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By

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PREFACE

Astrobiology has been rapidly emerging as a field of intense scientific and technological activity. The numerous recent space probes to various celestial objects, including comets and asteroids, to look for the possible existence of alien primeval life, have attracted much interest. It began with the Viking landings on Mars, followed by several other spacecraft. The Galileo Mission to Jupiter, and the Cassini Probe to Saturn, revealed that several of the moons of these giant planets could contain vast quantities of water beneath their surfaces. Europa, Ganymede, and Enceladus are all examples of this. Titan's intriguing liquid methane atmospheric cycle appears similar to that of Earth's water cycle. The icy worlds of Pluto, and the TNOs, beyond could also contain the crucial compound we know as water. So far, our own pale blue dot (terra firma) is the only celestial body known to definitely host life, and we do observe a wide diversity of life on Earth. It is of great interest to discuss the origin of life on Earth, including aspects such as the biological 'Big Bang,' large numbers in biology, the optimal design of several species, extremophiles, etc. The possibility of life on other objects in our solar system, especially on the satellites of the giant planets, is also of current interest.

The existence of over 3000 exoplanets has thrown up a menagerie of possible abodes for exotic life. Several of them are in their star's habitable zone; many suspected to hold more water than Earth. There are several planetary space missions currently in operation, and plenty are planned for the future. Several aspects of the suitability of life on exoplanets include: discussion on habitable zones, searching for suitable atmospheres, and biosignatures. Recent discoveries of Earth-like planets orbiting stars, such as TRAPPIST-1, Proxima Centauri, Ross 128b, Kepler-10c, Kepler-186f, Kepler-452b, and several others, have certainly piqued interest in these discussions. Besides, topics such as the role of magnetic fields in making planets habitable and hotter than many stars are of great interest within an astrobiological context.

The book further draws attention to the possibilities of life on free-floating exoplanets, which may be numbered in the billions. This will include a closer inspection of the environments that influence the origin and evolution of life, including the presence of chiral organic molecules, molecules such as methyl isocyanate, etc. The Astrobiological effects of radiation, including Poynting-Robertson Drag, lethal doses due to stellar activity, and even the possibility of white dwarf systems containing the building blocks of life are explored to arrive at a sound understanding of the sustainability of life on alien worlds. It is of further interest to discuss recent ideas regarding the origin of life in the Universe, and the earliest possible life in the cosmos (e.g. the detection of oxygen in a very distant galaxy and the presence of an extra-galactic hot molecular core).

Cosmological effects, such as the implications of a dark-energy-dominated universe for astrobiology, the astrobiological implications of neutrinos, and the influence of powerful blasts of gravitational waves on biological life, are further elaborated. Intriguing connections between bioenergies and stellar luminosities, the implications of population III stars for early life, and the significance of a universe without antimatter are further examined. Among other possibilities, the idea that primordial black holes can sustain longest-lived living systems is also suggested.

Astrobiology is a highly interdisciplinary subject area, involving astronomy, physics, biology, geology, chemistry (among the sciences), besides being a technology-intensive discipline. Methods to detect possible advanced alien technology require all available areas of human technology. Future telescopes, such as Colossus, can look for infrared radiation from Dyson spheres, high resolution spectrographs can search for powerful alien lasers and detect exotic elements and biomolecules depicting unique signatures. The use of the FAST radio telescope to look for reflected radio signals from ET artefacts (in the solar system) is also discussed. Alternative standard frequencies for interstellar communication and modification of the Drake equation are suggested.

Astroengineering activities (such as possible alien mega-structures around stars, sub- Hubble lifetime primordial black holes) are also mentioned in the book, with methods to detect them. It further suggests the relevance of ET artificial intelligence and ETAI searches in the future. Conveying the concept of time to ETs, and looking for other advanced signatures of their presence in interstellar space, are other topics discussed. Furthermore, the human influence effecting terrestrial life (the decimation of other species, global warming, the Paris climate accord, man’s role as the biggest exterminator) is elaborated. Warnings about humanity’s future, and the consequences for ETs, are other topics of current interest addressed in the book.

In short, by selecting a wide range of current hotly-discussed topics in astrobiology, we hope to convey the excitement of a growing new field with all of its multidisciplinary ramifications. It will hopefully stimulate interest in young researchers, scientists in other disciplines, as well as cater to the general reader.

As a highlight of this endeavour, we have included sixty-five numerical problems covering most of the diverse topics discussed in this book, with hints for solutions being provided for about half of them. The reader may enjoy browsing through these problems, and work through them at their leisure. We hope it will stimulate a creative interest in this emerging subject and draw some readers into advanced research.

We may add that the present authors have had several years' experience in offering academic courses in astrobiology (and its wide ramifications) at various levels, including graduate and outreach programmes. The Astrobiology Newsletter — for which the authors serve as editors — was started in 2004, with the intention of delving more deeply into the wide spectrum of topics this subject addresses. Over the past five years, more than four volumes, with a total of 25 issues (on average six a year) have been published. This regularly published newsletter is now available at researchgate.net and saganet.org. An earlier textbook entitled "Introduction to Astrobiology" (C. Sivram and A. Sastry, Universities Press, 2004) proved to be immensely popular, furnishing the basis for many courses conducted on the subject.

We hope this present work — with its updated inclusions on various aspects of this diverse subject, along with the large number of problems provided—will echo its predecessor in merit and attract the same support from readers.

