A JOURNEY THROUGH TIME

From the Creation of Galaxies to the Birth of Civilisation

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Introduction

This summary is intended to provide a brief and general outline of how the universe, the planets, and life and environment on Earth evolved. Much of the material in this summary is supported by practical observations, investigation, measurements and experiments, rather than by theory alone.

Section 1 The Known Universe

Note that moon with a capital 'M' and galaxy with a capital 'G' refer to Earth's Moon and our Galaxy (the Milky Way) respectively.

1.1 Measuring the Cosmos

Triangulation is the most basic method for measuring the distance of astronomical bodies from Earth. Using the diameter of the Earth's orbit as a baseline, their distance, up to about 200 light years (l.y), can be measured with good accuracy. Astronomers take bearings on a star six months apart. The distance of the star can be calculated from the change in the star's bearing when seen from each end of the baseline; this is termed parallax. Accuracy is limited by atmospheric distortion, and the increasingly miniscule angles involved with greater distance.

In 1912, Henrietta Leavitt was observing variable stars known as Cepheids and noticed that the longer the period, the greater the luminosity (the energy radiated from a star) peak. As all these stars were of the same system (one of our small satellite galaxies) they would all be at about the same distance. Therefore, if one knew the actual distance to some Capheids, one could determine the relationship between luminosity and period to determine the distance to any stellar system containing a Cepheid with fair accuracy. All stars are variable to a point; the Sun's luminosity varies by 0.1% with an 11 year period, but Cepheids vary far more with periods between 1 and 100 days. In 1918, Harlow Shapley determined the distances to some distant Galactic clusters containing Cepheids and calculated the luminosity of the Cepheids. From this he was able to determine the diameter of our Galaxy and the distance of the Sun from the galactic centre.

The Cepheid yardstick currently applies to galaxies up to about 100 million l.y away, using the Hubble Space Telescope (HST) augmented by image processing. Astronomers study star clusters in more distant galaxies and estimate the distance by assuming the brightest stars in the cluster have the same luminosity as the brightest stars in the Galaxy. The distances to galaxies that are too far away for even the brightest stars to be resolved are estimated by assuming that the brightest galaxies in a galactic cluster are as bright as the brightest galaxies in our own cluster. Supernovae, which can rival the brightness of a galaxy's entire core, can be used in a similar manner to determine the distance to remote galaxies.

In 1816, Joseph von Fraunhofer noticed that refracted spectra of light exhibited series of dark lines whose positions were different for light sources of different chemical composition. Around 1880, William Huggins found that these Fraunhofer lines were the fingerprints of the chemical elements. He discovered that the spectrum from the Sun was the same as that from a star when he compared them. Both had Fraunhofer lines for hydrogen and helium, thus showing that the Sun and the star had a similar composition.

Christian Doppler discovered that reflacted light from a pair of stars believed to share the same orbit showed that the lines shifted towards the blue end of the spectrum for the approaching star of the pair, and was red-shifted for the other as it moved away. He determined that the further the Fraunhofer lines were shifted, the faster a star was moving. Thus he could determine both speed and direction of travel of light sources in the night sky. The redshift of luminous bodies can be measured accurately from about 300 million l.y away.

Edwin Hubble discovered some Cepheids in the Andromeda galaxy, and, using the Leavitt-Shepley yardstick discovered that it was not a nebula within the Galaxy but was a separate galaxy. During the 1920's he announced that the Universe was not static, but was expanding. Having analysed the spectra from a number of distant galaxies he found the light from them all was red-shifted, and thus were moving away from us. His observations showed that everything at a given distance from Earth was moving at the same speed, and the greater the distance the greater the speed. He produced an equation expressing this relationship, Hubble's Law, which worked every time data was gathered from a new galaxy.

With distances and speeds calculated or estimated by the above methods, estimates of the rate of expansion of the Universe, known as Hubble's constant, can be made. According to current measurements the Universe is expanding at a speed which increases by roughly 21.5 km/s per million l.y of distance. Using this figure for Hubble's constant the approximate time elapsed since the Big Bang can be calculated, giving a result of some 14 billion years.

Closer to home, very precise measurements to nearby solid bodies, such as the Moon and inner planets, can be made by radar. Radar has also been used to map the surface features of Venus, which are obscured by its thick atmosphere. Even more precise measurements can be made with lasers, but they require a reflecting surface. A mirror was placed on the Moon during the first manned lunar landing for distance measurements using a laser.

1.2 The Big Bang and Galactic Formation

The Universe is believed to have begun with an immense explosion known as the Big Bang, producing superhot energy which in turn produced exotic particles. After some minutes the emerging Universe had cooled down sufficiently for photons and neutrons to develop. After about 300,000 years it had cooled to about 3,000 ^{O} C; protons and neutrons could link up with electrons to form the first atoms - roughly 80% hydrogen, 15% helium and some other light elements. At that stage the Universe changed from a luminous fog and became transparent; light and other forms of radiation could freely travel through it. That light still permeates the Universe, but is redshifted down in frequency by the cosmic expansion into microwave radiation, which is detectable by microwave receivers. This radiation is spread evenly wherever the detector is aimed, by the general dynamic expansion of the Universe. Any other radiation generated after the Big Bang would have a specific starting point within the Universe, so it would move outwards from that point only.

The Big Bang model is supported by observations, measurements and theoretical studies. The Universe appears the same in every direction from every point in space in a general sense; thus Earth's position in space is in no way preferred. The fact that the Universe is expanding about every point in space can be illustrated by an expanding balloon in that the distance between all adjacent points increases as the balloon inflates.

The primeval atoms of hydrogen, helium, etc, began to be accreted by gravity into huge clouds. About 400 million years after the Big Bang the particles became so compressed and hot that hydrogen atoms began to fuse, stars began to form and the first galaxies began to take shape.

The expansion of the Universe has now cooled the radiation from the Big Bang to -270 ^{O} C. Although almost uniform across the known Universe, there are very slight differences in its temperature from place to place which were first detected by the Cosmic Background Explorer (COBE) satellite in 1989. After the satellite data was thoroughly checked, George Smoot found these temperature differences in a computer-generated map of the early Universe. The difference, about 0.001 ^{O} C, results from variations in density of gas from the Big Bang explosion, the denser regions being warmer than average and the less dense areas cooler than average. More particles could evolve in the warmer regions as these have more energy. This would allow gravity to draw the denser groups of particles together into tighter and denser clumps, which would attract particles from the cooler areas. As they were emptied of particles, the cooler regions would become the voids between galaxies and the hotter areas would become the first galaxies.

There is a boundary in space-time which space probes cannot breach, or any of our telescopes penetrate. This boundary is a sphere of radius slightly less than the age of the Universe. It marks the furthest point in any and every direction from which light can reach us before returning back in time to the Big Bang. Similarly, every location in space-time will have its own "observable universe".

1.3 The Structure of Galaxies

Matter in the Universe is concentrated in gas clouds, stars with their planetary systems, neutron stars, dark matter, black holes and possibly other material, known or unknown, which in turn is concentrated in the galaxies. The galaxies are grouped in galactic clusters and these clusters in superclusters. Matter is distributed throughout the Universe in an irregular lace-like network; galactic clusters and superclusters are rarely isolated. The boundaries between them can be blurred and some fringe galaxies have uncertain allegiance to one cluster or another. Thus the Universe looks like 3D gossamer; each string being known as a filament.

