that planets are necessary sites for the existence of life, at least of the more complex variety.
- Once heavy elements are formed through nucleosynthesis, chemistry becomes important in forming the basic molecules of life.
- No one has solved the question of how we go from basic atoms and molecules to biological systems.
- However it came into being, living systems have developed through biology using the basic building blocks of organic chemicals.
- When looking for life, we can define some basic parameters that guide our search. These are generally taken to be the presence of liquid water and the absence of damaging radiation.
- A combination of distance to the associated star and the form of planet's atmosphere allow us to define a habitable zone for any planetary system. This will develop as the star evolves.
- Taking into consideration damaging radiation from supernovae, and the need for heavier elements to form planets and life, we can define a galactic habitable zone. This also develops as the stars in the galaxy evolves.
- There are a number of poorly understood big questions that constrain our current understanding of Astrobiology.

Life on Earth

Section 2

We do not know how life on earth really began many billions of years ago. Of course there are a number of theories, ranging from the emergence of life forms from a primeval soup of chemicals, to the introduction of life forms onto the planet by alien beings, to the 'infection' of earth by 'seeds' or 'organisms' from outer space, to its creation by some Supreme Being. Whatever the answer is, it is unlikely that Earth is unique in the universe and probably other similar or perhaps quite different planets occur, where life exists.

To begin, we might just as well consider the characteristics and properties of living systems found on our planet earth, so that we can gain some understanding of the essential requirements and limitations of living systems. With this knowledge, we might then be able to extrapolate and predict how life might exist on other planets in the universe, and explore alternative theories and mechanisms of life emergence.

Living and Non-living Systems on Earth and the definition of 'Life'

Analysis of living systems reveals that they are highly complex collections of molecules, varying in structure and complexity. Similar collections of molecules can be assembled and placed in containers, but such collections do not show any life characteristics. The major difference between these living and non-living systems, is that living systems are highly organised – from the atoms used to make small precursor molecules, that are then used to make more complex and often larger molecules and macromolecules, which are then used to make organelles, and ultimately cells. The level of organisation may not end at the cellular level, as more complex living systems may organise groups of cells into a range of tissues, which are used to produce organs and organ systems, and finally these organs and organ systems produce highly complicated multicellular organisms.

There are a number of definitions of what we mean by 'life', and there is no single definition. However, it is widely accepted that living systems display a number of specific characteristics :-

1. **Have a complex structure and organisation** - living systems are usually organised into units called cells, which may exist as single cells or be organised in multicellular units. This organisation is determined by information stored in DNA molecules in the living systems.
2. **Exhibit growth and development** - living systems need to grow, either in the size of their component cells, or in the number of their component cells, or both. This growth characteristic may also involve development, whereby certain cells may adapt their structure to perform particular functions. Again this development is directed and controlled using information, usually stored in DNA.
3. **Need energy generated from metabolic reactions** - living systems require energy. This energy is obtained from metabolic reactions either by

releasing energy from molecules contained within the cell / organism or acquired from its surroundings or from energy available in its surroundings e.g. light. These metabolic reactions must be controlled so that the internal state of the cell / organism is relatively constant (**homeostasis**), regardless of the conditions outside the cell / organism. The living system uses this energy to maintain itself, grow, reproduce, and move around in its environment.

4. **Need to move in their environment** – living systems move when they interact with their surroundings. This movement or locomotion varies depending on the cell / organism, but can range from slow to fast movements, short to long distance movement, and even transitory movement depending on the life cycle of the organism.
5. **Respond and then adapt to changes in their environment** – living systems can detect changes in both their internal and external environments e.g. changes in temperature, light levels, the concentration of nutrients and various chemicals etc. In addition, they can then respond and adapt to these changes.
6. **Need to reproduce themselves** – living systems need to create new individuals, either genetically identical to itself by asexual reproduction, or new variations of itself resulting from sexual reproduction through the production of new combinations of genes (the information is stored in DNA) from two individuals (male and female organisms of the same species).
7. **Need to evolve and adapt to new environments** – living systems need to change with the passage of time, as their external environment changes. These are permanent changes in all or some aspects of their life style – in their structure, physiology or behaviour (or all three) which arise from permanent changes in the information content of its DNA, so that the resulting organism can adapt successfully to its new environment.

Whilst some of these descriptions of life and living systems appear to be quite clear, some of these characteristics could be applied to non-living systems. For example, a salt crystal can grow and reproduce itself under the correct conditions; a fire reproduces itself and consumes energy. On the other hand, some living organisms are unable to reproduce themselves e.g. naked mole rats or worker bees.

Life Forms on Earth

One of the fascinating observations of biological systems and organisms is its diversity. One theory is that from a proto-cell or protobiont formed around 4 billion years ago, a living cell arose and from then up to the present time, this living cell has evolved to produce the huge number of organisms that can be identified today. To date, about 1.5 million different organisms have been identified and characterised ranging from bacteria, to yeasts, to fungi, to animals and plants, and including humans. Some organisms do not exist on the planet today – e.g. dinosaurs, mammoths, sabre toothed tigers - and our only evidence that they existed, comes from fossilised remains. It is estimated that these 1.5 million organisms represent between 5 and 30 % of the total number of different organisms on earth, with new organisms appearing daily by evolution whilst others are passing into extinction.

