The Origin of Life on Earth: Changing the Paradigm

Pabulo Henrique Rampelotto
Natural and Exact Sciences Center, Federal University of Santa Maria,
P.O. Box 5096, 97105-900, Santa Maria, RS - Brazil

1. Introduction

How did life begin on Earth? We know that life is driven by the universal laws of chemistry and physics. By applying these laws over the past decades, enormous progress has been made in understanding the molecular mechanisms that are the foundations of the living state (Luisi, 2006; Rauchfuss, 2008).

However, the history of science tells us that we can't be too smug. We must avoid the mistake of the physicist who, as the twentieth century began, stated confidently that we knew all there was to know about physics, that science just needed to clean up a few dusty corners. Then came relativity, quantum theory, the Big Bang, dark matter, dark energy and string theory. Similarly, in life sciences, the more we learn, the better we understand how little we really know. Recent studies and discoveries, which challenge the paradigms of modern biology, have forced us to rethink intriguing questions like "what is life?" and "what are the limits of life?" (Rampelotto, 2010a; Rampelotto, 2010b).

The question of life's origin is difficult to be discussed because the breadth of knowledge required to address it include a variety of disciplines like astronomy, planetary science, geology, paleontology, chemistry, biochemistry, bioenergetics and molecular biology. Despite the recent advances, we remain ignorant of the true historical facts concerning the origin of life on this planet (Rampelotto, 2009). Most of the early geological record of this period has been erased by later events (Fishbaugh, 2007). Nevertheless, we have two general approaches to study the origins of life: bottom up and top down.

The bottom up approach starts with the chemicals and conditions existing on the early Earth. It studies the small molecules that would form, and how they might polymerize into larger molecules (Penny, 2005). This approach goes from the simpler to the more complex, towards a simple living system.

Scientific theories within this approach largely fall into two rival fields: replicator first and metabolism first (Pross, 2004). Both models must start from molecules formed by non-biological chemical processes. In the replicator-first model, some of these compounds join together in a chain, by chance forming a molecule - perhaps some kind of RNA - capable of reproducing itself. The molecule makes many copies of itself, sometimes forming mutant versions that are also capable of replicating. Mutant replicators those are better adapted to the conditions supplant earlier versions. Eventually this evolutionary process must lead to the development of compartments (like cells) and metabolism, in which smaller molecules use energy to perform useful processes.

Metabolism first starts with the spontaneous formation of compartments. Some compartments contain mixtures of the starting compounds that undergo cycles of reactions, which over time become more complicated. Finally, the system must make the leap to storing information in polymers.

However, nobody knows the number of process before the final result was reached and life appeared and persisted. What we know for sure is the fact that presently, despite the recent advances, prebiotic chemistry is unable to put dates on steps between a system that is definitively non-living and a system which could be recognized as living.

The top-down approach can be divided in two methodologies: (1) deconstructing life as we know it into the smallest possible units that still exhibit some characteristics of living systems; and (2) mapping the genetic relationship of all life on Earth in an attempt to elucidate the properties of the "*last universal common ancestor*" (LUCA). Defining the nature of LUCA is one of the central goals for studying the early evolution of life on Earth, providing insights that cannot be obtained by other approaches.

Recent comparative genomics and proteomics studies demonstrate that the genomes and proteomes of the very first life forms may have been much more complex than originally hypothesized (Embley and Martin, 2006; Kurland et al., 2006; Seufferheld et al., 2011). Analysis of molecular clocks indicates that Eubacteria and Archaebacteria were present on this planet over 4 bya (Battistuzzi and Hedges, 2009). In view of the apparent complexity of the LUCA, particularly in terms of biochemistry, it would be reasonable to allow billions of years for its evolution from the primordial cell (which would require billions of years to evolve from the first organic molecules). Acceptance of such an extended period of evolution must lead to the conclusion of an extra-terrestrial origin for life on Earth. But, have we evidences to support this conclusion?

2. Life on Early Earth

Microbial fossils found in Archaean habitats demonstrate that the biosphere was already in an advanced evolutionary state at 3.5 bya (Schopf, 2006; Schopf et al., 2007). Much of the strata preserved from this period appear to have been colonized by morphologically and biochemically diverse bacteria that often produced unique mineralogical signatures (Fishbaugh et al., 2007). The widespread distribution of life preserved on Earth from 3.5 bya implies that it must have been present much earlier. Data on $^{12}C/^{13}C$ ratios of carbonaceous material in ancient rocks indicate biological activity at 3.8 bya (Rosing and Frei, 2004; Manning et al., 2006). Even earlier, at 4.2bya, there is evidence of life (although still highly debated), also based on radioisotopes (Nemchin et al., 2008; O'Neil et al., 2008). Therefore, there are compelling evidences (specially derived from paleontological and isotopic data) that complex microbial life was present very early on Earth, with the mainstream consensus at 3.5-3.8 bya (Fig 1).