There are three basic galaxy types, with variations – elliptical, spiral and irregular. Ellipticals comprise about 60% of nearby galaxies, spirals some 30% and irregulars the remainder. Elliptical galaxies vary greatly in size, including both the largest and the smallest. Their stars tend to be mainly older red and yellow types as there is relatively little gas or dust to provide material for new stars to develop. Spiral galaxies vary far less in size but more in shape. Star formation can be prolific in the arms but much less so in their ovoid cores. Irregular galaxies are relatively small but can be very bright as they tend to be rich in young, bright blue and white stars formed from a plentiful supply of gas and dust clouds.

Our home Galaxy is a spiral galaxy over 100,000 l.y in diameter and containing some 200 to 400 billion stars, possibly many more if the dead stars known as brown dwarfs are included. The Galaxy and Andromeda, a spiral galaxy about twice the size of ours and about 2.2 million l.y away, are accompanied by about 45 smaller satellite galaxies. Together these form the galactic cluster known as the Local Group, which is itself part of the Virgo Supercluster. Although the Universe is expanding, a galactic cluster is gravitationally bound and does not itself expand; the same applies to superclusters. Clusters vary in size from a dozen or so to a few thousand galaxies. The nearest cluster is the Virgo Cluster, a very large cluster of some 2,500 galaxies, about 50 million l.y away.

The Galaxy slowly turns on its axis, but not as a solid wheel; its rotational speed varies across the Galactic disc. The Sun, around 30,000 l.y from the centre, travels around the centre at about 225 km/s (800,000 km/hour) and completes one turn in about 220 million years. Dark clouds of gas obscure long-range views of the Galaxy at optical wavelengths so astronomers map the radio emissions at 21 cm from the invisible hydrogen gas that lines the spiral arms. Observing at infra-red also enables obscured parts of the Galaxy to be mapped. A radio source marks the centre of the Galaxy. From the high-speed orbital motions of gas swirling around this point astronomers conclude that it contains a supermassive black hole with a mass of a few million Suns, in common with most galaxies. A black hole is a region in space-time from which nothing, including light, can escape, because of its immense gravitational field. The faster the speed at which matter orbits a galaxy's core, the greater the mass of the black hole within; velocity measurements enable the approximate mass of the black hole to be calculated.

Near-spherical clumps of stars known as globular clusters orbit the galaxies. They are much larger than the open clusters which inhabit the Galaxy's spiral arms and are much more densely populated, containing hundreds of thousands of stars in a volume of space from tens to a few hundred l.y in diameter. Open clusters contain young stars whereas the stars in most globular clusters are amongst the oldest in the Galaxy. It seems that globular clusters came into being while the Galaxy was still forming, some 13 billion years ago. The age of these stars is revealed by their composition, almost entirely hydrogen and helium without the heavier elements produced by generations of supernovae present in younger stars such as the Sun. Almost 150 globular clusters are known in the Galaxy, and are a common feature of all but the smallest galaxies.

Galactic mergers are not uncommon; within a galactic cluster galaxies tend to attract each other owing to gravitational influence. They have played a major role in the development and growth of galaxies and the formation of new stars within them, although they were much more frequent during the earlier stages of galactic evolution. Stars themselves very rarely collide as they are so dispersed within a galaxy. Many large galaxies may have experienced many mergers within their lifetimes which can completely change their appearance. A number of interacting galaxy pairs, or more rarely small groups, can be observed today.

The largest members of our Local Group, the Andromeda galaxy and the Milky Way, are approaching each other at a speed of some 820,000 km/hour owing to gravitational influence. As the two galaxies begin to close, there will be considerable distortion in the shapes of both galaxies. In about 3 billion years' time, the night sky as seen from Earth will be filled by the Andromeda galaxy, which will first pass by before falling back to merge about a billion years later. It is believed that the result will be a large elliptical galaxy.

An invisible halo, containing some ten times as much mass as the visible stars and nebulae, surrounds the Galaxy and most other galaxies appear to have them. This has been confirmed by computer model; without the presence of the halo the stars would orbit individually rather than rotating more or less as a large wheel. The halo is known to be present because of its gravitational effect on the rotation of the rest of the Galaxy. What these dark halos consist of is not known - brown dwarfs or subatomic particles are possibilities (dark matter is matter that cannot be observed directly, only by its gravitational effects). Many scientists believe that the Universe has around a hundred times as much dark matter as visible matter.

In 1915, Albert Einstein proposed his theory of general relativity. He suggested that gravity is not a force as such, but a consequence of the curvature or distortion of space by the matter (stars, planets, etc) within it, rather than an attraction between masses as Isaac Newton proposed in 1687. Curved space bends the paths of all objects passing through it - planets are kept in their orbits by the curvature of space around the Sun. His theory also predicted that the path of light is bent by curved space. This was proven by Arthur Eddington around 1919, when he plotted the "normal" position of a star, and then checked its position when the Sun was close to it during a total solar eclipse. He found that the star was found to be in the position predicted by Einstein's equations. This proved that Einstein's theory of gravity was correct, in that the path of light was bent by a body with mass whilst travelling through space.

One way of identifying dark matter would be if dark matter of significant mass was to cross the light from a star, the light from that star would be distorted, a phenomenon known as gravitational lensing. One example, Einstein's Cross, consists of four magnified images of a distant quasar (see 1.4 below) refracted by the black hole nucleus of a spiral galaxy that by chance lies between the quasar and Earth. Careful analysis of lensed images can reveal the distribution of dark matter in lensing galaxies and galactic clusters. Gravitational lenses can also make the images bigger and brighter, giving a more detailed view of distant galaxies than otherwise possible, thus making them useful tools for observing the Universe.

1.4 Quasars and Black Holes

Radio telescopes have detected a large number of radio emissions throughout the Universe. When optical telescopes have been trained on these strong radio sources, quite often two merging galaxies can be seen. The first "radio galaxy" to be discovered was Cygnus A, an elliptical galaxy disrupted by a recent merger, found by British scientists in 1946. However, some radio sources seem to emanate from what appears to be an ordinary star. The first quasi-stellar object, or quasar, was discovered by Maarten Schmidt in 1963. This body, 3C273, is heavily red-shifted and is about 2.1 billion l.y away. For something so far away to have the appearance of a nearby star, a phenomenal amount of heat and light radiation must be emitted. This source is exceptionally old, distant, energetic, bright, and surprisingly small. The most distant quasar yet observed is moving away from us at about 94.5% light-speed and is some 13.5 billion l.y distant.

Observations with the HST have confirmed that quasars such as 3C273 lie at the heart of distant galaxies several billion l.y away, when galaxies were first forming. We see the nearer galaxies as they were much more recently and these rarely have quasars. This suggests that the nearer galaxies have generally evolved beyond the stage of having quasars at their centre and that the high energies of quasars were integral to the formation of early galaxies.

Huge black holes, between a million and a billion times the Sun's mass form the centre of quasars. Although a black hole cannot be observed directly, it resides in the centre of a circling disc of dust and gas clouds attracted from nearby nebulae and stars that have been shredded by its immense gravitational field. This material heats up to many millions of degrees, accounting for the relatively small but brilliant cores of these objects. At such temperatures the gases emit X-rays which can be detected by satellite observatories. In the case of binary stars where one has become a black hole, the Doppler shift as the remaining visible star orbits around an invisible point, indicates the presence of a black hole. The brightness of the nucleus depends on the mass of the black hole and the amount of hot matter surrounding it. Any gas not swallowed by the black hole is ejected at near light speed along or close to the rotational axis of the disc.

1.5 The Life Cycle of Stars

A star is a body that has enough mass for its centre to reach a temperature high enough for nuclear fusion to take place (over 10 million ^{O} C). The mass of a star largely determines its power output and longevity.