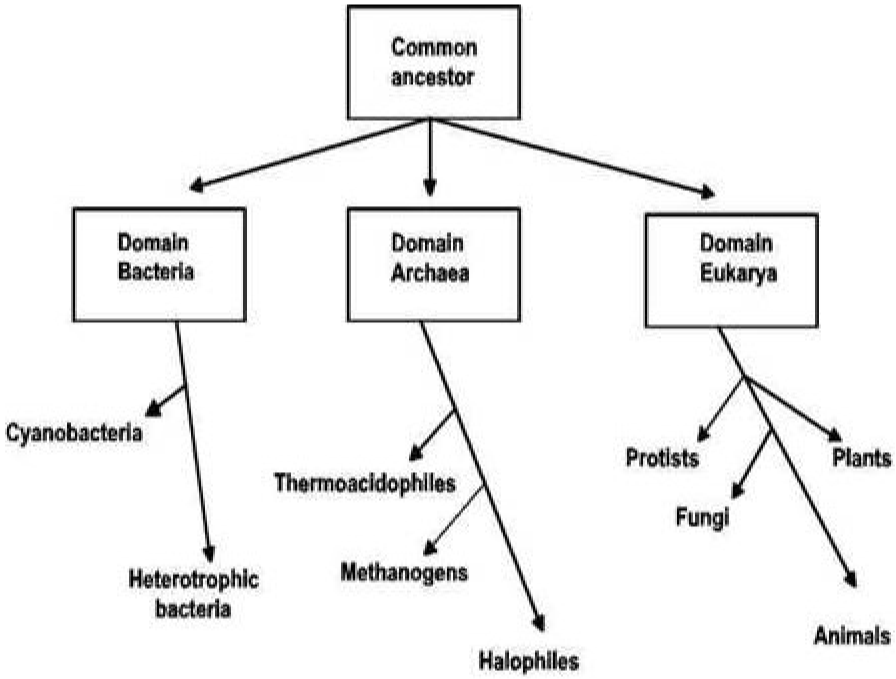
The huge number of different organisms characterised so far, has required the development of a classification system (called taxonomy), where organisms with similar or identical properties and characteristics are named, and grouped together. Such classification systems are divided into various levels (taxons) – domain, kingdom, phylum, class, order, family, genus and species, depending on the amount of detail used to group organisms together (see Table 2.1).

Table 2.1 Examples of prokaryotic and eukaryotic organisms

Example:	A human being - *Homo sapiens* a multicellular organism	A bacterium - *Escherichia coli* a single celled organism
Domain	Eukarya	Bacteria
Kingdom	Animalia	Procaryotae
Phylum	Chordata	Proteobacteria
Class	Mammalia	Gamma-Proteobacteria
Order	Primata	Enterobacteriales
Family	Hominidae	Enterobacteriaceae
Genus	*Homo*	*Escherichia*
Species	*H. sapiens*	*E. coli*

Originally this classification system divided organisms into five main groups or kingdoms (animals, plants, fungi, protista [e.g. protozoa, diatoms, algae] and bacteria). However, there seems to be a higher level of organisation, where these kingdoms are organised into 3 domains – Bacteria, Archaea and Eukarya (Figure 2.1). Two of these domains (Bacteria and Archaea) are prokaryotic, mainly single celled organisms that were once considered quite closely related and distinct from the other domain, the Eukarya, which are organisms with eukaryotic cells and range from single cells (protists) to multicellular fungi, plants and animals. From molecular evidence, it is clear that the Archaea share characteristics of organisms in both the Bacteria and Eukarya domains and thus are now considered as a separate domain of organisms. Organisms of the Domain Archaea live in extreme and biologically hostile environments on the planet today such as hot springs, thermal vents, salty lakes and sediments at the bottom of lakes and seas. Such archaeal organisms are thus called extremophiles (see Section 2.5) and are of particular interest to Astrobiology, as these extreme environments perhaps mimic or simulate the environment of the earth, just under 4 billion years ago where there is fossilised evidence for the existence of biological systems.

