The evolution of life on Earth

http://sgoodwin.staff.shef.ac.uk/phy229.html
10.0 Introduction

A combination of the fossil record, biology and genetics allows us to examine the evolution of life on Earth.

The origin of life is controversial and uncertain, but its evolution once on the Earth is reasonably-ish understood.

Two obviously critical questions in astrobiology are:

How common is the appearance of life on planets?

How does life then evolve if present? (And how long does this take?)
10.1 The origin of life

The origin of life is highly controversial, however there are two fairly robust statements we can make:

- Life probably appeared on Earth between >3.5 billion years ago. It might have appeared before or after the late heavy bombardment period (or delivered/promoted by it?).

- All Terrestrial life uses the same basic biochemistry: the same basic set of 20 amino acids, the same nucleic acid bases, molecules with the same chirality, and very often the same biochemical pathways. This probably means that all life on Earth had a single common ancestor (or there is only one way for life to work, and it was independently invented several times).
10.1 The origin of life

It is most often assumed that life formed on the Earth. I.e. It was on the Earth that non-living chemical systems developed and mixed and became ‘living’ systems.

It is possible that life on Earth came from elsewhere (panspermia).

This could be from elsewhere in our Solar System (Mars? Comets?), or delivered from outside the Solar System.

We have no evidence for life being delivered to the Earth, and it just pushes the problem of the origin of life back one stage, so we will assume life formed on the Earth.

(Panspermia ideas run the gambit of perfectly reasonable to slightly insane.)
10.1 The Miller-Urey Experiment

Life on Earth is based around complex organic molecules. In 1953 Miller & Urey set-up an experiment to simulate the conditions on a pre-biotic Earth. They passed electric sparks (to simulate lightning) through a mixture of $\text{CH}_4$, $\text{NH}_3$, and $\text{H}_2$. They showed that basic organic molecules such as amino acids are easily formed. However, the mixture of gasses they used is highly unlikely to represent the atmosphere of the young Earth (which was probably dominated by relatively inert $\text{CO}_2$).

But, the consensus is that simple organic molecules are fairly easy to form, and many are found in the ISM and meteorites.
10.1 The origin of life

There are many theories about the origin of life. Most centre around the Oparin-Haldane hypothesis (the 'primordial soup') which (very simply) says:

A plentiful supply of simple organic molecules was present in the early oceans with a plentiful supply of energy (Solar, tidal, volcanic). Chemical reactions then give rise to increasingly complex molecules and eventually to simple self-reproducing systems.

Recently it has been proposed that deep-sea volcanic hydrothermal vents in particular provide the idea conditions (energy and many chemicals) for life to develop.
10.2 The RNA world

But how did the first life get going? (The ultimate chicken and egg problem.)

In living organisms nucleic acids are only synthesised in the presence of proteins, and proteins are synthesised only if their corresponding nucleotide sequence is present. How could such a system have begun?

A reasonable hypothesis is a precursor 'RNA world' where RNA was the first 'life' to appear and was able to synthesise proteins itself, and replicate without the use of proteins (things that it does not do now, presumably as using proteins is far more efficient and/or successful).
10.3 The first life

During the proterozoic the first life appeared on Earth. The first life on earth was probably a bacteria – a prokaryotic organism the first good evidence for which is found \( \sim 3500-3900 \) mya. This life probably gained its energy by a \( \text{CO}_2 \) fermentation process.

The first significant organisms were probably cyanobacteria which were abundant \( \sim 3000 \) mya which were able to produce energy through photosynthesis.

Cyanobacteria are probably the origin of chloroplasts in eukaryotic cells.
The ‘Great Oxygenation Event’ (or ‘Oxygen Catastrophe’).

Oxygen was presumably created from very early times (almost certainly in the Archean), but could not accumulate in the atmosphere until oxidising sinks (mainly unoxidised sulfur and iron) were full which appears to have occurred ~2500 - 2100 mya during the early protorozoic (evidence for this is in the form of 'red beds' of oxidised iron).

This is known as the oxygen catastrophe because the large quantities of free oxygen were poisonous to the anaerobic organisms living on the Earth, and oxygen also removed many nutrients (such as iron) from the oceans through oxidisation.
10.5 The rise of the Eukaryotes

Eukaryotes appear at the same time as the oxygenation of the atmosphere and it maybe that the two events are linked. Eukaryotes appear to have evolved ~2100 mya.

Eukaryotes contain organelles unlike prokaryotes – in particular they can contain chloroplasts and mitochondria.

Both of these organelles have their own DNA and it has been suggested that they were once free-living prokaryotic cells (the endosymbiotic theory). It may be that these prokaryotic cells survived the oxygen catastrophe by this symbiosis.

Sexual reproduction appears about 1200 mya.
10.5 The rise of the Eukaryotes

Sexual reproduction appears about 1200 mya in the first (very small) multicellular eukaryotes.

Asexual reproduction makes a copy with only occasional differences in genes due to copying errors (or horizontal gene transfer). Evolution is therefore very slow, usually requiring a very lucky advantageous error (most will be disadvantageous).