The birthplaces of stars are swirling clouds of gas and dust (nebulae), consisting mainly of hydrogen and helium. Within these interstellar nebulae, denser knots of gas begin to collapse under their own gravity. As these contract, temperature and gravitational pressure rise until they become high enough to trigger nuclear fusion reactions that convert hydrogen into more helium. The heat released in this reaction, which is like a controlled hydrogen bomb explosion, is what makes a star shine, releasing vast amounts of energy. As the hydrogen is fused into helium atoms, the released energy does two things. First, most of it provides an outward explosive pressure to counterbalance the inward pressure of gravity in the emerging star. This enables a star to remain stable for up to billions of years, as a balance is maintained. Second, some of the energy not involved in this balancing act escapes the star, radiating outwards as heat and light energy.

Today stars are being born in nebulae such as that in Orion. Hundreds of stars are being born in this gas cloud which is over 20 l.y in width. The brightest can be seen through binoculars and other, embryonic, stars can be detected at infra-red wavelengths as they are not yet hot enough to emit visible light. When looking at today's nebulae, we are effectively seeing how the Sun was born.

Low output stars are the most economical, lasting tens of billions of years, whereas large stars may only last a few tens of millions of years because of their relatively high power output. The Sun is a medium sized star with an expected total life of nine to ten billion years; it was born some 4.6 billion years ago.

There is still enough hydrogen to fuel the Sun for some 5 billion years. After this time the hydrogen will be almost depleted and the predominant element will be helium. With less hydrogen to fuel the nuclear reactions there will be less outward pressure, which will disturb the balance with the inward pressure of gravity. As the inward gravitational pressures increase, they will in time become powerful enough to press the newly created helium atoms closer together. The helium atoms will start fusing together to form atoms of the next heaviest chemical element. This process will continue with successive elements becoming dominant in the star. With small and medium stars there is not enough mass to generate the extremely high temperatures and pressures to start the fusion process for elements denser than carbon. The star will contain a quantity of all the lighter elements prior to its final demise.

The Sun will expand many times in size into a red giant large enough to engulf Venus. At its largest the Sun will be too distended to be held in check by its own gravity and its outer layers will disperse into space, surrounding the star with picturesque loops and shells of gas. These are known as planetary nebulae; this name being given to them by eighteenth century observers who thought they were of planetary origin. These gases comprise the remainder of all the elements lighter than carbon that remain in the star. Stripped of its overlying gas, the white hot core will be exposed as a white dwarf little larger than the Earth but with much of the mass of the Sun. Ultra-violet light from the hot dwarf ionises the surrounding gas, which glows with a range of colours depending on its composition.

Nuclear reactions have ceased in white dwarfs. Since they are no longer generating energy, there is nothing to prevent the pressure of gravity from packing the atomic particles within them as closely together as is physically possible. As a result, white dwarfs are far denser than any material on Earth - a spoonful of matter from one would weigh several thousand kg. Over billions of years, the white dwarf cools and fades until it is no longer luminous and becomes a brown dwarf made largely of carbon.

Stars several times the mass of the Sun burn their hydrogen at a far higher rate than smaller stars and only last from tens to hundreds of millions of years. Towards the end of their lives they expand into red supergiants and have a much more dramatic demise than smaller stars - they explode as supernovae. The gravitational pressures and temperatures are so high that iron becomes the final dominant element in the star's core. The gravitational pressures are so strong that even though they cannot start the fusion reactions needed to turn iron into heavier elements, they can crush the core of the star until it implodes. The infalling gas rebounds violently from the incompressible core and triggers a chain of nuclear reactions in the star's outer layers. This releases so much energy that, for a short time, high enough temperatures and pressures develop for all the elements heavier than iron to be created.

All the chemical elements in Nature are forged in a supernova and are blown into space by the explosion. This has been confirmed by observation. By studying the spectra of refracted light from supernovae, scientists have analysed the chemical elements present. In addition stars with spectra of the elements up to iron have been similarly observed. They mix with the interstellar dust and gas of nebulae, later to form new stars and planets, completing a cycle of stellar life and death. We all contain atoms that were created in supernova explosions which occurred long before the Sun was born.

The central core remaining from a supernova is known as a neutron star and is around a million times denser than a white dwarf. A typical neutron star has the mass of one or two Suns and a diameter of 10 to 30 km. The matter is so dense that a spoonful weighs billions of kg. As they are small, neutron stars can spin rapidly, typically a few times a second to once every few seconds. A beam of radiation radiates from their magnetic poles and should this intercept the Earth the neutron star is observed as a rapidly oscillating radio source known as a pulsar.

Should the core created in the supernova have a mass greater than about three Suns it will collapse beyond the stage of a neutron star. The tremendous gravitational field causes the core to shrink ever smaller and denser, becoming a black hole. At the centre of the black hole the remains of the former star are crushed to a point of infinite density known as a singularity.

Over 1800 extrasolar planets (or exoplanets) have been discovered to date. So far, only larger planets have been found, mainly gas giants comparable with Jupiter. Currently Gliese 581c, orbiting the red dwarf Gliese about 20 l.y. away, is the smallest planet yet found. This is the only exoplanet known which lies within the host star's habitable zone; liquid water could exist on its surface. Gliese 581c is roughly 50% larger than Earth and about five times its mass. Most known exoplanets have highly eccentric orbits, which suggests the presence of other massive bodies within their solar systems. The most common method of detecting exoplanets is to measure perturbations in the course of a star caused by the gravitational influence of its planets. Occasionally a distant star system will be aligned in the same plane as our own. As a planet passes between the central star and ourselves, it blocks some of the light reaching Earth. Thus the presence of a planet is inferred and its size can be calculated. The planets discovered so far tend to be very different from those in our own solar system.

1.6 The Solar System

The Sun formed some 4.7 billion years ago from a cloud of gas and dust, which contained all the chemical elements ejected during a supernova explosion. As the cloud began collapsing due to gravity, a central body (the early Sun) and a planetary disc (protoplanetary disc or accretion disc) of surplus material developed as the young Sun began to cool. The disc then broke down into a series of concentric rings which would later form the planets. Planets are a natural by-product of star birth and are common in the Galaxy. These planetary discs have been seen by the HST around young stars such as those in the Orion nebula, but it has been found that the discs risk being evaporated by the radiation from nearby hot stars before planets have a chance to develop. The Solar System is about 4.6 billion years old.

While the planetary rings were beginning to develop, the Sun was going through the first stage of the life of a star of solar mass, when the Sun was far hotter than today and ejected large quantities of gas. As the Sun started cooling, particles of fine dust in the protoplanetary disc collided and stayed together. More collisions built up larger bodies, which under gravitational influence coalesced into increasingly large bodies (accretion) until the planets formed. It is estimated that this process took some 100,000 to a million years to complete. Gradually metal cores within the planets formed, driving out gases that had previously resided there. These gases became the early planetary atmospheres. The planetary orbits lie within a few degrees of the planetary or ecliptic plane.

Mercury soon lost its atmosphere because of its relatively small gravitational field and its surface exhibits many impact craters resulting from the bombardment of left-over material from its planetary ring. These craters are also present on many planets' satellites, such as the Moon. On Earth, the craters are rarely seen owing to erosion. Earth and Venus were larger and their greater gravitational fields retained most of the gases. Mars retained its atmosphere for far longer than Mercury, but has now lost most of it. Jupiter, Saturn, Uranus and Neptune have retained nearly all their gases.

Over time, repeated observations and measurements of the planets were made and Newton's or Einstein's mathematical equations for gravity applied. The sizes, masses and details of the planets and their orbits are now accurately known. Today's Solar System, starting from the Sun outwards, will now be described.