CHAPTER I

WONDERS OF LIFE ON EARTH

In this chapter we consider some of the remarkable wonders characterising various forms of life on Earth, starting from the simplest organisms, to those involving complex structures and organisations. Earth is the only planet (or even celestial body) known, thus far, to definitely have life in all types of environments, and in extremely diverse forms. But when did the earliest forms of life occur on Earth? Recent work in the area will direct our attention to the Naica crystal caves. Their origin has been dated back to more than 3.5 billion years. For the first four billion years, life on Earth was mainly populated by microbes. However, many thrived in hostile environments, such as the tardigrades. Terrestrial terraforming by algae could have transformed life on Earth into more complex forms. Meanwhile, increasing oxygen levels could have led to the Cambrian 'biological Big Bang' 550 million years ago. The Carboniferous era saw the domination of broad-leaved plants using photosynthesis to increase atmospheric oxygen. Trees continue to be the most dominant life form on Earth, contributing significantly to the biomass. We explore some of the incredible features of terrestrial life, both past and present.

Human organs, such as our eyes and ears, are optimal by the laws of physics. The eyes of an insect, wings of birds and flying insects, metabolism, heat production, etc., along with heart and brain power, demonstrate Nature's meticulous and optimal design. This paved the way for the inclusion below of discussions focusing on the fastest flying animals, universal bioluminescence, and whether or not dinosaurs were ectotherms. Intriguing coincidences, such as large numbers in biology, and the universality of mass to area ratio (underlying both biological and astronomical systems) are revealed. Damuth's law, continental drift and its impact on life, and Earth's weakening magnetic field are among other topics discussed.

Advanced technology practiced by ‘primitive’ biological systems

Even with our ever-growing technological prowess, we have a lot to learn from the advanced survival techniques adopted by several primitive biological life forms. We present here two recent examples, one of which has inspired a new technology adopted by NASA in its design of more sophisticated spacecraft for use in flights to Mars.

The only known animal to have bifocal lenses is apparently the larvae of the sunburst diving beetle. The larvae have a complicated eye structure that enables them to catch prey at a distance of less than half a centimetre. They have six pairs of eyes, including two pairs of bifocals that focus light on two slightly different planes. This, combined with a second retina, helps them to accurately judge distance to the prey. However, when the larvae mature the beetle loses this optical arsenal, returning to the normal compound eyes characteristic of insects. This could well inspire new optical devices for detection and close ranging.

Another example, which has already inspired a new design for a Martian spacecraft, is the behaviour of the Hawaiian puffer-fish which, in spite of being a poor swimmer, can quickly intake large quantities of water in order to convert themselves into virtually inedible balls several times larger than their usual size: thus confounding chasing predators. This is only a defence mechanism for the Hawaiian puffer-fish, but NASA has incorporated this ‘trick’ in their LSPD vehicle, i.e. low-density supersonic decelerator, being test flown, coincidentally, on the Hawaiian island of Kauai. This technique will make it possible to land heavier spacecraft on Mars. It is a saucer-shaped experimental vehicle that uses a six metre diameter, solid rocket powered balloon-like vessel, designated as a Supersonic Inflatable Aerodynamic Decelerator (SIAD). It aims to reach an altitude of forty thousand metres, using a helium filled scientific balloon that, when fully deployed, will swell to about one million cubic metres, thus displacing a thousand tons of air at ground level, i.e. a lifting capacity of this order. The design, to repeat, will enable heavier spacecraft to be used on Mars.

Thus we witness the remarkable ingenuity, manifested by several living organisms, necessary to survive the vagaries and hostilities of the environment found on Earth. One can only conjecture how life would have adapted to survive on other worlds with a more hostile environment.

Subterranean life

The presence of deep microbial biomes thriving on hydrogen compounds such as H_2S, indicate that Earth's deep crust could host living systems. In 2006, microbes residing four kilometres below the Witwatersrand Basin in South Africa, and existing on hydrogen, were discovered. The possible presence of such novel living systems raises the possibility of Martian microbial life (below the surface permafrost). These sub-surface bio-systems are not dependent on photosynthesis. Hydrogen production from several boreholes indicate that the oldest rocks of the pre-Cambrian continental lithosphere produce about one hundred times more gas than was previously estimated.

Sites having primordial water (trapped for one billion years) in Finland, Iceland, etc., and having high hydrogen levels, suggest, apart from the Witwatersrand Basin, that there may be other sub-surface places hospitable to microbial life. The Miller-Urey experiment made the 'primordial soup' hypothesis popular: the original 'warm little pond' of Charles Darwin. However, alternative theories (concerning the presence of sub-surface life) suggest that the primeval assembly of self-reproducing molecules might have occurred in the interiors of tiny rock pores located in the vicinity of deep sea vents (e.g. tubeworms feeding at the base of hydrothermal vents). In this scenario, the first cells need not have had membranes to shield them from hostile environments. However, these theories would only apply to planets having plate tectonics leading to deep-sea vents. Among the terrestrial planets, Earth is the only one known to have active plate tectonics. The presence of vast amounts of water (maintained by geysers and volcanic vents) in the rocky interior seems an essential prerequisite for plate tectonics, which is also crucial for creating and maintaining the oceans and atmosphere that are essential for life.

Recent studies show that plate tectonics on Earth began a billion years earlier than thought. For example, M. Hopkins et al. (Nature, 456, 493, 2008) found evidence of plate tectonics in zircon deposits that were formed about four billion years ago. These zircon crystals have formed in subduction zones, where one tectonic plate plunges below another. This seems to indicate the existence of active plate tectonics nearly four billion years ago, something that is consistent with the estimated ages of the oldest known fossils.