Figure 2.1. The organisation of living systems into domains

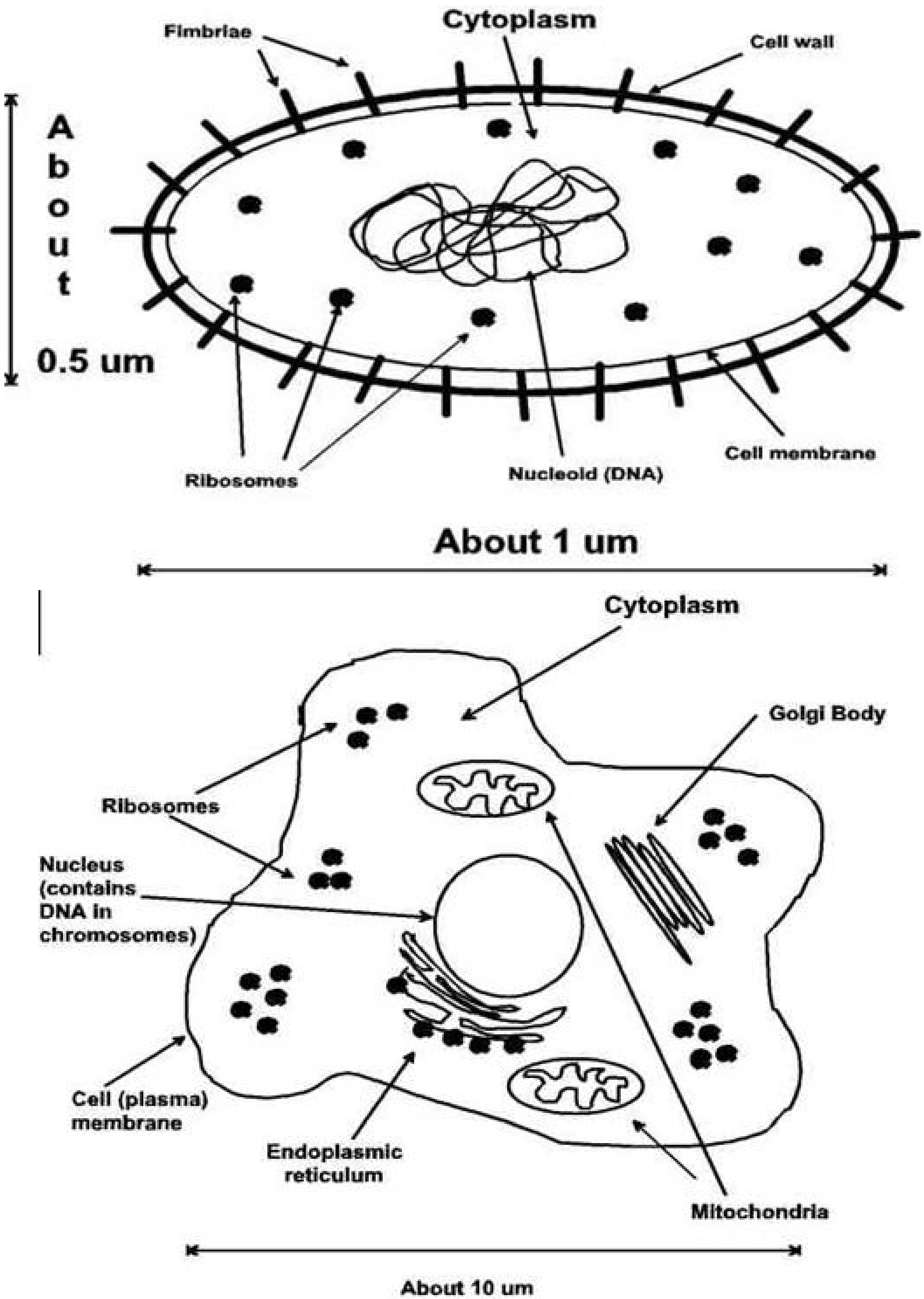


Prokaryotic and Eukaryotic Organisms

In the previous section, the terms prokaryotic and eukaryotic have been used. These are terms used to describe the general structure of the cell or cells of a particular organism. Hooke, in 1665, proposed that living systems were constructed of units called cells. Subsequent studies using microscopy showed that cells were membrane-enclosed structures with the membrane acting as a barrier to separate the cell (and its contents) from its surrounding environment. These microscopic studies have also revealed that there are basically two types of cell – prokaryotic and eukaryotic – depending on the structural features and components of the cell.

Organisms of the Bacteria and Archaea Domains are described as being prokaryotic, existing as rather small, single-celled structures and lacking any internal organisation within the cell body. Organisms of the Domain Eukarya (protists, fungi, plants and animals) are described as being eukaryotic, usually existing as much bigger cells, which have a number of intracellular membrane-bound components or organelles. These organelles have various names (and specific functions) such as a nucleus, mitochondria, a golgi body, and an endoplasmic reticulum. The simpler eukaryotic organisms (yeasts and protozoans) are single cells, but the vast majority of eukaryotic organisms (fungi, plants and animals), are multicellular in structure. Schematic diagrams of the basic features and differences in the structure of prokaryotic and eukaryotic cells can be found in Figure 2.2.

Figure 2.2. Schematic diagrams of prokaryotic (top) and eukaryotic (bottom) cells



These diagrams indicate the main differences between prokaryotic and eukaryotic organisms, and further details of the differences are listed in Table 2.2. The major difference is the **compartmentation** of eukaryotic cells through the use of membrane bound organelles, which are absent in prokaryotic cells. Indeed it is thought that mitochondria in eukaryotic cells and chloroplasts in plant cells may have arisen from the uptake and incorporation of precursor bacteria and cyanobacteria by certain ancient eukaryotic cells.

Table 2.2. Differences between prokaryotic and eukaryotic cells

Structural characteristic	Prokaryote	Eukaryote
Nucleus	None	Present
Chromosomes	Usually 1, circular	Usually more than 1, linear
Membrane-bound organelles	None	Many
Cell membrane	Yes	Yes
Cell wall	Yes	Yes – fungi Yes – plants No – animals
Ribosomes	Yes but 70 S*	Yes – 80 S*
Cell size	Most around 1 – 10 µm	Most around 10 – 100 µm
Method of cell division	Binary fission	Mitosis
Cytoskeleton	No	Yes
Membrane sterols		Yes
* The letter 'S' represents a 'Svedberg' unit which is a unit of size. Thus prokaryotic ribosomes are slightly smaller than eukaryotic ribosomes, but they still perform the same function – they are the sites of protein synthesis in the cell.		

The Environment of 'Early Earth'

The oldest rocks discovered on Earth so far are about **4 billion years old**, and were found in Greenland and Australia. Some of these rock samples are volcanic in origin, together with limestone and sandstone, suggesting that there was a considerable amount of water around when they formed, although the sedimentary rocks of this period (limestone and sandstone) do not seem to contain any fossils. The presence and formation of sedimentary rocks indicates that land masses had formed which were subject to weathering and erosion effects. This implies that liquid water and rain were present also, and predicts that the temperature of the planet was somewhere between 0 and 100 ^{o}C.

These findings and implications raise the question as to the origin of the water found on early Earth. The simplest explanation is that it was being captured from the environment (the early atmosphere and the planet's core materials) in the crystallisation and formation of various hydrated minerals of the planet. Whilst water could be sourced from outside Earth, for example from passing comets, this seems unlikely as the hydrogen – deuterium ratios of water from Earth, compared with that of comets, are quite different.

The composition of the early atmosphere can also be inferred from these early (or oldest) rocks and from the gases released from volcanoes. Such information reveals that iron pyrites (FeS) was present in large quantities in these earliest rocks and that nitrogen, carbon dioxide, water vapour and sulphur oxides were present in the atmosphere. There was probably only small amounts of oxygen present, arising from the breakdown of water under the influence of ultraviolet (UV) light arising from the Sun.

Overall the likely conditions existing on early Earth, do not seem to be the most favourable to allow life to begin and then adapt and modify itself. Indeed the early Earth environment would seem to be very harsh and extreme compared with

Exoplanets

Section 4

Exoplanets or extrasolar planets are planets outside our solar system orbiting other stars either in our galaxy the Milky Way or in remote galaxies external to our own. So far this course has focused on life that we have experience of and one of the key ingredients for developing and sustaining life is an environment. A logical starting point is to determine if the Earth is unique. The Solar System shows that there is at least one system that has terrestrial planets but are there others? Astronomers have speculated on this seriously for about 100 years, and been able to demonstrate the existence of other planetary system for just over a decade. Today, the ability to detect another Earth like planet is just beyond our reach. Within the next ten years we will be able to detect Earth like planets - but how many will we find?