The Sun is 1,392,000 km in diameter and its mean distance from the Earth is 149.6 million km (8 light minutes). It is energised by nuclear fusion reactions within the core which is at a temperature of some 15 million ^{O} C. Hot gases percolate through the radiative and convective layers to the surface layer, the photosphere, whose temperature is some 5,500 ^{O} C. The more tenuous gas layer above the photosphere is the chromosphere; beyond that lies the corona which is an irregularly shaped halo of plasma extending outwards into interplanetary space. The corona is far hotter than the photosphere at a temperature of some 1 million ^{O} C. The solar wind is an outflow of hot plasma from the Sun in all directions, has the same composition as the Sun's corona and travels at an average speed of some 1.6 million km/hour. Sunspots are regions on the photosphere that are at lower temperatures than their surroundings and are regions of intense magnetic activity. They have an eleven year cycle between maximum and minimum activity; 2006 was a year of minimum sunspot activity. Sunspots can be many times the Earth's diameter in size. They are often related to coronal activity such as solar flares, which are violent explosions in the corona and travel at about 1,000,000 km/hour. Sunspot activity can lead to interference with computers and disrupt communications equipment.

Mercury is the smallest planet in the solar system with a diameter of 4880 km (Pluto is smaller, but lost its planetary status in 2006 – see page 14). In the mid 1970's the Mariner 10 space probe photographed some 40% of its surface, showing a landscape covered with impact craters similar to those on the Moon and many huge faults with steep cliffs up to 300 metres in height. On the dayside, temperatures rise to about 400 ^{O} C, while during the long night fall below -180 ^{O} C. The relatively high density of the planet suggests it has a large iron core. There are no moons.

Venus (diameter 12,100 km) has an atmosphere of about 95% carbon dioxide topped with clouds composed of sulphuric acid droplets; the atmospheric pressure is some 90 times that of Earth. The dense atmosphere traps heat in an extreme greenhouse effect, resulting in surface temperatures of up to 450 ^{O} C. The visually impenetrable atmosphere was penetrated by the Magellan probe during the early 1990's using radar. The planet's surface was mapped and found to be dotted with volcanoes and impact craters with some upland areas and high mountains. Venus has no moons.

In its earliest phase the Earth heated up; this occurred first as the Earth accreted, and continued during intense meteorite bombardment which continued until about 3.8 billion years ago. Heat was also created during formation of the core. The decay of radioactive isotopes throughout the history of the Earth has also contributed heat. The original surface would have been an all enveloping magma ocean at several thousand degrees C; when this began cooling the Earth's crust began to develop, and was complete some 4 billion years ago. It is believed that the Earth's internal layers separated out from a homogenous ball of accreted matter (see above) and geologists are ascertaining when this occurred. The Earth's magnetic field is generated by fluid motions in the liquid outer core. Studies of the magnetism in 3.5 billion year old rocks suggest that they were magnetised when they cooled from a molten state in the Earth's magnetic field. This proves that the Earth's core was formed more than 3.5 billion years ago. Geologists have established the age of the core by studying a number of unusual isotopes. Radioactive dating and the distribution of these isotopes show that the core separated out roughly 50 million years after the Earth first accreted, about 4.55 billion years ago.

The innermost of Earth's layers is a hot metallic core, consisting mainly of iron, which is solid as it is under great pressure. Beyond this there is a mushy transition layer surrounded by the liquid outer core. Above the outer core lie the lower and upper mantles respectively, which make up about 70% of the Earth's volume. The crust is a thin outer layer of relatively low density rock, the depth of which varies from a few km under some areas of the oceans to a maximum of some 80 km under some mountain ranges. The Earth has an equatorial diameter of 12756 km, a mass of $5.974.10^{24}$ kg and its escape velocity is 11.2 km/s.

Up to about 80 km altitude, near its upper extremities, the Earth's atmosphere consists of about 78% nitrogen, 21% oxygen and 1% carbon dioxide, argon and other trace elements. The far more rarified ionosphere lies from 80 km to 600 km and the composition begins to change, having a greater proportion of lighter gases and also charged particles.

The Earth's magnetic field extends several tens of thousands of kilometres into space as the magnetosphere. The magnetosphere is a region which surrounds the Earth and largely prevents the charged particles of the solar wind from entering the atmosphere by deflecting them, protecting the Earth's surface. The magnetosphere is compressed on the day side of Earth due to the force of the particles and extends outwards on the night side. The solar wind can cause phenomena such as the aurora, visible in the Arctic and Antarctic regions.

During 1958 the first scientific satellites were launched and they detected areas of radiation around the Earth. With this data, James Van Allen discovered the Van Allen belts. These two doughnut-shaped belts lying roughly around the equator consist of charged particles. Between them, the Van Allen belts extend some 700 to 65,000 km from the Earth's surface.

The dynamics of Earth's orbit are very complex, largely due to the gravitational influences of the Sun, Moon, Jupiter and Saturn. The variations in orbit and movements of Earth's rotational axis have had considerable influence on the climate, particularly the ice ages, and the evolution of life and environment (see Section 2.4).
The 3 laws governing the motions of the planets were worked out by Johannes Kepler in 1609. "The orbit of a planet is an ellipse with the Sun at one of the two focii", which establishes the shape of planetary orbits. "A planet revolves around the Sun with the connecting line sweeping equal areas in equal times". This law establishes that the

planets move faster when closer to the Sun along their elliptical orbits and more slowly when they are further away. "The square of the sidereal period of a planet is proportional to the cube of the semimajor axis of its orbit". The third law establishes that the sidereal periods of the planets increase with increasing distance from the Sun. The sidereal period (or year) is the time that it takes a planet to make one full orbit around the Sun, relative to the stars. The tropical year (which is normally used) measures the return to the same point in the seasonal cycle. For Earth, the tropical year is 20m 25s shorter than the sidereal year owing to precession of the equinoxes, so the tropical year is not quite a complete orbit.

Precession of the equinoxes is the change in the direction of the Earth's axis of rotation relative to the Sun at the time of perihelion and aphelion. Perihelion and aphelion are the closest and furthest points of a planet's orbit to and from the Sun respectively. A consequence of this is a changing pole star - currently Polaris is within 0.5 ^{O} of arc of the north celestial pole. Thurban in the constellation Draco was the pole star around 3,000 BC. The Earth's axis takes some 22,800 years to precess over a full 360 ^{O}. The precession of the equinoxes is caused by the effect of gravitational influences of the Sun and Moon on the Earth's equatorial bulge. Owing to its rotation, the Earth is an oblate spheroid with the equatorial diameter being 43 km greater than the polar diameter.

The tilt of the Earth's rotational axis (obliquity) varies from 22 ^{O} to 24.5 ^{O} with respect to the plane of the Earth's orbit and with a period of some 40,000 years. Currently the angle of tilt is 23.44 ^{O}. It is believed that the Moon's gravitational field has stabilised Earth's obliquity over geological time which in turn has moderated extremes in Earth's climate over the ages.

The eccentricity of Earth's slightly elliptical orbit varies over time from a near circle at 0.005 to a maximum eccentricity of 0.058. The more eccentric the Earth's orbit, the greater the variation in insolation (energy received from the Sun) over the year and the more variable the climate; currently eccentricity is 0.017. In addition, the inclination of the Earth's orbit with respect to the planetary plane drifts up and down with a cycle having a period of some 95,000 years. The orbital ellipse itself precesses in space, primarily as a result of gravitational interactions with Jupiter and Saturn.