How early did life begin on Earth?

Based on fossil records, it is generally thought that life on Earth began 3.8 billion years ago in the form of single-celled creatures. However, an ancient zircon crystal, collected in Australia (by Jack Hills), is believed to contain a carbon deposit 4.1 billion years old. It is completely enclosed in the undisturbed (and crack free) zircon crystal, suggesting that a more recent geological process has not contaminated it. The collection involves some ten thousand ancient zircon cells dated as several billion years old (E. Bell et al., PNAS, 112, 14518, 2015).

Thus it appears that life originated on Earth barely half a billion years after its formation: 4.6 billion years ago. In this context, it is interesting to note that the earliest stars (and primeval galaxies) formed in the Universe less than half a billion years after the Big Bang (hot dense phase): A remarkable coincidence, perhaps?

Naica crystal caves host long dormant life

Recently, bacteria and archaea were detected buried deep in the caves of Naica (in Mexico), beneath Limestone Mountains used by miners in search of silver a century ago. The director of NASA’s new astrobiology institute in Moffett Field, California, Dr Penelope Boston, reported this discovery at the annual meeting of the American Association for the Advancement of Science (AAAS). The organisms were encased in shafts of gypsum, possibly as old as 50000 years. They were able to revive them in the laboratory.

Microbes were isolated from outsized needles of gypsum grown over the years (crystals metres long). They were, presumably, a class of extremophiles, thriving in extreme conditions of heat (70^0C), humidity and an acidic environment. At those depths no light can penetrate, implying that microbes must obtain heat from processing rock minerals and use chemosynthesis (rather than photosynthesis) to thrive. Defects in the long gypsum needles (like voids) collected fluids and encased the microbes.

Thus it appears that the famous giant crystals of Naica Mine host dormant life, making them very relevant to the search for similar life forms beyond Earth (maybe below Martian surface). There have been previous claims connected with the revival of bugs supposedly dormant for millions of years, trapped inside salt or ice crystals, as well as insects trapped in amber. However, such claims have been controversial. Perhaps the first life forms to be detected outside Earth (including Mars) could well be such dormant entities.

The gypsum cave organisms are apparently not related closely to anything in known genetic databases. At least, terrestrial life has the ability to cope and adapt to most hostile environments.

Tardigrades could exist in hostile alien environments

As astronomers eagerly search for water-dominant exoplanets, and look for planets in the habitable zones of their parent stars (where water can exist as a liquid) as suitable abodes for ET life, we should bear in mind the existence of tardigrades on Earth: considered the world's toughest creatures with incredible survival abilities. These miniscule creatures (also called water bears) can survive intense radiation, freezing cold, extreme dehydration and even the vacuum of space. The DNA of two species of tardigrades has now been decoded, thus revealing the genes that enable them to be revived even after desiccation.

Recent studies have indicated that these, the toughest terrestrial creatures, could survive almost any cosmic disaster likely to befall planetary worlds. They can survive extreme dehydration and are capable of springing back to life after several years when placed in the presence of water. Their key to survival is genetic. Extreme dry conditions trigger the organism's genes to produce proteins in their cells. When water is available, it refills these cells, dissolving the proteins. An understanding of this survival skill could have spin-offs, such as vaccines being stored and transported without refrigeration.

Most animals have ten so-called HOX genes, but tardigrades have only five. Most roundworms lack the same five, so tardigrades may be closely related to worms. In any case, their ability to survive extremely dry (waterless) conditions and be successfully revived many years later, shows that even dry exoplanets could host such life.

Did terrestrial terraforming by algae transform life on Earth?

A strange aspect of terrestrial life, not yet adequately explained, pertains to the fact that, although our planet has had long-life-sustaining oceans (and benign climates) for over three billion years — for 3.8 billion years according to current estimates — all life on Earth was initially single-celled, mostly bacteria. Hardly any evolutionary innovation had taken place for three billion years. Algae, more complex than bacteria but still single-celled, had been in existence for one billion years (some biologists call it the ‘boring billion’) without causing much ecological change.

However, large complex organisms appear in fossil records from about 600 million years ago, with their DNA tightly and safely enclosed inside a nucleus. These are eukaryotes, which like all plants and animals today had an evolutionary advantage over bacteria. Recent work suggests that it was the planetary takeover by oceanic algae, about 650 million years ago, which initiated the transformation of terrestrial life. The events leading up to this apparently took place 100 million years before the Cambrian explosion, describing an eruption of complex life, recorded all over the world, that puzzled even evolutionary pioneers such as Darwin. This suggests some ‘biological prehistory.’

The evidence for this ecological kick comes from the work of Jochen Brocks and his team (at the Australian National University) who drilled sediments into the bedrock below the Australian desert, digging up tiny traces of biomolecules, which have been traced to the molecular remnants of algae cell walls. These molecules are related to cholesterol and appear very stable in organisms (nanogram traces of pre-Cambrian oil picked out from the fog of contaminants measured). It turns out that these fat molecules were absorbed into sediments, and over geological periods, became embedded into the bedrock only to be now drilled up and analysed 600 million years later. These molecules mark the explosion of oceanic algae, with their population perhaps increasing by a factor of one thousand. The diversity shot up in one biological Big Bang and never shrank again.