Extrasolar planets or **exoplanets** are those that lie outside our Solar System, orbiting other stars. Over the last century we have learnt that the Milky Way galaxy contains approximately 10^{11} stars, and that there are a similar number of galaxies in the Universe, so it seems reasonable to assume that some of them might have one or more planets. Explicit in our discussion here, and the search for extra-terrestrial life to date, is the assumption that life requires a planet to act as host. Thus of even more interest is if, like the Earth, any exoplanets can support life.

This work is still new and only a few hundred exoplanets have been detected so far. The information we have suffers from a serious selection effect - only those exoplanets that are massive and show observable variations within the timescale of observations so far (approximately 10 years) have been discovered. To go beyond these parameters requires the development of new technology and techniques, and observations over a longer timescale.

A pre-History of Exoplanet Discovery

The first determined effort to look for a planetary system was made using Barnard's Star. Early in the 20th Century this star was noted to have an exceptionally high motion (called **proper motion**) across the sky. Calculations showed that Barnard's star would eventually pass within 3.8 light years ofour solar system and would provide an opportunity for astronomers to look directly at a second planetary system - but this would take about 10,000 years. Consequently astronomers have developed techniques and technology that can detect planets much sooner. **Van de Kamp** devoted a considerable part of his life initially to investigating the high proper motion but later on he examined small fluctuations in the position of the star. These were regular and he claimed they arose because of one or two large planets orbiting Barnard's star. This was announced to the world in the 1960s. It was not until the 1990s that this technique would be used to show that a distant star had a planet orbiting it and have the result independently confirmed. The existence of a planetary system around Barnard's star is still unconfirmed.

The first exoplanet was detected orbiting the pulsar PSR 1257+12 in 1992 using a **timing method**. Such an environment could not conceivably harbour life, at least as we have considered it in Sections 1 to 3. The first exoplanet in a system similar to that of the Sun was discovered in 1995 orbiting the star 51 Pegasi using a **radial velocity** method. Following these first detections exoplanets have been discovered at with increasing frequency. The first multiple planetary system was also detected in 1995 and in the same year the first **transit** of a planet was observed. These terms will be defined below as we look at techniques for detecting planets. Chapter 6 of *An Introduction to Astrobiology* provides an alternative description of the detection methods. The European Space Agency also provide a summary at http://www.esa.int/esaSC/SEMYZF9YFDD_index_0.html

Techniques for detecting Exoplanets

Until recently determining whether exoplanets existed has been beyond the capability of our technology. Within our Solar System planets have been identified by the fact that they move with respect to the stars. But we cannot simply point a telescope at a nearby star and count the planets as we would when observing the moons of Jupiter. So what are the problems?

Although there are many stars in the galaxy only a few are sufficiently close that an associated planetary system would have a large enough angular diameter on the sky that it could be easily resolved by the very best telescopes. The vast majority of extrasolar planetary systems are unresolved when seen through a telescope. The theoretical limit on resolving power was first given by Lord Rayleigh. The Rayleigh criterion specifies for a telescope of diameter, D, viewing an object at wavelength, λ that the angular resolution θ will be

$\theta = 1.22\ \lambda/D$ radians. Equation 4.1

Common measures of angle

Radians are a measure of angle such that a circle of 360° contains 2p radians. There are 60 arcminutes in one degree, and 60 arcseconds in an arcminute. Thus a degree contains 60×60 =3600 arcseconds, and so:

1 radian = 360×3600/2p = 206,264.8 arcseconds.

An arcsecond is thus $1/206{,}264.8 = 4.848\times10^{-6}$ radians.

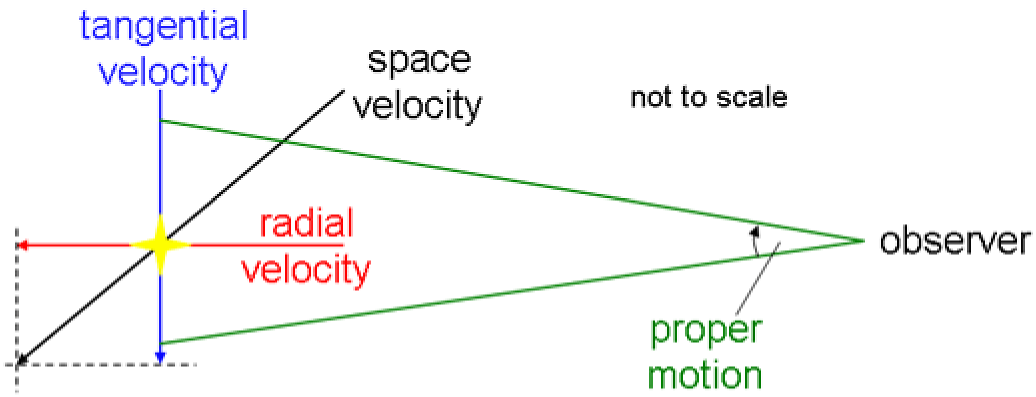
The smaller this angle θ, the finer the detail a telescope can distinguish. This can be made small by building telescopes with larger diameter apertures, and can be much better than 1 arcsecond for a large (ground based) telescope. However ground based telescopes have to see through the atmosphere which restricts all routine ground based observation to perhaps 0.7 arcseconds at best. This means that the maximum useful diameter is around 20 cm (at λ=550 nm, the middle of the optical range). While space-based or adaptive-optics systems can overcome this limitation in principle, planet discovery by direct imaging will remain a costly approach.

In addition to the difficulty in resolving a exoplanet from its host star, planets are not intrinsically very luminous the optical light. As in the Solar System, their optical light is dominated by that reflected from their host star. They are much fainter than the host star, making contrast a serious difficulty. So direct optical observations are extremely difficult. As planets have temperatures of a few hundred K, they emit most strongly in the infrared. Thus in this wavelength regime direct observations are more viable, but discovery remains costly in terms of observation time. As a result indirect methods have been used to detect exoplanets in significant numbers. In all cases they rely on detecting the effects of the planets' motion around the host stars.