The Moon raises tides in the solid body of the Earth as well as in the oceans. When the Moon orbited much closer to the Earth than at present, tides are estimated to have produced displacements in the Earth's solid surface of up to 1 km. This would have produced intense stress and deformation within the Earth, which, coupled with other factors, would have contributed to melting of the early Earth. This may eventually have led to the development of the Earth's crust as the surface cooled down. It is believed that the lunar tides have influenced the evolution of life, particularly at the stage where organisms began to inhabit the land.

The Moon's elliptical orbit precesses around the Earth every 18.6 years and is inclined at 5.2 ^{O} to the planetary plane. The Moon rotates synchronously, in that it is locked in phase with its orbit so that the same face is always presented to the Earth. The lunar day from phase to phase (synodic period) is 29 days, 12 hours and 44 minutes. With respect to the stars (sidereal period), the Moon takes 27 days, 7 hours and 43 minutes to orbit the Earth, but since the Earth – Moon system has advanced around the Sun in the meantime, the Moon must move further to get back to the same phase. The Moon is 384.400 km (mean distance) from Earth and 3,476 km in diameter. It consists of an iron-nickel core some 200-300 km in diameter; the remainder being made up of various types of rock aged between 3.1 and 4.6 billion years. There is strong evidence that indicates that the Moon was derived from Earth some 4.5 billion years ago as the result of a massive oblique impact with a smaller planet soon after the initial formation of the Earth. The planet disintegrated on impact and a large quantity of pulverised rock was propelled into space, orbited the Earth and accreted to form the Moon. It is thought that the tilt of the Earth's axis is a result of this impact.

Mars is 6780 km in diameter and has a mean surface temperature of -150^{O} C. Its atmosphere is about a hundredth as dense as that of Earth at the surface and is composed of carbon dioxide and traces of other gases. In spite of the thin atmosphere, extensive and violent dust storms can arise on the planet's surface. Even at its warmest the surface temperature rarely rises above 0 ^{O} C. Mars has polar ice -caps of water ice and frozen carbon dioxide. Space probes have mapped the surface which comprises some impact craters, uplands, deep valleys, high mountains, sand dunes, volcanic craters and ancient river systems. The presence of river systems, and other geological evidence, show there was once flowing water on Mars. Landers have analysed soil samples in an unsuccessful attempt to find microscopic life. It is believed that the early atmosphere of Mars, coupled with the presence of water, could have been suitable for the emergence of microscopic life forms and that fossils of these may exist. Mars has two very small moons, potato-shaped rocks some 20 km across, which may have been captured from the asteroid belt.

The asteroid belt is a belt of rocks 150,000 to 300,000 km wide, largely ranging in size from pebbles to mountains. The smaller asteroids are irregular in shape, the larger are nearly spherical. In the past the average size was greater than now, but collisions over time tend to break them down. A small proportion of asteroids has left the belt under the gravitational influence of Jupiter and been brought closer to the inner planets. Indeed, an "asteroid watch" has been implemented to check for any asteroids that may be on a collision course with Earth. About 65 million years ago a meteorite some 10 km wide struck Mexico. This collision scattered a dense blanket of dust into the atmosphere that was largely responsible for altering the climate such that over two-thirds of life on Earth was extinguished. The 180 km wide crater is covered in soil, but its existence and age were established as a result of small variations in the local gravitational field and studies of rocks from drillings.

Meteorites are asteroids, rocks, etc, which fall on Earth at an average of 550 each year. The smallest meteorites capable of surviving entry through the atmosphere are about 10 mm in diameter. The largest meteors are capable of creating large craters such as Meteor Crater in Arizona, USA. This crater, 180 m deep and 1200 m diameter, was made some 50,000 years ago by an iron meteorite some 30 m across and weighing about 110 million kg. Smaller meteorites can be collected and dated by analysing their radioactive elements, indicating the age of the Solar System.

Jupiter is the largest planet in the Solar System with a diameter of 142,980 km and a mass 318 times that of Earth. It has a very dense solid metallic core surrounded by a thick mantle of hydrogen in the metallic state, because of the high pressure. Above this is a layer of liquid hydrogen topped with helium and hydrogen, with some methane and ammonia. To the south of the equator lies the Great Red Spot, a 15,000 by 30,000 km oval vortex of rising warm gases which has been present for over 200 years. There are smaller white oval features which are also storms, on a background of banded, multicoloured, swirling clouds. The Galileo spacecraft released a probe into Jupiter's atmosphere. Buffeted by winds of up to 720 km/hour the descending probe failed through the effects of 150 ^{O} C in temperature and a pressure of 22 times Earth's atmosphere nearly 200 km below the visible surface.

Jupiter has 67 recorded moons and a system of three tenuous rings extending beyond them. From the planet outwards the four largest satellites, discovered by Galileo, are volcanically active Io, Europa (believed to have an icy crust with liquid water below), Ganymede and Callisto. Their diameters range from 3,100 to 5,300 km. The Galileo spacecraft has produced detailed images of these satellites. They may have formed around Jupiter in a similar way that the planets formed around the Sun, and at the same time as the planet. The vast majority of the outer planets' moons are large rocks up to some 400km across.

Jupiter and Saturn are thought to have been the first planets to form, when gases were most plentiful around the young Sun. As a result the two planets are similar in composition and internal structure. Saturn's surface features are more subdued - it is subtly banded, with occasional temporary white storm spots. The atmosphere has windspeeds up to 1600 km/hour and is colder than that of Jupiter. The Voyager space probes, the later Cassini Saturn orbiter and HST have produced detailed images and new information on Saturn, its larger satellites and ring system.

Saturn, with a diameter of 120,535 km has 62 moons, the largest being Titan with a diameter of 3,300 km. The Huygens probe, delivered by the Cassini spacecraft, landed on Titan in 2004. Titan is the only satellite in the Solar System to have a thick atmosphere; methane lakes and precipitation have been discovered. Titan has rugged, variable terrain. Saturn has a conspicuous ring system comprising seven concentric rings separated by gaps which extends from 7,000 to 42,000 km from the equator. The rings are up to one hundred metres thick and are made of dust and ice particles. They may originate from passing comets captured by Saturn and disrupted, or original material that did not accrete into a moon.

Uranus contains proportionally more methane and ammonia than Jupiter and Saturn, but much less hydrogen and helium. The planet is basically a sphere of liquid and gas whose bland, greenish surface shows few visible cloud features. Uranus has a diameter of 51,120 km, over 29 small to medium satellites up to 1,600 km diameter and a system of eleven tenuous rings. Uranus has 27 moons.

Neptune was discovered because of perturbations of Uranus' orbit as Uranus was not quite keeping to the orbit calculated for it. Mathematicians calculated the position of a possible planet beyond Uranus and this led to the first observation of Neptune by telescope. Neptune, diameter 49,530 km, is the furthest planet from the Sun, at a distance of 4.5 billion km (256 light minutes). The planet is blue in appearance as there is more methane in the atmosphere than Uranus. Neptune was seen close up by the Voyager 2 spacecraft (as was Uranus), and distinct cloud features were seen. Neptune has 14 moons, the largest being Triton with a diameter of 2,700 km, and a tenuous system of four rings.

Beyond Neptune is a doughnut-shaped belt of bodies known as the Edgeworth-Kuiper belt (EKB), which extends from about 6 to 12 billion km from the Sun. Pluto is now regarded as one of the very largest members of this belt; the largest known member of the EKB is Eris, some 1,400 km in diameter, slightly larger than Pluto. These bodies (known as Kuiper Belt Objects) consist of frozen gas, water ice, dust and rock and are the left-overs from the formation of the outer planets.