Remarkably, this evolutionary flip occurred after one of the greatest environmental catastrophes the Earth underwent (the so-called ’snowball Earth’), when ice covered the planet pole to pole, with equatorial temperatures plunging to -60^0C (C. Sivaram and A. Sastry, *Introduction to Astrobiology*, Universities Press, 2004). The build-up and eventual eruption of volcanic CO_2, causing a ’super greenhouse’ effect, ended this episode after 50 million years. According to Brocks, the glacial action released nutrient phosphates, which were washed away into the oceans as thawing progressed. The contemporary agricultural green revolution is dependent on phosphates (excavated in mines all over the world) and perhaps the pre-Cambrian biological evolution was similarly powered. At a recent Goldschmidt Geochemistry Conference in Paris, Brocks and Butterfield debated whether the explosion of algae drove the rise of animals or, rather, that the rise of animals, like sponges, paved the way for algae.

Trees as a dominant form of life

A recent estimate, made by a global group of 38 researchers (T.W. Crowther, et al., Nature, 525, 201, 2015), puts the total number of trees on our planet at a colossal three trillion (more precisely 3040 billion). This implies that there are more than 420 trees for every person on Earth (the world human population having exceeded seven billion). So the largest amount of biomass on Earth is in the trees (estimated to be about 1.5 trillion tons). The total mass of human population would be a mere three hundred million tons (five thousand times less). The quadrillions of insects and worms are estimated to have a biomass of fifty billion tons (about two hundred times more than humans). Thus, with all of the congestion and pollution we face in our grossly overcrowded cities (especially in third world countries), our total biomass is trivial when compared to green vegetation and lowly insects.

How many trees are there in Bangalore? According to a report published by the Indian Institute of Science (May 2014), there are 14.58 lakh trees for a city populated by nearly a hundred lakh (10 million) people. This means that there is only one tree for every seven people, 3000 times less than the global average (in July 2014 about ten thousand trees were axed for development). As is well known, there is a symbiotic relationship between trees and animals. We intake (inhale) oxygen, the waste product of plants, and emit (exhale) carbon dioxide as waste, which is consumed by plants and converted into oxygen through photosynthesis, which builds up starches and sugars for our food consumption. Ecological equilibrium is maintained as long as this input and output remains balanced.

However, as we continue to burn large amounts of fossil fuels and chop down twenty billion trees every year to construct more building spaces, we destroy a natural source of carbon dioxide consumption (the trees) and add to global warming by pumping at least a billion tons of excess CO_2 into the atmosphere every year. Indeed, the earliest plants and trees (formed in the carboniferous era, 400 million years ago) changed the atmospheric composition to one-fifth oxygen, leading to advanced animal life, and culminating in humans. We are undoing this legacy through deforestation. Would trees dominate Earth-like planets, especially if oxygen is crucial for advanced life?

Biological Big Bang and oxygen levels

About 600 million years ago, there was an explosive increase in the number of animal species and living systems. It is now considered likely that this was kick-started by increased amounts of oxygen. More than 700 million years ago, the oxygen level of the Earth's atmosphere was hardly one per cent of today's levels. A recent study, involving the measuring of selenium isotopes, shows that in one hundred million years the oxygen level rose to over ten per cent of today's levels. This ushered in the age of animal life.

Hitherto, it was not known how quickly the Earth's oceans (atmosphere) became oxygenated. Oceanic microorganisms such as phytoplankton are also currently responsible for releasing much of the Earth's oxygen. But it is estimated that global warming is already reducing their population, thus posing a risk to future oxygen levels in the atmosphere, which could, in turn, affect advanced animal life.

The 'biological dark matter' problem

The so-called dark matter (DM) problem is well known in cosmology. We do not know the makeup of at least 95% of the Universe. Our type of matter (baryonic), consisting of familiar atoms and molecules, many crucial for life, supposedly constitutes barely 4% of the total matter in the Universe. At least 70% is in the form of a mysterious dark energy (DE), which exerts negative pressure and causes gravity to become repulsive, thus accelerating the expansion of the Universe at the present cosmic epoch. The remaining 25% or so comprises of the dark matter that dominates the masses and clusters of galaxies. There are several dozen postulated candidates for DM, ranging from axions, WIMPS, MACHOS, gluinos, Q-balls, neutralinos, etc., with several on-going experiments making dedicated searches without arriving at any positive result so far (K. Arun et al., Advances in Space Research, 60, 166, 2017). Moreover, the problem is growing more acute, as recent observations have indicated the presence of ultra-diffuse galaxies (UDG) with more than 98% DM. Indeed, there is a galaxy with 99.96% DM, with the DM mass several thousand times the combined masses of the stars (Beasley et al., Astrophysical Journal Letters, 819, 2, 2016). There are many such galaxies almost wholly made up of DM.

Biologists have recently come up with their own version of Dark Biological Matter (DBM), i.e. completely unknown species. Earth is suspected to be home to at least one trillion species, but hardly six million are catalogued. Thus, this indicates that 99.999% of the species on our own planet are unknown: we are in the dark about them. They are not identified, but we know they exist. When biologists at Indiana University (Kenneth Locey and others) compiled microbial, plant, and animal community data from all sources, it totalled only 5.6 million species on land, sea and air. Research shows that the world is teeming with undiscovered species, many thousands more than those identified and classified. Thousands of new species are being discovered every year (frogs, toads, insects, etc.) but the number of unknown (dark) biological species is far greater.