In sexual reproduction the genes of two slightly different individuals are mixed to create a new mixture of genes. Sex has many disadvantages, but ‘speeding-up’ evolution and adaptation seems to be its major advantage.
10.6 Multicellular organisms

The earliest known multicellular fossils are \(~1200\) mya, but they are fairly simple. The development of multicellular life is a vital step forward in the evolution of life. The ability of eukaryotic cells to specialise was vital for multicellular life to develop.

Theories for the development of multicellular organisms include:
- **Symbiosis** (cells with different specialities becoming interdependent),
- **Cellularisation** (specialist structures within a cell becoming separate cells),
- **Colonial theory** (cells failing to separate after division and then specialising).
The Cambrian Explosion is the sudden appearance, over only ~10 my, in the fossil record of a huge diversity of new organisms ~545 mya.

The Cambrian explosion saw body size increase from ~mm size to many cm, the appearance of biomineralisation (skeletons, including shells and exoskeletons), and the appearance of animals.

Skeletons are particular important as they allow muscle attachment for locomotion (a feature of animals) and protection.

The atmosphere appears to have increased in oxygen content at about this time (from ~1% to ~15%).

The proterozoic/phanerozoic transition is also marked by fluctuations in \(^{32}\text{S}/^{34}\text{S}\) and \(^{13}\text{C}/^{12}\text{C}\) isotope ratios suggesting that some significant event changed the uptake of these chemicals in biogeochemical cycles to change.
10.7 Prerequisites...

The development of large body sizes: this development must have been in place, but was it already in place or did it develop at the Cambrian explosion?

To have a large body (>1 mm) an organism requires efficient circulatory, respiratory and excretory systems (as surface exchange becomes too inefficient).

These require cellular differentiation which means each cell only `expresses' a subset of its genome. Also cells need to know where they are and what they should be (using hox genes, chemical signalling, and other methods).
10.7 Biological causes?

- **The development of biomineralisation**: the ability to include minerals in cells to form hard body parts may have been an evolutionary advance (also requiring significant amounts of oxygen) that developed at this time. This allowed large organisms, and animals to develop.

- **Predation**: the evolution of predators made hard body parts an advantage, allowing protection (armour or burrowing) or faster escape (locomotion).

- **Developmental**: changes in early embryonic development (via hox genes) could cause body shapes to change significantly (but why so much at once?).
10.7 Environmental causes?

• **Oxygen reaching a critical threshold**: without oxygen organisms have great difficulty precipitating minerals to form skeletons. In addition organisms which intake oxygen by direct absorption reduce this intake if they have a shell. Oxygen levels seem to have risen significantly at the end of snowball Earth.

• **The availability of nutrients**: the break-up of a supercontinent at the end of the proterozoic may have uplifted large quantities of inorganic nutrients (especially phosphorite) from deep sea sediments.

• **New ecological niches**: the break-up of the supercontinent will also have increased the number of shallow sea and continental shelf habitats available to life.

• **The end of 'snowball earth'**: the end of an extreme glaciation will have opened new habitats to those organisms that survived (possibly favouring those with hard shells more able to withstand the cold?).
10.7 The importance of the Cambrian explosion

In astrobiology the Cambrian explosion is extremely important. It was the (rapid!) transition from small, simple organisms to large, specialised organisms (especially animals and plants).

The crucial question is: was the Cambrian explosion a natural result of a few billion years of evolution to be expected everywhere life develops, or did it have a special (environmental?) cause unique to the Earth?

In the answer to this lies the probability of finding other advanced life and intelligent alien civilisations...
The post-Cambrian explosion period is characterised by a long-term increase in biodiversity. Major events: 360 mya plants evolve seeds and colonise land, 300 mya colonisation of the land by animals, 250 mya PT mass extinction kills ~90% of species.
Summary

3900-3500 mya The origin of life is unclear, however a few 100 Myr after the end of the heavy bombardment period evidence for life appears.

3000 mya photosynthesising cyanobacteria evolve and start to produce free oxygen.

2500 mya significant amounts of oxygen accumulate in the atmosphere and some bacteria evolve aerobic respiration.

2100 mya the first eukaryotes appear

1200 - 1000 mya the first small multicellular organisms appear (which reproduce sexually, which developed around 200 my before).
Summary

750-580 mya Snowball Earth? Only tropical oceans are free of ice?

545-535? mya The Cambrian Explosion and the development of animals.

360 mya Planets colonise the land after the evolution of seeds.

300 mya Animals begin to colonise the land (at this time the supercontinent of Pangea).

65 mya the KT mass extinction kills most dinosaurs.

3 mya the first bipedal ancestors of humans appear.

50-10 kya Technological civilisation develops
Key questions

Was the early appearance of life on Earth typical? Does life always/normally/sometimes/rarely appear this quickly?

Is it a problem if life takes a while to appear?

Once life was established is our evolution a typical pathway? What other ways are there of doing it?

Was evolution on Earth fast, slow or about typical?

Does evolution have any ‘bottle necks’? E.g. are there any single points that are difficult (and so rare to get past)?