Comet cores (nuclei) are made of ice and dust, are typically 1 to 30 km across and tend to be irregular in shape. The space probe Deep Impact struck comet Tempel 1 during

2004 and analysis suggests that the cratered surface is softer and dustier than expected. Comets consist of the original primordial matter that originally formed the Solar System. Short term comets with periods less than about 200 years lie within the EKB; some 150 are known. Halley's Comet which returns every 75 to 76 years is an example. If any of these bodies has an orbit in the same direction as the planets and is close to the planetary plane, it may be deflected gravitationally by one of the outer planets and thrown into a new orbit taking it close to the inner planets.

Beyond the EKB lies the sparse Oort Cloud comprising millions of icy bodies, which forms a rough sphere around the Solar System at a distance of one to two l.y from the Sun. Here roam the long-period comets which may take up to 1 million years to reappear. As their orbits have random orientation with respect to the planetary plane they can appear from any direction.

When a comet comes within the orbit of Mars, it is close enough to the Sun for the frozen gases to start vapourising. A bright, expanded head and a long, tenuous tail which points away from the Sun are formed, caused by the solar wind. Each time a comet passes the Sun it loses matter and over time becomes smaller and less visible. When the orbiting Earth crosses one of the cometary trails, small fragments are captured and burn up as they enter the atmosphere, leaving the luminous trails known as shooting stars. There are a number of meteor showers throughout the year - examples in order of richness are:- the Perseids (Aug 11-13), Quandrantids (Jan 3) and the Geminids (Dec 13).

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Section 2 The Evolution of Life on Earth

2.1 Dating Rocks and Fossils

Geologists rely on exposed rock in such places as cliffs, river valleys, road cuttings, quarries and mines for relative dating. However, such sites are scattered and no single one will have exposures of a complete sedimentary sequence. Thus a sequence at any one place will only represent a small proportion of the overall geological time span. In addition sediments already deposited can be eroded away, or covered in soil and vegetation. A modern geologist can work out which way the rivers were flowing, where in the sea the sediments were accumulating, the nature of the Earth movements that caused the uplift and the age of the rocks from a single outcrop.

To develop as complete a sequence as possible, it is often necessary to study part sequences exposed at different sites. One exposure may reveal layers A to G (bottom to top) and another some distance away may show layers G to M. The two sites can be regarded as providing a complete sequence of layers A to M if layer G can be proven to be the same layer at each site. For example, if it has the same colour, grain size, mineral composition, or fossils if any. This is known as the Principle of Lateral Continuity.

The Principle of Superposition generally applies to sedimentary rocks, such as sandstone and shale. This states that in any undeformed sedimentary rocks any bed, or stratum, must be older than those lying above it and younger than those below. Interpretation can be challenging when the strata are very deformed or even overturned. Where igneous rocks, such as granite and basalt, are intruded from below into older overlying rocks, the basic principle of relative dating is the Principle of Crosscutting Relationships, in that igneous rock must be younger than the rock it is cutting through. The above principle also applies to faults, which must have taken place more recently than the formation of the rocks that are faulted. The Principle of Inclusion applies to both igneous and sedimentary rocks. This states that pieces of rock embedded in another must be older than the latter rock. Thus pebbles embedded into a sedimentary formation must be older than that formation. The physical correlation of strata according to rock type is only possible over distances of some tens or hundreds of kilometres because sedimentary layers change their characteristics along their length. Fossils, however, offer an independent method of correlation which can be applied on a worldwide basis and enable a global relative chronology to be established.

In the early 19th century William Smith found that successive sedimentary strata in southwest England contained different assemblages of fossils and that a characteristic fossil assemblage could be used to recognise a particular layer wherever it occurred. This became known as the “law of faunal succession”. Geologists realised that a particular fossil assemblage was a good indicator of the age of the corresponding stratum and that it occurs in the same rocks of the same age irrespective of their type. Gradually the correlations of southwest England were extended to the entire country, to Europe and then worldwide.

Much later it became appreciated that fossil assemblages change with time because of the evolution of the relevant fauna and flora. Species arise, expand, modify, contract and become extinct at different times and at different rates. Thus at any time there is a characteristic mix of species that represents that time only, albeit with some geographical variations. William Smith acquired this information by studying the fossil assemblages in successive layers and noting the relative ages of the layers using the Principle of Supposition. He compiled the first geological maps in 1815. The best fossils to use in dating are those that change quickly with time, and which occur worldwide. This kind of dating can only be used where there are fossils, which means up to about 590 million years ago. Prior to that creatures did not evolve preservable hard parts. Radiometric dating is not generally applicable to sedimentary rocks, so relative dating by fossils is still the chief method of working out the history of sedimentary strata.

Absolute dating of organic matter or igneous rocks is based on the decay of the radioactive isotopes of chemical elements that naturally occur in very small quantities. This method was refined in the late 20th century. An isotope is one of two or more forms of an element differing in atomic mass. The number of neutrons in an atomic nucleus affects the mass of the atom. For example Carbon-12 has 6 protons and 6 neutrons in the nucleus giving a total atomic mass of 12; Carbon-14 has 2 extra neutrons giving an atomic mass of 14. Because of the two extra neutrons, C-14 is said to have an unstable nucleus. C-14 is a radioactive isotope of carbon and emits alpha, beta and gamma radiation. Living organisms, but not inorganic matter, absorb C-14 which has a half-life of about 5,600 years. In practice accurate results can be obtained from samples of plants or animals that died 50,000 to 60,000 years ago. The half-life of potassium-40 as it decays to argon-40 is about 1.25 billion years and is very useful for dating igneous rocks, which are non-porous and trap the argon-40. All radioactive isotopes (parents) decay exponentially to stable, non-radioactive isotopes (daughters) at a constant rate, which is unaffected by environmental factors such as temperature. Each radioactive isotope has its own decay constant which is expressed in terms of half-life. Half the parent isotope decays in one half-life, half the remainder (or one quarter of the original) decays during the second half-life, and so on.

To date igneous rocks, it is best to use isotopes whose half-lives are roughly the same as the rocks to be dated. If the half-lives are too short the isotopes will have decayed almost completely, if much longer the rate of decay will be so slow that the daughter-parent ratio will change little with time. The isotopes chosen must also be sufficiently abundant and widespread.

The Earth must be older than the oldest rocks found, which have been dated at about 3.8 billion years of age. The age of the Earth cannot be measured directly, but there is indirect evidence that suggests an answer. Almost all meteorites have radiometric ages of about 4.6 billion years. The oldest rocks collected from the Moon are of about the same age. As it is believed that meteorites and the Moon are made from material that formed at the same time as the Solar System, this suggests that the Earth was also formed about 4.6 billion years ago.

From the late 1970's, biologists have found a new way to study the evolution of life. They are deciphering the code in the genes, effectively reading the "blueprint" of a living organism. The code is a sequence of molecules known as nucleotide bases, which together make up DNA (deoxyribonucleic acid). This is the genetic material in living organisms; different sequences result in different characteristics in the living organism. The "language" of the genetic code is always the same irrespective of the organism; particular sequences of bases in the DNA virtually always have the same meaning. This is a strong argument that all living organisms are related, however remotely. Evolution at gene level involves changes in the sequence of bases in DNA. Comparing these sequences from a number of different living organisms has helped scientists to establish evolutionary relationships, pointing to gaps in the fossil record.

In 1859, Charles Darwin published "The Origin of Species". He became aware that new varieties of plants and animals could be bred by carefully selecting offspring which have particularly sought-after characteristics. He decided that if humans can guide the evolution of domestic animals or plants in a very short timescale, perhaps nature could do the same. Thus was born the idea of natural selection. Darwin's view was the competition between organisms drives evolution by favouring any characteristics which give the offspring a competitive edge. Gradually, over time, these "selected" characteristics accumulate, resulting in an organism which is very different from its remote ancestors. It is now known that the characteristics of an organism are encoded in its genes, which are passed on to its offspring. The study of genetics has verified a crucial part of Darwin's mechanism of evolution.

