# Are we lucky to be alive?

*John S. Reid*

Some questions are bigger than others. This one has many contexts but the intriguing aspects I am thinking of are the planetary conditions needed to create life as we know it. Now that thousands of other planets have been found around other stars, the subject is a hot topic. As if the diversity of planets in our solar system wasn't enough, extra-solar planets give us a glimpse that there is an even wider range of environments 'out there'. Are the right conditions for life found in numerous other places? The topic also deeply impacts on our own origins. What conditions on Earth have favoured the development of intelligent apes (us!)? Could other animals have acquired the kind of intelligence we have in preference to our ancestors, and now be ruling the world instead of us? Could our ecology have stabilised for many hundreds of millions of years, or more, with dinosaurs remaining the top predators, the forests the realm of large insects and the little mammals that were our distant predecessors still skulking in small holes and crevices? There are many related questions. Good answers are in short supply, as yet, but there are certainly more hints than there used to be and there is a growing awareness that the whole issue is a multi-layered subject whose complexity we are only just beginning to appreciate[1].

First, a few pieces of common knowledge. Life is made from the most abundant chemically active elements in the universe, C, H, N, O, P, S, to give them their usual chemical symbols, along with minor (but important) additions of other elements. Most life is made from the same basic molecules, which is why simply by eating meat, fish, plants, mushrooms, insects, yoghurt (bacteria) and indeed almost anything living, we can turn our food into human beings, so long as we can break down complicated constituents into simple ones and aren't inhibited by poisonous products. As an aside it's worth reflecting that most people who study physical science have no difficulty with the concept that our constituents can be identified as being built from elements in the periodic table. The reverse concept, that elements in the periodic table can combine to produce molecules that themselves can aggregate into structures that are alive is really quite hard to swallow. It's equally true, of course. We know from the study of life on Earth that a wide variety of DNA-based life can be formed, but can totally different combinations of elements result in totally different structures meriting the accolade of life and, indeed, sentient, conscious, reflective and innovative life? No-one knows. If chemistry and physics, perhaps with the help of some biology, totally master the ability to control the formation of compounds, can we invent synthetic life? Will we find such other life in other parts of the Universe? This digression could go further but back to the main theme of life on Earth.

The conditions that support life on Earth have changed hugely since life first appeared. Indeed, life began here in conditions that would kill most present life, in particular in anoxic conditions. We don't exactly know if life began in the vicinity of sub-sea fumaroles, tidal pools, volcanic hot springs, or where, but wherever it was conditions were very different from the thriving habitat of the familiar front garden or farmer's field.

Surprisingly enough, the big problem with life is not that of creating basic molecular constituents. It's certainly not trivial, but it would seem that initiating the simplest forms of life based on self-reproducing molecules is well within the compass of natural chemistry, given plenty of time. Selection of those molecules that will lead to life is a second requirement over and above the chemical production of many relevant molecules. Life's molecules are highly specific and therefore might be thought of as unlikely to come together but that is not a reason why it didn't and doesn't happen as a natural process. An unlikely event of any kind will almost certainly happen if the number of opportunities for the event are large. On a planetary scale over millions of years the opportunities for creating life from the chemical raw materials must have been huge. We know two relevant facts about life on Earth. First, all life we have found and studied has sufficient in common that we know it must have evolved from a common ancestor. i.e. it requires only a single genesis to account for life as we know it. [It's a very interesting question with a quite unknown answer to ask how many other possibilities there are for life similar to current Earth life but derived from a variant basis. Perhaps there are no other possibilities, or just a few, or millions. If the answer isn't the first one then I think that it is likely that in the quite near future mankind will create new life with a different basis, a second genesis if you like. Genetic biology is developing rapidly]. Secondly, several strands of evidence show that life started on Earth almost as soon as conditions became cool enough for it to do so (about 3.8 billion years ago). My view is that life is a 'cosmic imperative', to use the phrase of Christian de Duve, and will form using the basic elements of the Universe and their chemistry when conditions are suitable for a long enough time. 'Long enough' may be millions of years but a short time in terms of the life-time of stars and planets.