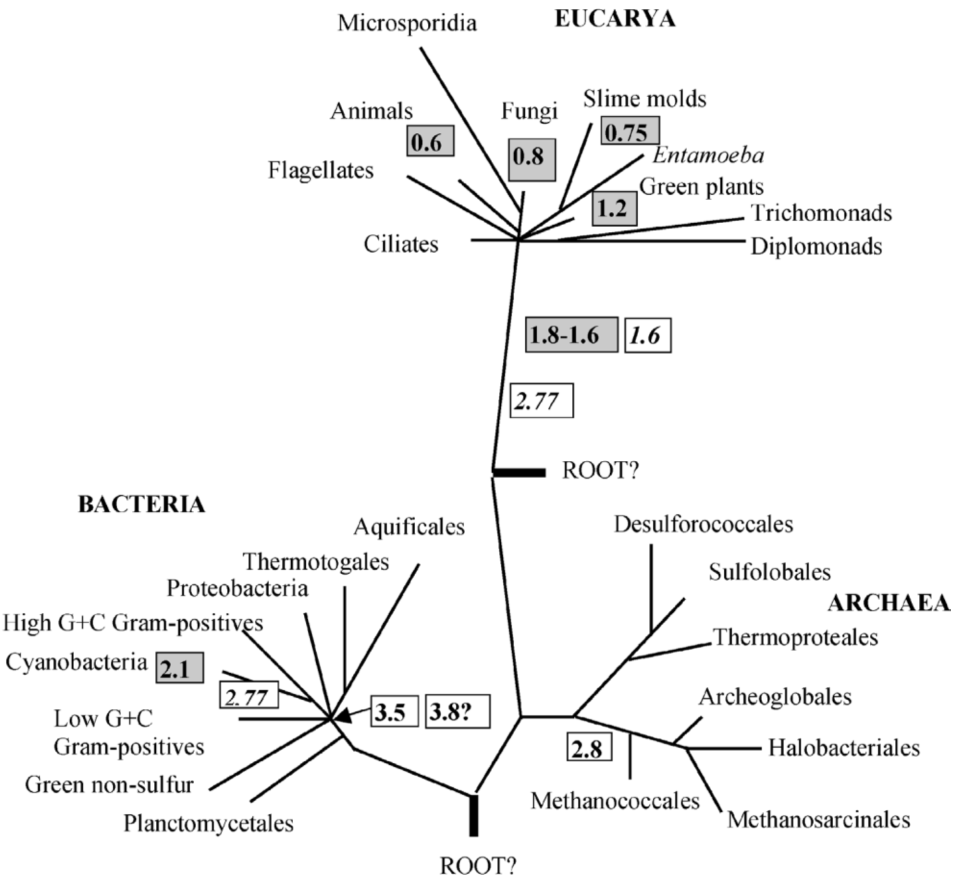

Fig. 1. The three domains of the tree of life (Javaux, 2006). Calibration of the tree by isotopic evidence (white boxes), biomarkers (white boxes in italic), and fossils (shaded boxes).

After Earth was formed, it is believed to have undergone a period of heavy bombardment for 700 million years, up to 3.8 bya (Gomes et al., 2005). During this period, Earth was continuously bombarded by planetoids and other debris from the formation of the solar system. Such heavy bombardment period (especially from 4.1 to 3.8 bya, *i.e.* during the Late Heavy Bombardment) would have destroyed all complex organic molecules, which means that the development of a prebiotic chemistry during that time would be impossible (Ehrenfreund and Sephton, 2006). Note, this period of heavy bombardment is drastically different than an isolated impact, which can create a unique habitat, promoting life (Cockell et al., 2006).

The predictions of mass annihilation in planet sterilizing impacts (Nisbet and Sleep, 2001; Ryder, 2002) suggest that life arose after the heavy bombardment stopped. In this scenario, once Earth became habitable, life was able to reach a structural or cellular state of evolution comparable to contemporary organisms in only a few hundred million years or even less than 100 my (considering the evidences of life at 3.5-3.8 bya).