The identification of these unknown species is a challenge for biologists, just as the identification of the true nature of dark matter and dark energy (DE) are for cosmologists. Earlier, the total mass of insects and bacteria microbes (so-called low forms) was estimated to be several quadrillion tons, compared to a puny two hundred million tons for all humanity. We have of course exterminated thousands of species, including several million of our own. We just do not have the resources (manpower, financial, or technical) to identify most of the species on our own planet in the near future. As astrobiologists keenly look for life forms in faraway worlds — even beyond the solar system — it should be humbly borne in mind that we are still unaware of most of the different life forms (many exotic and thriving in extreme conditions) lurking and living under our own feet. This lack of awareness is similar to our limited comprehension of the DM in our solar neighbourhood.

The humble dung beetle, like Earth, may well be sustained and nurtured by these trillions of unknown species, perhaps long after mankind has ceased to exist. The International Day for Biological Diversity (22 May) is a reminder of how little we understand the ubiquitous diversity of living systems on our own planet. Again, while decoding the human genome with its billions of nucleotides, it turns out that 98% or more of our DNA genetic material has no known function and is dubbed junk DNA. This can be thought of as ‘dark’ genetic material or dark DNA. Perhaps the very use of the adjective ‘dark’ to describe all unknown constituents, either in cosmology or biology, is synonymous with our ignorance of actual reality despite the vast accumulation of knowledge and data.

Our optimal organs

The idea that biological structures are ‘optimal’ is finding support. It has long been known that the human eye is close to the diffraction limit.

This can be easily shown. The resolution of the eye is about one arc minute. Thus $\theta \approx \lambda/D$ where λ is the wavelength at which the eye is most sensitive, i.e. 550 nm. Coincidently, the Sun also emits its peak radiation at this wavelength. D is the diameter of the pupil of the eye and is 0.2 cm. Thus:

$$\theta \approx \frac{\lambda}{D} = \frac{5.5 \times 10^{-5}\, cm}{2 \times 10^{-1}\, cm} = 2.7 \times 10^{-4} rad \approx 60\,\text{arcsec} \approx 1\, arcmin$$

The eye can also receive individual photons. The threshold of vision is about a billionth of a candle power. From a sixth magnitude star (naked eye threshold), the eye receives six visible photons (as a rule of thumb). For a planet orbiting a red dwarf, what should be the pupil diameter to get the same resolution? It would have to be twice as large. Such organisms (humans) would have bigger eyes, in fact twice our size.

While the human visual system operates at a single photon level, our auditory system (threshold 10^{-16} W/cm^2) is limited by thermal noise. Sea sponges develop single mode optical fibres that rival current technology (V. Sundar et al., Nature, 424, 899, 2003), while micro-cavities in the brittle star skeleton act as perfect lenses (J. Aizenberg et al., Nature, 412, 819, 2001).

The fluid-filled semi-circular canals of the vestibular system are essentially of the same size for all mammals from mice to whales. The semi-circular vestibular canals of fish, reptiles, amphibians, and birds are of similar size, pointing to an underlying natural optimal design (G.M. Jones et al., Proceedings of the Royal Society of London B, 157, 403, 1963). We should try to understand the optimality of biological structures on Earth and then attempt to explore similar possibilities on other worlds.

Heart power and brain power

At each contraction of the ventricle, about 75cc of blood per second flows out and the average blood pressure is about 100 mm of mercury. This implies that the power exerted by an average heart is about one watt.

Thus with a population of about ten billion, the total heart power is ten gigawatts (ten thousand megawatts) or about 0.1 per cent of the total installed power plant capacity in the world. On different habitable planets, would the power consumed by a heart pumping blood be different? Could a higher ambient atmospheric pressure increase the power required? What about the surface gravity of planets?

A bird's heart beats several times faster than man's (as it does for smaller mammals like mice) but their lifetime is shorter. Therefore, the total number of heartbeats in a lifetime is roughly a constant for all mammals (about $3\text{x}10^9$). What, then, would be the power required for dinosaurs as tall as buildings (if the blood is to be pumped to such a height)? These are points to ponder.

The human brain consumes an average of around thirty watts of power. Although the brain has only about three per cent of body mass, it consumes about a fifth of the power. The brain carries out at least a hundred quadrillion operations every second, well above current state-of-the-art computing machines. So a population of ten billion would expend around 300 gigawatts (0.3 TW), i.e. three per cent of the installed power capacity in the world of around 10 TW.

For a power consumption of 30W, what is the theoretical maximum processing rate? How close is the brain to this? Is there an upper limit to brain size? One has to account for the heat produced by the brain, which will have to dissipate it through its highly convoluted surface while maintaining body temperature. These questions are relevant when discussing 'brains' of highly 'advanced' ETs or their robotic substitutes or counterparts.

Fastest flying animals: some interesting features

The flight characteristics of birds are still the unparalleled models for aeronautical design. Migratory birds such as swifts can reach 120 km/h in horizontal flight. When diving for their prey from a great height some falcons can reach speeds of 300 km/h. They follow the shortest cycloid path.

Recently, Brazilian free-tailed bats have been recorded flying at over 160 km/h in horizontal flight, making them the fastest flyers among the animal species. These nocturnal creatures literally shoot through the night skies at this speed. The study was conducted at the Max Planck Institute for Ornithology. Their longer than average wings, and aerodynamic projectile-like body shape, along with their low body weight (special bone structure) are the main factors contributing to their record-breaking flight speed.