Already, though, we have begged two difficult questions. What is life? I was told recently by a professor of astrobiology that there are some 25 different definitions of life. There clearly is no simple answer. The physicist Erwin Schrödinger published a well-known book in 1944 just on this subject. He argued that life had to be composed of complex aperiodic molecules. We've learnt a lot more about this subject since then, with the net result that it is now even harder to draw the border between the living and non-living. Notwithstanding, we're going to take it for granted that we've met enough examples of living things to be able to recognise quite a lot of life, even if there might exist other life forms we haven't yet encountered. The second question is whether life needs liquid water to form and function? There are certainly good chemical reasons why life as we know it works with liquid water. Whether something different could function without it is an open question. Fred Hoyle in *The Black Cloud* and Gregory Benford in *Eater* both imagine life forms that might exist in space but these are good stories, not science. No-one has yet come up with a possible scheme of alternate life based on real chemistry, though hydrocarbon-based life on Titan is looking increasingly possible as our understanding of both the environment on Titan and the chemical implications are explored. Our starting position is that life as we definitely know it does need liquid water. It needs other pre-requisites too but the fact is that on Earth, at least, there are virtually no sterile naturally occurring wet environments, a few highly contaminated sites excepted. This doesn't mean that life could have started in any wet site but it does hint strongly that Earth-type life at least needs water.

Liquid water can exist on the surface of planets within the so-called 'goldilocks zone' (or 'habitable zone') around a star, the region a few light minutes across where the surface temperatures of bodies are right. Exactly where the region is in relation to the parent star depends on the energy output of the star and also on the atmosphere of the planet. Early in our solar system history the Sun was a few tens of percent weaker than it now is but Earth and Mars would both have had a lot more of the greenhouse gas carbon dioxide than they have at the moment, and Venus a lot less. All three planets likely had conditions that would have supported surface water, brought to them by impacting icy comets. However, even outside this zone, liquid water can exist. The solid surface of a planet or moon may be too cold but temperatures increase as one goes into the interior so it's quite conceivable that liquid water can exist beneath the surface of a moon. Today, within the icy reaches of the moons Europa, around Jupiter, and Enceladus around Saturn, liquid water likely exists. It also probably exists kilometres below the surface of many other moons, including Titan, not as pure water but mixed with concentrated salts or ammonia. Moreover, the gaseous, cloudy atmospheres of Jupiter and Saturn that reflect light back to us are at cryogenic temperatures but deeper into the atmospheres of these planets it gets warmer and there is a level where liquid water drops form the cloud, before it gets even hotter deeper within.

So, on planets and moons like the ones in our solar system, liquid water hasn't been a rare commodity, especially in the early solar system when the outer bodies had more heat than they now do. What is rarer is the continued presence of liquid water in one place over several billion years. Will life once started be sustained? Mars has dried up, Venus has overcooked. Matters would have been even worse if our Sun had been a variable star instead of very steady, if the Sun had been a very massive star with a lifetime of well under a billion years, if the Sun had been a member of a binary or multiple star system whose planetary orbits were unstable or highly eccentric, if the Earth had migrated closer to the Sun following a common evolutionary pattern in extra-solar planetary systems where inner planets lose orbital angular momentum by various mechanisms. We are beginning to appreciate now that a lot of places where life could well start will not sustain life for the time that has been needed here to evolve the kind of ecology we are surrounded with. On Earth that has taken roughly 3.8 billion years since the first traces of life appeared, on top of a further 0.8 billion years before the Earth became cool enough and stable enough for the process to start. In short, life on Earth has needed a steady, preferably singleton, neighbouring star, at the right distance away and of intermediate mass, intermediate between the bright, massive stars in the night sky with short lifetimes and the many low mass stars which are also there but can only be seen with the aid of a telescope. One problem with less massive stars, say only 10% of the Sun's mass, is that they are so cool that the goldilocks zone is very close to the star, so close that the influence of the tides from the star gradually slows the spin of the planet until it orbits with one side always facing the star (just as our Moon always shows the same face to Earth). The backside of the planet then becomes dark and uninhabitably cold, perhaps even cold enough to condense out any atmosphere.