For this reason, according to the conventional theories, the earliest living cells emerged as a result of chemical evolution on our planet within a very short period of time. In fact, debris from the heavy bombardment could have delivered significant amount of organic matter (of prebiotic interest) helping Earth to become habitable (Bernstein, 2006). Recent studies have shown that carbon-rich meteorites contain abundant individual soluble molecules including hydroxy-, imino-, keto- and amino acids (Kminek et al., 2002), nucleobases and other N-heterocycles simple sugar-like polyols (Cooper et al., 2001) and fatty acids (Deamer et al., 2002), as well as many other classes of compounds (Pizzarello et al., 2006).

However, is it reasonable we assume that living systems could have emerged in such short period of time, even with a possible favorable prebiotic chemistry? According to our knowledge about the history of life, this possibility seems not to be feasible.

From 3.8 bya (or 3.5 bya from cellular fossils), prokaryotes ruled Earth for more than 2 billion years (Fig. 2). Eukaryotes appeared in the fossil records just 1.5 bya (the presence of steranes in Australian shales indicates that eukaryotes were present 2.7 bya. However, this issue is problematic because sterols are present in some bacteria) and multicellular organisms, 0.75 bya (Knoll et al., 2006). While derived evolution is clearly more efficient than *de novo* evolution, why then did life take a further 3.0 bya to arrive to the first multicellular eukaryote, when most of the basic, often unique, developments appear to have been established in the first 300 million years or less?

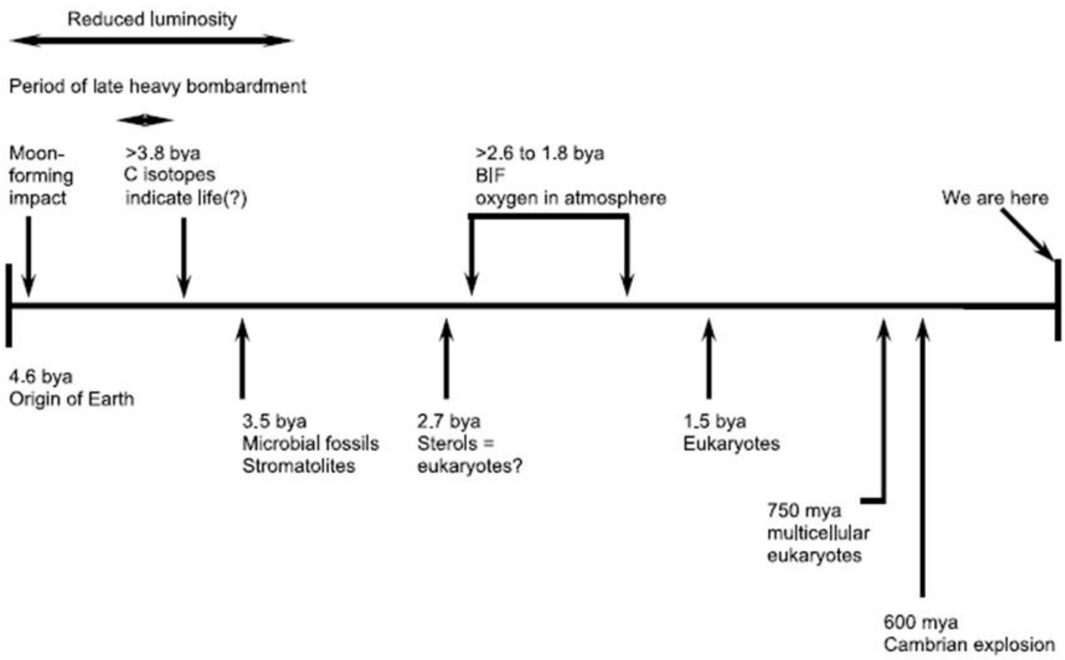

Fig. 2. A schematic representation of the Earth's timeline demonstrating key geological and biological steps in Earth's evolution.

However, despite the evidences, up to now, a fully satisfactory explanation connecting the history of life's evolution and its origin was missing. In the main article of this issue (Joseph and Wickramasinghe, 2011), Dr. Rhawn Joseph and Dr. N. Chandra Wickramasinghe demonstrate, through genetic analysis and based in a well refereed literature, the extra-terrestrial origin for genetic life and the first gene. According to the authors, it has been established that, at least, 382 genes are necessary to sustain life in its simplest cellular form. Over the course of evolution the genome has been repeatedly duplicated in size. Therefore, the first minimal gene set must have originated from a smaller gene set, which has its source from an even smaller set of genes, and this process of duplication leads us back to the birth date for the first gene. Be it 4.4 bya or 3.5 bya for when life appeared on Earth, five separate sets of analyses lead to the same conclusion: the first gene was established at least a billion years before Earth was formed, and more likely over 10 billion years ago.