Long and narrow wings enable faster flight than shorter and wider wings. The bats weigh around 12 grams. At 160 km/h, their kinetic energy in flight is:

$$K = \frac{1}{2}mv^2 \approx 12\,J$$

The power required or consumed during the flight is, Weight x v = mgv = 5 Watts.

For an athlete running 100m in 10s, an average horizontal speed is 10m/s. For a 70 kg athlete, the kinetic energy is ~3500 Joules and the power consumed by the athlete is: mg x v = 7 kilowatts ~10HP.

Mass for mass we are much brighter than the Sun (i.e. in infrared), we generate 120W. This is the steady power emitted by our body as a warm-blooded animal, related to basal metabolic rate. The ratio of the peak power of the athlete (running the 100m dash) to the steady power emitted is thus ~50. We might also draw attention to the curious coincidence that for smaller mammals, like rats (and also bats), the power emitted per gram is the same as the Eddington luminosity for stars (i.e. $10^5 ergs/s \approx 10^{-2} W/g$). For the 10 g bat mentioned above, this works out to 0.1 W, and the power expended by it in flight is 5 W.

Thus, for the Brazilian bat (the fastest flying animal), the ratio of the peak power required during flight to the steady power emitted (in IR) as heat over its surface is also 50/0.1 = 50, the same as that for the fastest human athlete.

Dinosaurs: endotherms or ectotherms?

There has been a lot of discussion and debate as to whether or not the colossal beings dubbed dinosaurs were warm-blooded (like modern mammals) or cold-blooded creatures. Warm-blooded terrestrial denizens seem to follow Kleiber's law, which relates the basal metabolic rate (BMR) to the mammal mass M. Thus:

$$B \propto M^{3/4} = kM^{3/4}$$

where *k* is more or less a constant value measured around 90 $kg^{3/4}$ Kcals.

Thus a human (weighing about 70 kg) has a BMR of 3000 Kcals, whereas a 5 ton elephant has B ~70000 kilocalories. A 5 g mouse would expend energy of 3 kilocalories to maintain its body temperature and thus has to constantly imbue nutrients (gnawing) to generate this heat. Furthermore, each of us humans emits infrared power of a few microns wavelength; appropriate to our body temperature of about 120 watts. Kleiber's law seems to hold over a wide range of warm-blooded creatures, from shrews to African elephants, (perhaps even blue whales which generate 200 W/m^2) i.e. over ten orders of magnitude.

So if dinosaurs were indeed endotherms, for a 50-ton gargantuan the BMR would have been six hundred thousand kilocalories, i.e. the equivalent of 30 kilowatts of power (glowing in the IR). This would imply that they would have been consuming several hundred kilograms of food every day (about one hundred tons per year).

How this would affect the ecology, or whether Damuth's law would hold, is to be studied. There has been recent work by J. Grady et al. (Science, 344,1268, 2014), whereby plotting (in a mass independent way) the growth rate as a function of the metabolic rate for 400 living and extinct animals shows that dinosaurs lie between endotherms and exotherms.

It is proposed that they are more like 'mesotherms,' a class of species that can raise body temperature (if required) but need not maintain it at any specific level. This could have restricted endotherms from becoming bigger (and dominating the planet) while competing with sluggish exotherms. In any case, the body temperature should not reflect much difference (compared to mammals), as the surface area scales as $M^{2/3}$, demonstrating a very insensitive dependence of temperature on mass.

We estimated that if dinosaurs were indeed endotherms, a 50-ton gargantuan, the BMR would have been a hundred thousand kcal, i.e. equivalent to 30 kW of power (glowing in the IR). This would imply that they would have been consuming about a hundred tons of food per year. So, our total world food production may not have been able to support more than a million dinosaurs worldwide.

We also suggested how Damuth's law, which holds in this context, is to be studied. The work of Grady et al. implied that dinosaurs lie between endotherms and exotherms. More recent work by R. Eagle et al. (Nature Communications, 6, 8296, 2015) appears to support this. They basically evolved a new method to chemically analyse dinosaur eggshells and gauge their body temperatures.

While the body temperature differed between different dinosaur species, the measured temperatures suggested that at least some dinosaurs were not fully endotherms. They could have been intermediate between crocodiles and modern birds. Endotherms have to eat a great deal to stay warm. For herbivorous dinosaurs (like Diplodocus) this implies eating a ton of vegetation daily.

The above team used a pioneering procedure to measure the internal temperatures of dinosaur mothers living 80 million years ago. The team found that the Titanosaur mother's temperature was about 38 degrees Celsius, close to a healthy human temperature of 37 degrees Celsius.

Titanosaurs are one of the largest dinosaurs (Tyrannosaurus is closely related to modern birds). The fossilised eggs were unearthed in Argentina and the Gobi Desert.

If warm-blooded, what, then, would have been the heartbeat rate of such dinosaurs? Small birds like canaries (literally hot-blooded) can have heart rates of more than a thousand beats per minute. For elephants it is twenty per minute. The scaling of heartbeat rate goes as: $(\text{Mass})^{-1/4}$, or inverse the fourth power of mass. So a 50-ton dinosaur could have had a heart beat rate of a very slow 5-10 beats per minute. How much heart power would they generate? For long-necked dinosaurs the heart must pump blood to the height of a building.