There are several other causes of instability that could have affected life on Earth. The interaction between planets in a system can change some of the orbital characteristics of every planet. The Earth's orbit is fairly circular, which implies that its distance from the Sun is fairly constant. Even so, the orbit is not quite circular and the energy we get from the Sun varies by 6.9% from minimum to maximum and, depending how this falls over the seasons, this variation influences the range of climates in the Earth's hemispheres. The variation is probably enough to induce glaciation on a timescale of 20,000 years, not enough to wipe out life but enough to make significant changes to the balance of life. On a longer timescale, the eccentricity of the Earth's orbit varies due to the effect of other planets in the solar system (notably our nearest neighbour Venus and the big planet Jupiter). A more eccentric orbit creates greater climate changes. One informed estimate from a computer simulation of randomly chosen versions of our solar system is that only 1.5% of them produced conditions on Earth as stable as they have been. Another instability induced by other planets is tipping of the spin axis of a planet. Mars' axis has much the same tilt as ours at the moment, though it has tipped as much as 60º in the past; Uranus' axis is on its side; Venus axis is up-ended. Altering the axis tilt makes big changes to seasons, changing all ecosystems on the planet: perhaps not life exterminating but certainly making for environmental instability on a planetary scale. Our particularly large Moon is credited with stabilising the Earth's spin axis so that it varies by only ±1.2º at present. Are we lucky to be alive? It's beginning to look that way.

Being in the right place relative to our neighbouring star isn't the only issue. Being the right size is also important. The Moon is in almost the same place relative to the Sun as the Earth, yet it is lifeless. The Moon is about a quarter of the Earth's diameter: too small. Mars seems lifeless now. It is about half the Earth's diameter. Is it too little as well? What's going on? There are several effects related to the size of the planet. First, liquid water evaporates. Given a few dry days, puddles dry up and disappear. Their water goes into the atmosphere. Given millions of years, will the atmospheric water itself evaporate into space? Water molecules are lighter than all the other important constituents in our atmosphere: nitrogen, oxygen, argon, ozone, carbon dioxide. Water will stay in the atmosphere if the local gravity is strong enough. A planet or moon's surface gravity is determined by its density and its radius and for similarly composed bodies the larger the radius the larger the gravity. The Moon's gravity at 0.17 times the Earth's, which isn't enough to hold on to water vapour (or any other common atmospheric gas) for the lifetime of the solar system even though it's more than hot enough during the lunar day for liquid water to sit on the surface. Mars' gravity is 0.38 times the Earth's, still not big enough to hold onto its water vapour.

Being a lot larger than the Earth isn't a particular benefit either. For instance, with gravity five times the Earth's it would take five times the energy to lift anything a metre off the surface, five times the effort to move. Twenty centimetres would be a very respectable leap off the ground for us. An atmosphere containing the same amount of gas as ours and at the same temperature would be five times as dense on the surface, making movement harder and wind more destructive. Even a denser atmosphere wouldn't stop most objects having almost five times the kinetic energy if they fell down and hit the ground. Waves on the sea would be lower and one imagines, at least, that the advantages of living in the sea would outweigh any attractions of a land more suited to crawling, creeping and slithering than standing upright. Imagining what might be in such a place is just science fiction, given our present knowledge, but it certainly would not be a land of animals and plants as we know them.

Size also controls the ability of a planet to hold on to some of its primordial internal energy. Internal energy comes in the form of heat of formation and radioactivity. The Earth has enough to sustain a large liquid core and mantle upon which its crust of rocks sits, or rather floats. This has had two important consequences on Earth. Water plus heat has given rise to plate tectonics, the water providing the lubrication for the advancing edge of a tectonic plate to slip underneath its neighbour, pushing it up. Plate tectonics builds land, counteracting the effects of erosion. Plate tectonics recycles calcium (needed to build skeletons, shells and teeth at least) that would otherwise be locked up in calcium carbonate rock (limestone) and recycles carbon dioxide, also locked up in limestone but needed to sustain plant life on land. Too much water of course would result in no land at all: no tidal pools, no grass, no dinosaurs, no birds, no insects or apes. Mars and Venus now have neither surface water nor plate tectonics.