2.2 The Emergence of Life

This section covers the Precambrian era, from about 4.5 billion (when geological history began and Earth's crust was forming) to 550 million years ago; see page 10 for Earth's earlier history. Radiometric dating of exotic isotopes present during the Earth's early history has enabled the Earth's atmosphere to be dated. Its composition was similar to that of gases emitted by volcanoes and hot springs, which strongly suggests that the earliest, very dense, atmosphere was an accumulation of gases from the Earth's interior. Studies suggest that most of the atmosphere had accumulated within 200 million years of Earth's birth – by about 4.4 billion years ago. The principal gases in the earliest, very dense, atmosphere, in order of abundance, were methane, water vapour, nitrogen, ammonia, hydrogen sulphide and sulphur dioxide. Over time the atmosphere changed until about 4.3 to 3.8 billion years ago, when its main constituents were carbon dioxide and nitrogen with lesser quantities of water vapour, hydrogen, methane, ammonia, carbon monoxide and other gases. Large quantities of water vapour, originating in the material from which the Earth accreted, were released as the planet degassed. As temperatures fell, liquid water came into existence and began to form oceans, and carbon dioxide was gradually absorbed from the atmosphere.

4.5 to 3.8 billion years ago (the Hadean period), as the Earth was cooling, there was intense volcanic activity with frequent earthquakes and numerous hot springs at the time that life is believed to have evolved. Warm, shallow and highly saline seas were becoming widespread. Water-deposited sediments some 3.8 billion years old have been found so the average temperature at the Earth's surface must have been less than 100 ^{O}C at that time. At this time electrical storms were widespread and the surface was bombarded by ultraviolet radiation. The skies were dull orange in colour and the atmosphere contained volcanic ash. In addition the Earth was experiencing the remnants of the intense meteorite bombardment that had been present throughout its earlier history. Much of Earth's water is thought to have been provided by impacts from icy comets.

The earliest evidence of life found is in a 3.8 billion year old banded sequence of silica and iron-rich rocks known as a banded iron formation (BIF) in Greenland. The evidence of life is in the form of carbon, which is believed to be the remains of organisms that lived about 3.8 billion years ago. In 1996 Maarten de Wit and Frances Westall found fossilised remains of organisms, so small that a scanning electron microscope is required to see them, that are identical in shape to modern bacteria. The rocks that contain these fossils were formed near hot springs in a region of intense volcanic activity. Evidence for this is found in adjacent pillow-shaped lava flows which erupted under water and are dated at around 3.5 billion years of age.

One of the earliest bacteria to have appeared was a primitive single-celled organism living in or near hot springs that suggests that life may have started in such an environment. Further evidence for this has been found some 2.5 to 3 km below today's oceans – bacteria cluster around volcanic vents of superheated water known as black smokers. The bacteria can withstand water temperatures up to 100 ^{O}C and exploit the energy released when the chemical-rich hot water mixes with the cold seawater. In fact entire ecosystems with relatively complex life are supported by this environment, which is independent of sunlight. More recently geologists have discovered "extremophile" bacteria living in hot rocks inside Earth's crust. As primitive life can flourish in extreme environments on Earth, it may well exist elsewhere in our solar system, and in others. Another theory is that the basic ingredients for life, or even bacteria, arrived on Earth from a comet.

It is not known when living organisms evolved the ability to photosynthesise - the use of light energy to convert carbon dioxide and water to organic matter (food) and oxygen gas. This would enable bacteria to become independent of hot springs and spread further afield. Photosynthesis is the principal source of free oxygen gas on the Earth. Today photosynthesizing bacteria are responsible for distinctive cushion-shaped structures known as stromatolites. These are found in a few places on Earth such as Shark Bay in western Australia. Stromatolites have been found in rocks 3.5 billion years old; by 2.5 billion years ago there were large continental areas where the bacteria thrived. It appears to have taken well over a billion years before the oxygen emitted by the bacteria had much effect on the atmosphere. This is known because BIFs were laid down in Hamersley, western Australia, about 2.5 billion years ago. The iron in these deposits was carried in solution by a river system; if the atmosphere was rich in oxygen at this time, the iron would have oxidised and not been deposited in the shallow sea where the Hamersley BIFs formed. Thus the oxygen level in the atmosphere at that time must have been low.

About 2.1 billion years ago, the concentration of oxygen in the atmosphere began to increase markedly. The evidence for this is that BIFs ceased to form in lakes and the sea. It appears that the oxygen produced by the photosynthesising bacteria exceeded the amount of oxygen that was removed from the atmosphere by oxygen-consuming reactions such as the oxidation of soluble iron, sulphur and dead organisms. Oxygen levels became such that iron rusted on land, staining rocks red and sandstone deposits began to appear. It is likely that the creation of ozone in the upper atmosphere began about 2.1 billion years ago, providing protection against ultra-violet radiation.

Gradually the oxygen levels in the atmosphere increased and the ozone layer developed, turning the skies blue. About a billion years ago, the oxygen content of the atmosphere was approaching the present-day level of 21%. Over the course of about a billion years, life itself had radically altered the composition of the atmosphere, enabling life as we know it to evolve. Indeed, bacterial activity over time in animals, plants, soils, etc, is essential for the continued existence of life. Fossils of single-celled organisms over 100 times larger than earlier organisms from which they evolved, became increasingly common and varied in progressively younger rocks until about 900 million years ago (mya).

Between roughly 900 and 600 mya there was a series of ice ages in what was probably the coldest period in Earth's history. According to the fossil record there was a dramatic decline in the acritarch population at this time. During this time, the continents were amalgamating to form the first "supercontinent", known as Rodinia. Evidence for this is found in the eroded roots of ancient mountain belts in Scandanavia and North America. These are the remains of a period of continental collision between 1.3 and 1.1 billion years ago; 750 mya Rodinia straddled the equator. However, remains of glacial gravels and glacial scratchmarks on rock surfaces found today in Africa, Australia, South America, northern Europe and North America, suggest that as Rodinia moved towards the south pole, ice sheets began to accumulate. The Earth was now in the grip of one of the major Ice Ages, and the ice sheets extended towards the equator.

After about 590 mya, the Earth began to warm up and the first multicellular life forms, known as the Ediacara fauna, appeared. Fossil impressions of these soft-bodied organisms were first found in late Precambrian rocks in southern Australia and have since been found in similarly aged rocks worldwide. These impressions have similar shapes to worms, jellyfish and other such organisms.

2.3 The Cambrian to the Present

During the early Cambrian period (550 to 505 mya), there was a dramatic appearance of a wide variety of invertebrate marine animals with skeletons, which produced the first true fossil remains. These creatures included the first shellfish, corals, and the many-legged, segmented trilobites; also the first seaweed appeared. During this period the

Rodinia supercontinent broke up and sea levels rose, resulting in widespread flooding of coastal regions and a considerable increase in the extent of the oceans.

The widespread seas continued into the early Ordovician period (505 to 438 mya), retreated and then expanded again towards the end of the period. The dramatic increase in the diversity of life continued – crustaceans, the first fish including early vertebrates, coral reefs spread, and the first simple marsh plants appeared on land. At
the end of the Ordovician, the continents amalgamated and the resulting large landmass, Gondwanaland, drifted away from the equator towards the south pole. Another Ice Age ensued; evidence for this is present in glacial gravels found in North Africa, Brazil and Arabia. By about 440 mya the region which would become North Africa lay over the south pole. The second mass extinction occurred at this time when about 70% of life was extinguished.