Universal bioluminescence

Ever since the first bathyscaph (pioneered by Piccard) descended into the depths of the ocean, it has been known that, devoid of sunlight, the benthic life (kilometres down) shine by their own light. The ocean depths are chock-full of bioluminescent life. New research at the MBARI (Monterey Bay Aquarium Research Institute) has now revealed that at least three quarters of the denizens of the deep, up to four kilometres beneath the surface, emit their own light, thus revealing their large numbers and amazingly diverse existence.

Over 350,000 such individual animals were identified by MBARI video technicians utilising the VARS database, which contains at least five million observations of these benthic creatures. It seems that the vast majority of deep-sea creatures have evolved to produce bioluminescence, which involves the production and emission of light by biological systems (including fireflies and glow-worms on land). The mechanism for producing the light involves luciferin, luciferase, and ATP (adenosine triphosphate), which is the universal molecule on Earth to generate cellular energy (via the Krebs cycle, etc.). If there is benthic life on Europa or Enceladus, are they likely to be bioluminescent? Could this serve as a beacon for future landers on these worlds?

Universality of mass to area ratio: from biological to astronomical structures

Astronomical structures ranging from super clusters of galaxies, to globular clusters, follow more or less a mass to radius squared ratio, i.e. M/R^2 of the same numerical magnitude given by, $M/R^2 \approx 1g/cm^2$. Curiously, this also holds for the Universe as a whole ($M \approx 10^{56}g, R \approx$

$10^{28}cm$). We interpreted this in terms of the universality of dark energy dominating the Universe and, as current observations suggest, it could be nothing other than Einstein's cosmological constant $\Lambda \approx 10^{-56}cm^{-2}$. We had the universal relation:

$$\frac{M}{R^2} = \sqrt{\Lambda}\frac{c^2}{G} \approx 1g/cm^2$$

(Here *c* is velocity of light and *G* is Newton's Gravitational constant).

It could be understood as a balance pressure of dark energy density $\left(\sim\frac{\Lambda c^4}{8\pi G}\right)$, balanced by the gravitational force pressure energy density $\left(\frac{GM^2}{8\pi R^4}\right)$, thus giving the above relation (for the observed $\Lambda \approx 10^{-56}cm^{-2}$). It was also of interest that even the electron and a typical hadron follows the same M/R^2 value (e.g. for electron $m_e \approx 10^{-27}g, r_e \approx 10^{-13}cm$ again implying $M/R^2 \approx 1g/cm^2$). Several other examples for other particles are also given in Sivaram (Astrophysics and Space Science, 215, 185, 1994). It is remarkable that the typical mass and radius of ancient (primordial) galaxies also seem to satisfy, the $M \propto R^2$ relation (M, R being the mass and radius of the galaxy). This ancient galaxy is found to be relatively small, about a tenth of the Milky Way, i.e. about one kiloparsec across. Also, its mass turns out to be about one per cent of that of our galaxy.

This M/R^2 ratio is more or less of the same value and holds for biological structures. The body mass index given by M/L^2 e.g. M ~50 kg, L ~2 m, is typically again $\sim 1g/cm^2$. This also holds for important individual structures in the body like the brain and skin. For instance, the typical brain mass is 1500 grams and the surface area of the brain (with the convolutions ironed-out) is about 2000 cm^2. This gives $M/L^2 \sim 1g/cm^2$. The total mass of skin is 5kg, covering one square metre, this gives $0.5gm/cm^2$. The same value holds for other structures including elephants and trees (a hundred metre tree weighs 200 tons, for instance). A mouse of 5 grams mass and 2 cm length gives $M/L^2 \sim 1g/cm^2$.

It is difficult to find a general physical basis for biological structures similar to the balance exhibited between repulsive dark energy and gravitational force for large astronomical structures.

It turns out that in the case of underwater behemoths like whales and other cetaceans it could be somewhat different, although within an order of magnitude. For cetaceans submerged in fluids (e.g. water), we have the drag force, $C_D \rho_W A v^2$ ($A \sim R^2$ is the area, ρ_W is the density of water, v is the velocity with which the organism can move on average), and the weight Mg (g is the acceleration due to gravity). Balancing these gives:

$$\frac{M}{A} \approx \frac{C_D \rho_W v^2}{g}$$

If $v \sim 20 km/h$, g = 980 cm/s^2, C_D = 0.1 – 0.2, then we have, $M/R^2 \approx 2.5 - 5$.

It is interesting to conjecture whether cetaceans existing below the surface of oceans on either Europa or Titan (their gravity being 1/7) have a similar M/R^2. If we assume M/R^2 does not vary much, on a lower g planet v would be higher (since v^2/g is a constant). A lighter fluid would produce a higher velocity, etc.

There is another curious coincidence: the densities of most biological entities are close to that of water. This is understandable, as most biological structures are predominantly composed of water; humans are seventy per cent water by weight, and blood plasma is ninety per cent water, as are many vegetables, fruits, etc. Curiously enough, the average density of main-sequence stars like the Sun and Sirius, as well as giant planets like Jupiter, etc. is again close to water density.

Even terrestrial planets have densities a few times that of water. Here the explanation (i.e. for stellar bodies) is quite straightforward. The average distance between atoms is the Bohr radius, i.e. 10^{-8} cm. So in a volume of 10^{-24} cm^3, we have a mass of 10^{-24} g (i.e. the proton mass since the electron mass is negligible). This gives 1 gcm^{-3}, i.e. water density. The radius of the Sun is $N^{1/3}$ x Bohr radius, N being the total number of atoms (mainly hydrogen) in the Sun. $N = 10^{57}$ for the Sun. This gives us the solar radius as just observed. $N^{1/3}$ just implies that the average separation is the Bohr radius. For heavier elements, constituting planets (rocky material), the density would be a few times higher. If we take the total number of atoms, say 10^{28} in a person, this implies a linear dimension of $\sim 10^2$ cm, which is the observed value.