A large molten core generates a magnetic field too, whose most important life-supporting effect is to deflect energetic solar wind plasma around the planet. The combined effect of magnetic field and an atmosphere comparable to the Earth's in thickness is to shield life from the destroying effects of the solar wind and cosmic rays. The magnetic field also helps prevent the atmosphere being stripped away by the solar wind. The Moon, Mars and Venus have no magnetic field worth speaking of; the Moon has no atmosphere and Mars very little.

A global ocean would provide shielding for life, too, but life beneath the waves, on Earth at least, has not lead to the development of animals who have invented technology, who have developed complex societies whose deeds have been recorded, who have discovered the existence in nature of radio waves, and many other achievements of us on land. There's no intrinsic reason why marine animals couldn't do all that but oceans provide long-term stability that isn't present on land, which leads us to another point.

Evolution requires change. Static conditions don't encourage change. The path from self-replicating molecules to single-celled organisms to multi-celled creatures to the life we see around us is very long. In detail, as far as we can tell, evolution has followed one of an uncountable myriad of paths that life could have taken. What has driven the evolution of life along its particular path on Earth has been environmental change due to events whose timing and detail have been almost random, though whose inevitability has been less so. It's frequently said that 99.9% of all species of life have become extinct. Maybe the figure is even higher since we have only a hazy notion of species that existed very early in the Earth's history. As Carl Sagan pithily put it "*Extinction is the rule. Survival is the exception*". A background figure for the change in species is that one species in a million becomes extinct every year from 'natural evolutionary causes'. New species arise, too, though if you look in Darwin's 'Origin of Species' you won't find a figure for this, only an argument that the same mechanism that produces variation within species over a modest timescale produces new species over a longer timescale. Over the Earth's history there have been at least 5 periods where natural causes have been drivers of massive, comparatively rapid evolutionary changes, changes that have been accompanied by 'mass extinctions' involving a loss of at least 50% of the then current living species and, in the aftermath, the creation of new species to fill the ecological gaps in the new order. Mechanisms that have driven these 'disasters' (from the point of view of continuity and stability) have been plate tectonics, glaciation ('snowball Earth') and meteoric impact.

Plate tectonics provides a mechanism for evolutionary change. Plate tectonics generates moving continents, changing landscapes, earthquakes and volcanism, all of which impinge on life. Sometimes plate tectonics has induced quickly acting pan global effects. At one time almost all the Earth's land was one continent (Pangaea). At the end of the Permian period great rifts appeared in what is now Siberia, outpouring lava, rock and gases for some half-a-million years on a scale probably not seen since the early Earth. Over 80% of the Earth's species became extinct as a result of the sustained degradation in conditions for life. This was some 250 million years ago. Amongst the life that went were forests, soil churning animals and trilobites, a group of scuttling shallow water animals of great diversity that had evolved and survived changing conditions for approaching 300 million years. In the Triassic that followed, the dinosaurs rose to prominence, surviving for over 150 million years. Their demise came from another natural driver of evolution, meteorite impact. Yet another natural cause of change, possibly also the cause of mass extinction on Earth, is climate change resulting from the long-term effects of modest orbit change.

The point of this apparent digression into species extinctions is that one needs stable planetary conditions to sustain life but one also needs evolution to develop life. Evolution needs change to drive it. Too much stability won't promote evolution. There are natural change mechanisms but they can be present in too great amounts or too little. Too much volcanism and life is constantly set back; likewise with too much meteoritic impact or too much orbit change. Too little, and evolution is slow even on a geological timescale. On the Earth, matters have turned out by a combination of chance and circumstance right enough for me to be writing this on a computer and you to be reading it, probably on a computer too. Are we lucky to be alive? I would say, 'incredibly so'.

Is it luck that some form of intelligent life is present on the Earth after some 4.6 billion years of the Earth's existence? I have no idea. Put another way, would we expect to find intelligent life on a similar planet around another star? Events on Earth could easily have turned out differently. We don't differ genetically very much from many other animals alive today (who have all also had the benefit of approaching 4 billion years of evolution) so it seems to me quite possible that other species could have developed comparable intelligence in a very similar time (on the geological scale), if we hadn't. Major events influencing evolution could have turned out differently so that terrestrial evolution might have been speeded by half a billion years, or set back by an even greater length of time. I believe that we are certain to find life on another planet like the Earth (an 'exo-Earth') but it's far from certain we'll find life any more advanced than mats of algae, or perhaps an alien version of trilobites or dinosaurs.