Stellar motion

Before discussing two of the methods for detecting planets, we will describe the basic motion of a star in the local neighbourhood. Although most stars move round the galaxy in approximately circular orbits they show some statistical fluctuations relative to the average of the local group of stars. When observed from the Solar System all the nearby stars will have a velocity relative to the Solar System, its **space velocity** as illustrated in Figure 4.1.Three orthogonal components are required to describe the velocity. [Orthogonal means that each component is at right angles with the others.] It is convenient to use a spherical system based on the radial direction (line of sight) and the two dimensional coordinates on the plane of the sky. A velocity along the line of sight is known as the **radial velocity.** The component of the total velocity that is projected onto the plane of the sky results in the star's **proper motion** in two coordinates, and is measured in arcseconds per year. The proper motion can only be converted to a velocity when the distance to the star is known. As it is often difficult to measure distances there is usually considerable uncertainty in this **tangential velocity**.

Figure 4.1: Space velocity of a star and the relationship to radial velocity, proper motion and tangential velocity. Note that the radial velocity can be away from the observer for appropriate space velocities.



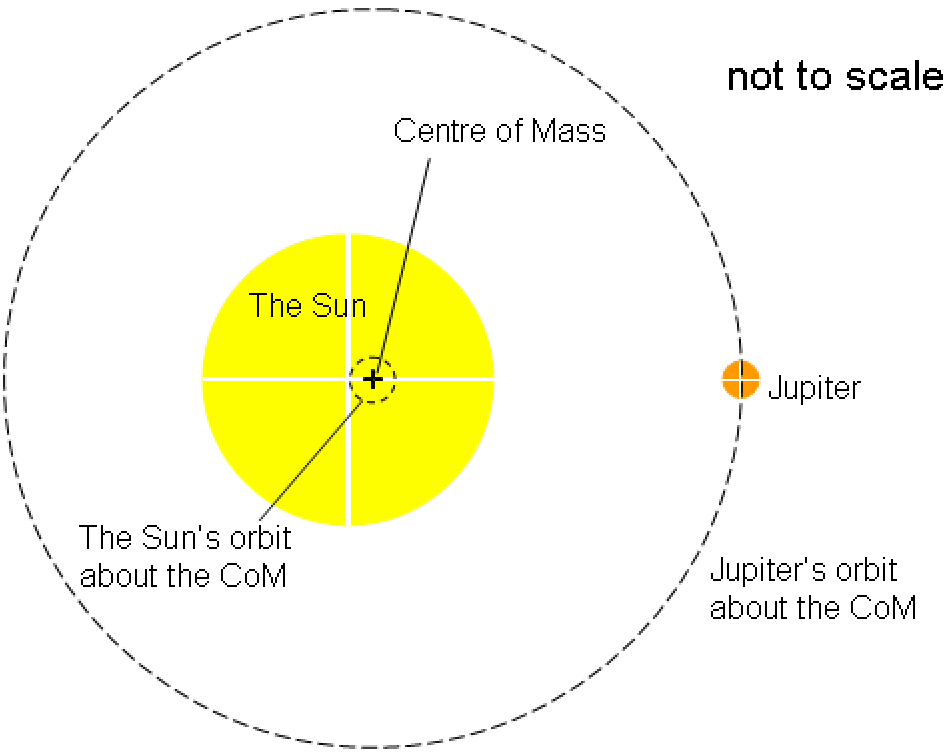
Radial Velocity Measurements

See Chapter 6.6.2 of *An Introduction to Astrobiology* for a discussion of this method. also described as Doppler spectroscopy. It relies on the effects of a planetary system on the observed motion of the host star. Using spectroscopy of the star we can measure periodic variations in the **radial velocity** and detect the presence of orbiting bodies.

This is by far the most commonly used technique and most of the extrasolar planets to date have been found using this method. An up-to date list is available in the Interactive Extra-solar Planets Catalogue (http://exoplanet.eu/catalog.php).

In the Solar System we tend to refer to the planets orbiting the Sun. In fact all the bodies, including the Sun, orbit about the **Centre of Mass** (CoM) of the Solar System (Figure 4.2). Because the Sun contains most of the mass, this point lies within our star, but offset from its centre. If a star has a planet or planetary system associated with it, then it will move slightly as its centre orbits the system's CoM. Observations are made of the central star's radial velocity and if periodic oscillations are detected then the existence of an orbiting object can be inferred. The larger the planet's mass, the larger is the effect on the host star and therefore the easier it is to discover a planet. But those with a long orbital period (and so lower orbital velocities) are more difficult to discover both because a longer length of time is required to make the measurements, and because the velocities to be determined are much lower.

Figure 4.2: The Sun and Jupiter orbit around their common Centre of Mass. The white "cross hairs" on each disc indicate the centre of each body, which will move along the orbit of each body. Note that in the real Solar System the presence other planets (especially Saturn) complicates this picture significantly.



As the Sun moves around its orbit, an observer outside the Solar System would see it periodically approaching and receding. Its radial velocity is changing due to the presence of the planets, with Jupiter being most important. From this we can see that the radial velocity of any star with planets will change as it orbits the Centre of Mass of the planetary system.

As an example let us consider Jupiter orbiting the Sun. Proceeding as if these are the only bodies in the system then from the definition of the Centre of Mass we can write:

$M_{Sun}r_{Sun} = M_J\, r_J$ Equation 4.2

where M_{Sun} is the mass of the sun (2×10^{30} kg) , M_J is the mass of Jupiter (about 2×10^{27} kg) and r_{Sun}, r_J are the orbital radii of each body about the CoM. (Strictly the orbital radius is the mean distance from the CoM, as all orbits in the Solar System are elliptical to a greater or lesser extent.)

The Sun is about 1000 times more massive than Jupiter so the size of the orbits are also in this ratio: $r_{Sun}=r_J/1000$. As Jupiter completes one orbit (about the centre of mass) every 12 years the Sun must also compete one orbit around the centre of mass in 12 years. So the velocity of the Sun about the CoM is:

$v_{Sun}=2pr_{Sun}/ P=2pr_J/1000P$

where P=12 years is the orbital period. Here we have taken the length of the orbit as equal to the circumference of the circle of radius r_{Sun} and divided it by the time the Sun takes to travel around that orbit.