From the early Silurian period (438 to 408 mya) to about 250 mya, the northern continents slowly converged on Gondwanaland. The existing simple marsh plants developed into vascular plants with stems and leaves which were capable of living out of water. Some freshwater fish were present; also starfish and sea urchins in the seas.

By the early Devonian period (408 to 360 mya) worms, snails, myriapods (ancestors to centipedes and millipedes) and scorpions had arrived on dry land; insects subsequently evolved from the myriapods. Fish diversified and sharks appeared; the first amphibians emerged. Plants evolved into spore – and seed – bearing varieties; the fossil record shows that late Devonian forests contained tree ferns 10 metres high.

During the Carboniferous period (360 to 286 mya) amphibians became abundant and the first reptiles evolved from them. Large tropical forests flourished in the widespread swamps of the time. Dead trees and plants sank to the bottom of the swamps where over time they were buried under successive layers of sediments until they became coal deposits. Towards the end of the Carboniferous there was an ice age, which led to the partial glaciation of Gondwanaland.

In the early Permian period (286 to 250 mya) the ice age gradually receded, and dry desert conditions spread over the continents. During the Permian, reptiles gained supremacy over the amphibians on land, and conifer trees made their first appearance. 250 mya the supercontinent of Pangea stretched almost from pole to pole, the remainder of the Earth being a single vast ocean, known as Panthalassa. At this time an enormous volume of lava erupted onto the Earth's surface over a period of several thousand years. During the eruptions large quantities of dust, carbon dioxide, water vapour and sulphur dioxide were released into the atmosphere. The dust blocked out much of the daylight and the Earth darkened and cooled. The sulphur dioxide reacted with water to form dilute sulphuric acid which precipitated as rain. It is thought that major ocean currents of the time were disrupted, adding to the devastation (see page 25). It is estimated that some 90% of land and marine animals became extinct. This third mass extinction was the single greatest catastrophe in the history of the Earth.

Following the Permian extinctions, the Triassic period (250 to 208 mya) witnessed a new expansion of life, and the dinosaurs became dominant; in addition new marine invertebrates arrived in the seas. Owing to Earth movements, extensive coal deposits were thrust upwards and exposed to the atmosphere. As these deposits weathered, large quantities of carbon dioxide were released into the atmosphere and the climate became warmer; the landmass that would become Europe and North America developed a tropical climate.

In the Jurassic period (208 to 144 mya) dinosaurs became much more diversified, with a range of species ranging in size from less than a metre to several tens of metres in length. Some were herbivorous, others aggressive carnivores – the majority lived exclusively on land. A late Jurassic fossil found in Bavaria had feathered wings and is regarded as the first bird. About 160 mya the northern part of Pangea (Europe, North America and Asia) began to split from the southern part (Gondwanaland, comprising Africa, South America, Australia and Antarctica).

The first flowering plants appeared during the Cretaceous period (144 to 65 mya), and became dominant by the end of the period. Associated with the flowering plants was the increase in the number and diversification of insect species. The dominant vertebrate species were the dinosaurs, which were peaking in size. The mid-Cretaceous was a particularly warm time, and life thrived. As sea levels were at their highest in the planet's entire history, large volumes of water were displaced on to the continents, creating extensive shallow seas where plankton thrived, and their shells accumulated on the sea floor to become chalk. Much of this organic matter was buried, gradually heating up to form today's oilfields. Some 130 mya Gondwanaland began to split up, and Africa and South America began to part about 100 mya.

Some 65 mya there was a considerable outpouring of lava in western India similar to that at the end of the Permian, again with dire consequences for life on Earth. In addition a meteorite about 10 km in diameter struck Mexico at about the same time, leaving an impact crater 180 km across. The Earth's crust was damaged and local melting occurred; the molten rock has been dated, giving the time of the impact. In addition traces of iridium, a very rare element found in many meteorites, were found; much more than would otherwise be expected in the area. As a result of these two events, considerable quantities of dust and toxic gases were released into the atmosphere. The sunlight being partially blocked by the dust, and a general cooling of the climate were the major factors for the extinctions at this time. Over 75% of marine creatures and all larger land animals, including the dinosaurs, became extinct.

It took about the first million years of the Tertiary period (65 to 1.8 mya) for life to recover from this mass extinction. The surviving small animals from the Cretaceous began to spread, diversify and increase in size – bats, horses, elephant-like animals, whales and others evolved some 55 to 45 mya. The early primates also appeared at this time – rat-sized climbers with opposing thumbs, forward facing eyes and proportionally larger brains, which lived in tropical and sub-tropical regions. By about 26 to 18 mya ape-like mammals had evolved, the later species having longer life-spans. About 5 mya, the first human-like apes (hominids), known as Australopithecines, evolved; they walked on two legs but were small-brained compared with humans. Some 2mya, hominids called Homo habilis with larger brains appeared. They were hunter-gatherers who used shaped rock tools and may have been capable of very limited speech.

During the early Tertiary, the climate again became warm, but wetter than today. The tropical rainforests extended to middle latitudes and there were polar woodlands. By about 30 mya, the climate had cooled; the polar forests had disappeared, an ice sheet had developed in Antarctica, the higher latitudes had become treeless tundra, and grasslands appeared at lower latitudes. Some 3 to 2 mya, glaciation of the north polar regions started and the Antarctic ice sheet continued to grow, reducing sea levels.

Some 55 to 45 mya, Australia separated from Antarctica, and Europe separated from North America 40 to 35 mya. Since the breakup of Gondwanaland, India had been drifting northwards and by about 35 to 30 mya, collided with southern Asia and began raising the Himalayas. By about 20mya Africa was approaching Europe and Asia was developing. By the end of the period the world map was similar to that of today.

About 1.7mya, during the Quarternary period (1.8 mya to the present) a new species of hominid, Homo erectus, appeared. Homo erectus fossils are scattered across Europe, Asia and China – they were taller (up to 1.8 metres in height) than previous hominids and made relatively elaborate tools, such as axes and knives. By 200,000 years ago, Neanderthal man, who was better adapted to coping with ice age conditions, appeared. The Neanderthals were highly successful hunter-gatherers, with a complex social structure and who were probably capable of speech. They buried their dead and used fire. For no clear reason around 35,000 years ago their numbers declined and they eventually became extinct. During the last million years the Earth's climate oscillated violently between warm and cold periods, forcing rapid evolutionary changes in vertebrates as habitats changed and many species of large mammal became extinct. The flora tended to change latitude with moving climatic zones without much evolutionary development, although some species disappeared.

100,000 to 90,000 years ago, Homo sapiens appeared, lighter, more athletic and with a larger cranium to house the extended brain. Over time tools and weapons of increasing sophistication were invented, giving humans a great advantage over all other predators. Some 10,000 years ago, about the time that the mammoths were becoming extinct, the last ice age ended and a warmer climate gradually returned. Since then the climate has been relatively stable and this may have made the development of agriculture and human culture possible. At about this time, humans started to practice agriculture, bringing about a more secure food supply and enabling people to change from a nomadic to a settled existence. In addition, the first domestication of animals took place, starting with the dog. Over the following millennia sheep, goats, pigs, cattle, horses and other animals were domesticated. The first cities were gradually developed from villages some 6,000 years ago. Copper and tin were produced from ore and combined to produce bronze about 5,000 years ago; iron was obtained from ore some 3,000 years ago. Over time the march of human progress has led to today's global civilisation.

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