What of the future? It's a pity that the woolly mammoth, the sabre-toothed tiger, the rhea, the dodo, the quagga, the Tasmanian tiger and a good many more animals have become extinct in more or less historical times, on our watch if you like. The world could well be a more interesting place if they were still with us. It's a pity my father and grandfathers are dead, for the world could well be a better place in a very small way if they were still with us. Death, however, is both natural and essential; the extinction of species has been both natural and part of evolution. That said, evolution entered a new phase many thousands of years ago. Selective breeding has generated a huge variety of dogs, for example, that would not have existed on Earth but for mankind's involvement. The same is true of cats, pigeons, cows, sheep, chickens, peas, wheat, tea, coffee, apples and pears and almost any animal and plant involved in the domestic economy. Selective breeding seldom generates new species, though Darwin argued that it was only a matter of time, and of course is no moral excuse for thoughtlessly exterminating existing species.

Selective breeding introduced a non-random element into evolutionary change. Direct genetic manipulation takes this to a new level. Looking back in time, our forbearers used to make most of their domestic artefacts directly from natural products. Think of leather or linen clothes, wooden furniture, clay pots, flint axes and so on. None of these items occurred as part of the natural world (i.e. the world without human influence, though there's nothing 'unnatural' about people). Their presence in archaeological sites tells us that humans once lived there. Now look around a modern house and the very materials from which many products are made are totally artificial: the plastics, the paint, the silicon wafers, the optical glass and much more. What will we see if we look around in only 1,000 years' time? My prediction is that much of the plant life and some of the animal life will be the product of directed genetic manipulation. Change will have taken place on a timescale of centuries, not the timescale of geological eras. Directed evolution will have largely replaced the 'random' evolution of the past that was driven by large-scale environmental events.

This is not really a new trend. For example, virtually none of Britain's landscape today is what it would have been if mankind hadn't settled here after the last ice-age. In the process of changing the landscape many co-habiting 'naturally established' species have either been reduced to clinging on in tiny niches or have gone altogether. In large animal terms, think of bears, boars, wolves and beavers for a start: not extinct species, but eradicated from Britain by the simple process of deliberate countryside change and hunting. Some effort is now being spent on re-introducing at least wolves and beavers. This opens up a question beyond our scope, namely how much room is there for species in a managed ecosystem? Clearly there isn't room for every species that has ever lived on Earth. The accelerating trend of evolution in its broadest scope creates responsibilities for the human race that match anything we have had to face up to in the past.

What has all this to do with planets being in the right place and of suitable size? Just that when we look for life on other planets, we shouldn't expect that we'll always find life that is a product of the kind of evolution we've known until now. We may well find planets whose biospheres are entirely filled with the products of directed evolution, the result of millennia, or more likely millions of years, of control by the indigenous intelligent life. On the other hand, we may just find just mats of bacteria, seas soaked in archaea, or something else intriguing but primitive. Indeed, if you are not a believer in the cosmic imperative of life, you will not be surprised to find no life at all on perfectly habitable planets.

Finding a possible exo-Earth is likely to happen within a few years. Being able to tell what kind of life it has could take a century, or more. Before that, we need to look closely at what life our own solar system has to offer. We may still find life beneath the surface of Mars, perhaps, for the case is not yet settled. Might we find it in the atmospheres of Venus or the major planets? Beneath the surfaces of Europa, Titan, Enceladus, or other moons? There are quite a few candidates for places that might support some form of life closer to home than exo-Earths. Even so, it won't be easy or cheap to find out. I'd like to be around when the first definitive answers arrive.

*JSR*

*Footnote*

[1] Look for recent publications by names such as J. Horner, B. W. Jones or D. Waltham for deeper and more quantitative discussions of some of the topics mentioned here.