Taking a_J from Table 3.1 (**Note:** The column heading Orbit in this Table should indicate km, not $\times10^6$ km), the velocity is then

$v_{Sun} = 2\ p \times7.7833\times10^8/(\ (12\times365.25\times24\times60\times60)\times1000) = 0.0129$ km s^{-1}.

Thus the apparent radial velocity of the Sun as measured from outside the Solar System will change by +/-0.0129 km s^{-1} over the course of 12 years. This gives us an idea of the sort of change we might expect in an extra-solar planetary system. If we can measure this change we can detect the presence of a planet. To do this we make use of two consequences of physics: Doppler shift and absorption lines.

Doppler shift

Doppler shift is the change in the wavelength of a wave, such as light, due to the motion of its source relative to the observer, as illustrated in Figure 4.3. An object travelling towards an observer will result in **blue-shifted** light as the waves are compressed; one travelling away will stretch the waves resulting in **red-shifted** light.

Human Factors

Section

9

Human factors influence space exploration in many ways, from our desire for adventure to our ability to cope with the physical and mental demands of space flight. This Section aims to give a brief introduction to some of the physiological and psychological considerations that need to be taken into account to ensure successful space missions.

Human factors research is currently in its infancy as there is limited data regarding how the body physically and mentally respond to long-term spaceflight. Further, until recently, consideration of the psychological consequences of space travel was not deemed a necessary area of study. By the end of this Section you should have a better understanding of how human factors can play a key role in the success or failure of a space mission. In the remaining Sections we look at human space flight and one logical consequence - the colonisation of space.

The human need to explore space

The pursuit of space exploration has occurred for many reasons and the resulting scientific research has had many positive benefits. For example, space research has been used effectively to promote science education within schools and helps to motivate children to engage in science subjects. In addition, the space industry has lead to the development of many products which we use in everyday life, such as TV satellite dishes, some medical imaging techniques, joystick controllers and even the materials to create invisible braces. Space exploration has led to improvements in international relations, with a reduction in East-West tensions occurring as a result of joint space missions being undertaken by Europe, USA, Japan and Russia. In addition, it may be that in the future the exploration of space will become economically motivated and we will be able to mine distant planets and asteroids for valuable resources.

Although there are many logical and practical reasons why the exploration of space may be attractive, the reasons listed above do not fully explain why so many individuals wish to travel in space. Space exploration is a high risk business, a significant number of disasters occurring throughout its history. From the early failure of the Russian Soyuz 1 mission to tragedies of the Challenger and Colombia disasters, the potential dangers of the space environment are highlighted. In addition, any individual who wishes to become an astronaut has to undergo extensive periods of training without any guarantee that they will be chosen for a mission. However, many people still apply to become an astronaut.

Some researchers have speculated that we have an innate biological drive to explore and that this has been part of human nature since the beginnings of the human race. Indeed human civilisations have a long tradition of exploring from the Polynesians, to the Romans and the Norseman, right up to the present day with the exploration of the Polar Regions, deep sea habitats, jungles and deserts. Some have argued that exploration of space is linked with the species' drive to survive. It could be that in the future, we are forced to move from Earth to live amongst the stars.

Selection criteria for astronauts

Throughout human history there have been individuals who have been drawn by the excitement of exploration. It seems that for some people adventure, even if dangerous, is attractive. In 1914 Ernest Shackleton (www.south-pole.com/p0000097.htm) needed to recruit men for his Nimrod expedition, which aimed to reach the South Pole. It is claimed that he recruited his crew by placing an advert in a London newspaper (although exact details concerning the original advert have since been lost). The advert is said to have read as follows:

> "Men wanted for hazardous journey. Low wages, bitter cold, long hours of complete darkness. Safe return doubtful. Honour and recognition in event of success."

Shackleton received 5,000 applications, which he divided into three piles labelled, ‘Mad’, ‘Hopeless’ and ‘Possible’. He then set about selecting his crew on a basis of a number of selection criteria including optimism, patience, physical endurance, idealism and courage. Shackleton’s mission to get to the South Pole failed by 97 nautical miles but on his return to England he was hailed as a hero and knighted. Of his failure to reach the South Pole, Shackleton remarked: "Better a live donkey than a dead lion."

When the European Space Agency last advertised for trainee astronauts, they received over 22,000 applications from which nine astronauts were selected. The European Space Agency (ESA) (www.esa.int/esaHS/ESA1RMGBCLC_astronauts_0.html) and NASA (www.nasajobs.nasa.gov/astronauts/content/broch00.htm) have a very robust astronaut selection procedure. In addition to having extensive military pilot training or an advanced scientific background, all candidates need to be physically fit. After the initial selection process, NASA requires all potential astronauts to undertake a one to two year training course which also acts as an ongoing evaluation of their suitability to under take missions in space.

The need to advance research in the area of psychological screening for astronaut selection was highlighted in February 2007 when NASA astronaut, Lisa Nowak was charged with the attempted murder of her love rival, Colleen Shipman. It is alleged that just six months after a successful space shuttle flight, Nowak drove halfway across America and sprayed pepper spray in the face of Shipman. In a statement Michael Griffin (NASA Administrator) stated that "she is in major trouble, and clearly we failed as an institution to recognize that she was very troubled." The fact that NASA failed to recognise that Lisa Nowak had psychological health problems is quite worrying. Nowak had recently been a crew member onboard the Utilization and Logistics Flight 1.1 shuttle mission to take supplies to the Space Station. If these mental health problems had become apparent during the mission they could have had serious implications for mission success.