When a star evolves, the core is compressed and the atoms are squeezed much closer together, so the densities now become higher. In a neutron star, the separation between neutrons is the nuclear radius of a fermi, so for $N = 10^{57}$ (a solar mass) we get a radius of ten kilometres, which is the neutron star radius. The density is a hundred trillion times that of water. For white dwarfs, the separation between squeezed 'atoms' is the electron Compton length, and this multiplied by $N^{1/3}$ gives the white dwarf a radius similar to that of Earth. The density now is a million times that of water.

Large numbers in biology

The lore of large numbers in cosmology and astrophysics is well entrenched, attracting the attention of stalwarts such as Eddington, Dirac, Dicke, Hoyle, Carter to name a few. Some of these numbers are 10^{38} (ratio of electromagnetic force to gravitational force between protons or electron and proton), 10^{40}, and their powers like 10^{19}, 10^{20} or 10^{57}, 10^{78} or 10^{80} (the latter three are the total number of nucleons in a typical star like the Sun (10^{57}) or of white dwarfs and neutron stars and the total number of nucleons in the Universe, i.e. 10^{78} or 10^{80}). We also have about $5x10^9$ photons per nucleon in the Universe and numbers like 10^{11} (number of stars in our galaxy or 10^{11} galaxies in the Universe) or 10^{19} (ratio of Planck mass to proton mass).

There is an exhaustive literature on the ubiquitous occurrences of these numbers in many cosmic phenomena from the Big Bang to black holes and dark matter, and many explanations involving basic Physics, apart from the anthropic principle. Are such numbers prevalent in Biology too? It is amusing to point out quite a few similar numbers involving parameters underlying biological structures.

For instance, the total number of neurons in a typical human brain is 10^{11} (the same as the number of stars in our galaxy and the number of galaxies in the Universe). Again, the human population is $7x10^9$, comparable to the number of photons per nucleon in the Universe. Now, in a typical large galaxy cluster there are 10^{15} stars. The total number of cells in our body is also 10^{15} as well as the total number of insects a few times 10^{15}. Each neuron is connected to a thousand axons, so the total number of brain cells is also 10^{15}. The number of stars in our local group of galaxies is around 10^{12}, the same as the number of trees on our planet. The total number of atoms in the human body is about $5x10^{27}$, thereby resulting in the total number of atoms in all animals put together at the large number of 10^{38}.

If one considers the total biomass on Earth, the total number of atoms is again 10^{40}. There seems to be a one-to-one correspondence (coincidence) between large numbers in cosmology and biology. The typical number of atoms in a star, or number of stars in a galaxy, can be calculated by balancing various forces such as gravity, radiation pressure or electron (neutron) degeneracy pressure. Is there some optimisation (in biology) that fixes the number of neurons or cells in the brain or the number of atoms in a tree? These questions remain to be answered. In any case, it is fascinating that the same group of large numbers also appear in biology (at least on Earth) as in cosmology.

Here is one more coincidence. Every square centimetre of our body receives $7x10^{10}$ solar neutrinos. So the total number of neutrinos passing through our bodies in a lifetime is the same as the Avogadro number, i.e. $6x10^{23}$. The number of UV photons from the Sun going through our bodies every second is approximately 10^{20} and from the remaining stars in the galaxy: $\sim10^{10}$.

Loudest noise emitted by living systems

Blue whales, the largest animals existing on Earth (weighing more than dinosaurs), also emit the loudest sounds (for communication, etc.), estimated to be around 180 decibels. This corresponds to a sound intensity of $\sim10^2$ W/cm^2. Assuming the threshold for sound detection (e.g. our ear) in water is around 10^{-15} W/cm^2, one can estimate the distance over which these sound signals can be received by other whales. How long would the sound take to cover this distance under water? Fortunately these behemoths are not land-based, especially if we recall that the ear splitting (literally) threshold is around 130 db. for the human ear.

Damuth's law

G. West and J. Brown (Physics Today, 57, 36, 2004), in a study of life's universal scaling laws, emphasised the importance of Kleiber's law for a very wide range of organisms. An ecological manifestation of Kleiber's law may be the basis for Damuth's law, which is widely used. If in an ecosystem one plots the population density (number per square kilometre) n of various species versus the typical longitudinal size, length scale 1, for each species, it is then observed that the population density n scales as $1^{-2.25}$ (that is, $1^{-9/4}$) all the way from bacteria to the largest mammals, over eight orders of magnitude. The data from bacteria to the largest mammals, plotted on a log-log plot, has a slope of – 2.25 (T. McMahon and J. Bonner, *On Size and Life*, Scientific American Books, W. H. Freeman & Co., 1983).

As body mass M scales as (size)^3, that is 1^3, population density for each species scales as $M^{-2.25/3} = M^{-0.75}$. Thus, combined with Kleiber's law, Damuth's law has an elegant and useful interpretation. It implies that the amount of food generated per day and per square kilometre is consumed by the species in the ecosystem in such a way that all resources are conserved. If this does not happen, the ecosystem will evolve until it dies. Metabolic rate is proportional to $M^{3/4}$. So the product of resources