The Right Stuff

It is only recently that detailed psychological screening has been included in the astronaut selection procedure (Santy 1994). In the past, astronauts, such as those selected for the Mercury mission (Figure 9.1), were chosen on the assumption that it was possible to spot the **'right stuff'** in a candidate. In the case of the Mercury astronauts this meant that all seven had a military background. However, there is a

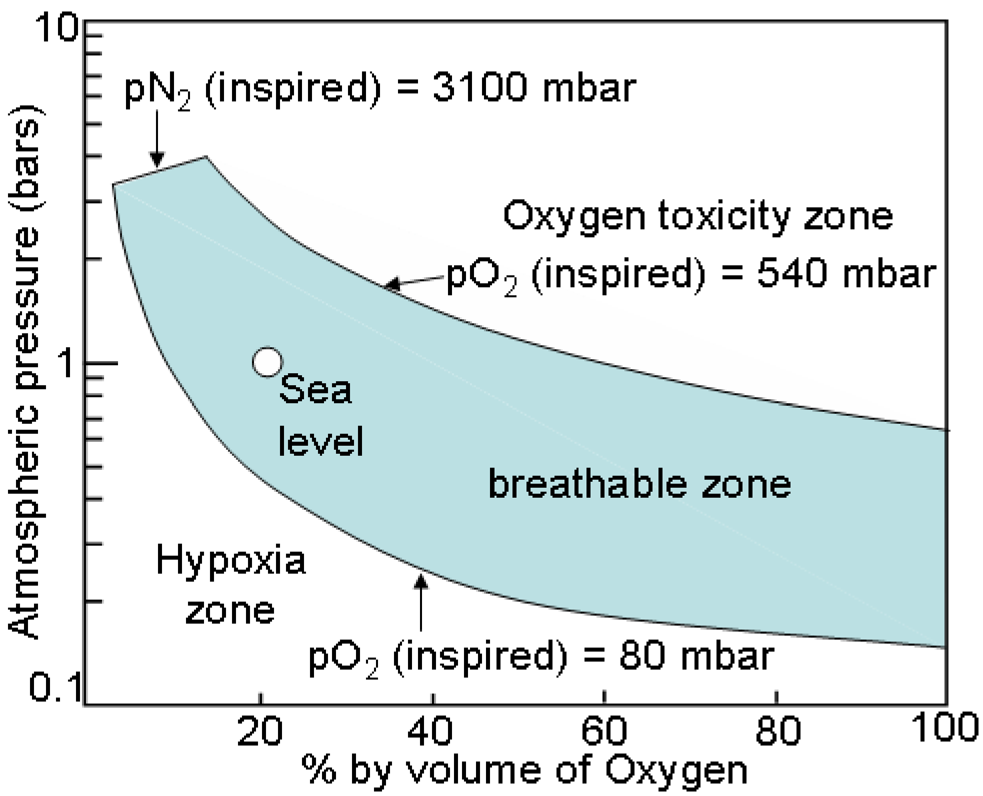
Skylab cabin contained 70% oxygen and 30% nitrogen at a pressure of 3.8×10^4 Pa, the low pressure making it easier to maintain the atmosphere over long periods. The Space Shuttle is designed to operate at 1.01×10^5 Pa with 80% nitrogen and 20% oxygen, the normal Earth surface mix and pressure.

Partial pressure

The pressure of a gas is determined by the combined random motions of its constituent particles. Where a gas consists of different atoms or molecules, each type (species) contributes according to the fraction of the particles it contributes. This is equivalent to the fraction by volume. The part of the pressure a given species contributes is its partial pressure, and it is this that determines how that species interacts with its surroundings in settings where the pressure is important, such as respiration.

It is worth taking a moment to look at the effects of different atmospheric compositions. In Figure 10.2, where the oxygen content is indicated as a fraction of the total atmospheric pressure. Most people do not realise that oxygen is toxic in certain concentrations.

Figure 10.2. Breathability of atmospheres as a function of total pressure, oxygen fraction and the inspiration of nitrogen. This assumes the non-oxygen fraction is nitrogen. 1000 mbar = 1 bar.



We can see that Figure 10.2 indicates fractions of oxygen content that would kill oxygen-breathing terrestrial life. Conversely below certain levels hypoxia is encountered, which is why climbing high mountains is difficult without breathing equipment. At high pressures and low oxygen fraction nitrogen can forced into the blood stream, effectively causing nitrogen narcosis (the bends) as experienced by

Colonising Space - Terraforming

Section 11

Terraforming is the transformation of a planetary environment into one that can support human life in a manner comparable to Earth. Research into the changing of planetary environments can be divided into the ecocentric and the technocentric. The former avoids large-scale engineering solutions, and are often content with life-bearing planets; the latter advocates large-scale technological intervention to create autonomous human-supporting systems. The required changes to reach this terraformed state are fairly well understood. The basic aim of terraforming is to create an uncontained biosphere.

When considering the potential for life beyond the Earth, we looked to our terrestrial experience to guide us. While there is potential for life to be derived from fundamentally different processes to those seen on Earth, it is extremely hard to construct an alternative structure to support life. When we looked at planets that might bear life, much the same considerations guided our arguments about where life could be found, and what form it would take. In this section we will be looking at how humanity might colonise space, again examining the Earth to understand what might be required. We will look at **terraforming**, or the changing of existing planets to support life in the way Earth does today.

Definitions

As ever with any subject, there are specialist terminologies that need to be specified. In a speculative area such as this those very definitions are often open to discussion and argument. The following terms are broadly but not universally accepted.

Terraforming
: A process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life. The ultimate in terraforming would be to create an uncontained planetary biosphere emulating all the functions of the biosphere of the Earth — one that would be fully habitable for human beings.

Ecopoiesis
: The fabrication of an uncontained, anaerobic biosphere on the surface of a planet. As such, it can represent an end in itself or be the initial stage in a more lengthy process of terraforming. (The original invention of this term actually encompassed something broader than terraforming, to include any modified planetary environment to support life.)

More controversially some writers have extended the definition of either or both of these terms to include the generation of a life-supporting planet by natural means, whatever they may be. For the purposes of this module, the definitions above are assumed.

Philosophy

Following on from the controversy over basic definitions, approaches to terraforming can be divided into one of two camps. They are broadly related to the degree of change of the initial (or natural) environment of the planet being terraformed, although they also have political and economic aspects. They are:

Ecocentric
: Aiming to create ecospheres without specific utility for humans. This is a limited form of ecopoiesis. James Lovelock (who proposed the Gaia theory) is a proponent of this approach. An extreme form of the ecocentric view is to avoid any change in natural environments. Necessarily the ecocentric approach rejects high-energy technical solutions (engineering).

Technocentric
: Aiming to create ecospheres specifically to support human life. This essentially means technological intervention, and implies the destruction of existing planetary environments in the pursuit of living space for people. Robert Zubrin is a proponent of this approach.

Required conditions

As we saw in Section 2 there is a wide range of conditions under which life can exist. A more restricted range is necessary for humans and similar animals. These are summarised in Table 11.1.

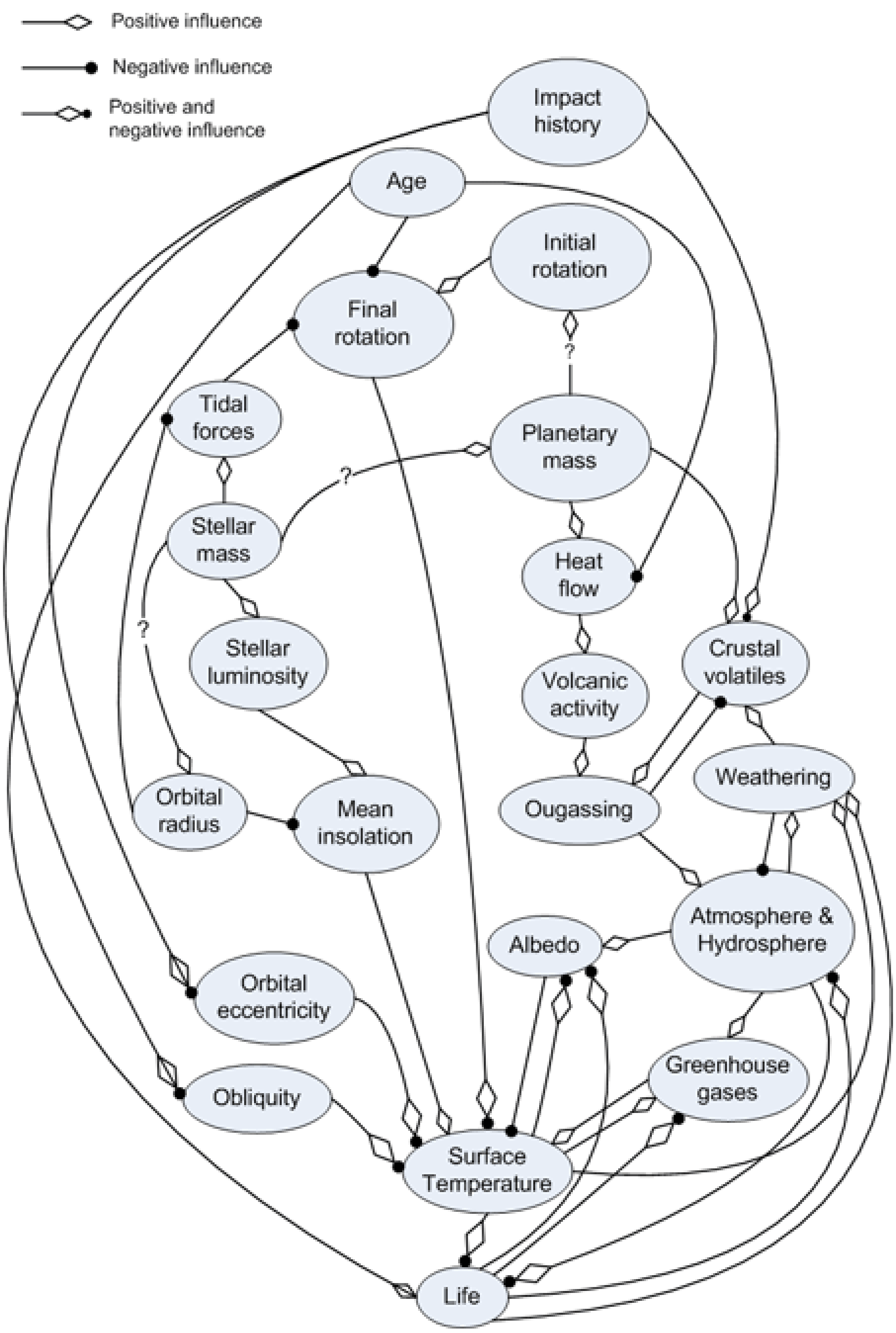
Table 11.1 Range of conditions required for the support of terrestrial life.

Feature	Range of conditions	Life
Temperature	-20°C to 40°C	humans & other animals
Pressure	10 mbar to 3700 mbar	plant life
	140 mbar to 3700 mbar	humans & other animals
O_2 partial pressure	80 mbar to 540 mbar	limits of hypoxia and toxicity
Gravity	unknown	extremes will affect multi-cell organisms
Photosynthesis	more than 6×10^{17} photons m^{-2} s^{-1}	for shade-adapted plants
UV radiation	wavelengths below 300 nm	multi-cellular organisms suffer radiation damage
Ionising radiation	as low as possible	
Water	liquid, stable and abundant	required by multi-cellular organisms
Salinity	less than 0.1% NaCL	for most life
acidity	pH between 5 and 9	most plants
minerals	accessible selenium, copper, molybdenum, iodine, zinc, nickel	trace elements needed for many life forms

These limits interact, as illustrated for oxygen and nitrogen in Figure 10.2, where the oxygen content is indicated as a fraction of the total atmospheric pressure. For example Figure 10.2 indicates fractions of oxygen content that would kill oxygen-breathing terrestrial life.

In addition there are a lot of other factors with an indirect influence on the ability of a planet to support life. These are summarised in Figure 11.1.

Figure 11.1. Factors with an impact on a planet's ability to support life. Large version available online.



As we saw in Section 3 the Earth has suffered extensive bombardment by asteroids and comets in the past - it has an **impact history**. If we ever travel beyond our Solar System we would want to understand what stage in the local impact history a potential inhabitable exoplanet is at. More immediately, impact history in part defines the inventory of elements available on planets and satellites in the Solar System. This constrains the utility of industrial processes, the