This detailed study, supported by pioneer works in this field (Sharov, 2006; Sharov, 2010), provides the foundation of what may become a new paradigm in science.

3. The Origin of Life on Earth: Changing the Paradigm

The paradigm for modern biology about the origin of life includes the assumption that life as we know it began here, on Earth. We owe our understanding of the role played by paradigms in science to the work of Thomas S. Kuhn (1962). As Kuhn argued, scientific research is conducted within the confines of a paradigm. In addition to theories, paradigms include methods, instrumentation and subsidiary assumptions concerning a particular subject matter. Paradigms are invaluable tools for scientific research. They facilitate the construction of hypotheses, the design of experiments and the interpretation of results. However, as Kuhn discussed, paradigms sometimes act as blinkers, hindering the exploration of nature by discouraging certain avenues of exploration and biasing the way in which results are interpreted. As a result, important scientific discoveries, and the theoretical advances that wait upon them, may be delayed for many decades.

For much of the twentieth century, origins of life researches have centered on the premise that the first living beings in our planet are the result of a long chemical evolution, which preceded a biological evolution. This theory, initially introduced by the Soviet biochemist A. I. Oparin (in 1924) and independently by the British biologist J. B. S. Haldane (in 1929, before the first Oparin's book was translated to English), postulates that life originated on Earth after a long evolution of simple organic molecules up to more complex ones, including self-replicative macromolecules. The classic Miller-Urey experiment performed in 1953 was the first evidence that the Oparin-Haldane's theory could be correct. This experiment demonstrated in laboratory the formation of organic compounds (of biological interest) in similar conditions to the primitive Earth's atmosphere. The work of these pioneers gave birth to one of the most well accepted paradigm of the twentieth century.

However, in the same way that our knowledge of the universe is expanding, an increasing number of scientists is questioning the dominant dogma of the origin of life on Earth, and embracing a cosmic perspective (from Astrochemistry to Astrobiology). The change of the Earth-centered paradigm, which postulates Earth as the center of the biological universe, for a biological cosmology paradigm, which forces us to accept our true ancestral connection with the cosmos, will significantly improve our understanding of life and give a new perspective to "*the growth of biological thought*"[1].

To conclude, panspermia and abiogenesis are not rival theories. Such dichotomy is just a consequence of our anthropocentric, Earth-centered way of thinking. In fact, panspermia and abiogenesis are two complementary disciplines when considered within the new emerging paradigm of biological cosmology (or cosmic biology).

[1]*In reference to the landmark book written by Ernst Mayr,* ***The Growth of Biological Thought****, first published in 1982.*

References

Battistuzzi, F. U., Hedges, S. B. (2009). A major clade of prokaryotes with ancient adaptations to life on land. Mol. Biol. Evol. 26, 335-343.

Bernstein, M. (2006). Prebiotic materials from on and off the early Earth. Phil. Trans. R. Soc. B 361, 1689-1702.

Cockell, C. S. (2006). The origin and emergence of life under impact bombardment. Philos. Trans. R. Soc. B 361, 1845-1856.

Cooper, G., Kimmich, N., Belisle,W., Sarinana, J., Brabham, K., Garrel, L. (2001). Carbonaceous meteorites as a source of sugar-related organic compounds for the early Earth. Nature 414, 879-883.

Deamer, D. W., Dworkin, J. P., Sandford, S. A., Bernstein, M. P., Allamandola, L. J. (2002). The first cell membranes. Astrobiology 2, 371-381.

Ehrenfreund. P., Sephton, M. A. (2006). Carbon molecules in space: from astrochemistry to astrobiology. Faraday Discuss. 133, 277- 288.

Embley, T. M., Martin, W. (2006). Eukaryotic evolution, changes and challenges. Nature 440, 623-630.

Fishbaugh, K. E., Lognonné, P., Raulin, F., Des Marais, D. J., Korablev, O. (2007). Geology and Habitability of Terrestrial Planets. Springer, New York.

Frebel, A., Christlie, N., Norris, J. E., Thom, C., Beers, T. C., Rhee, J. (2007). "Discovery of HE 1523-0901, a strongly r-process-enhanced metal-poor star with detected uranium". Astrophys. J. 660, L117.

Gomes, R., Levison, H. F., Tsiganis, K. Morbidelli, A. (2005). Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. Nature 435, 466-469.

Haldane, J. B. S. (1929). The orgin of life. Rationalist Annual 3, 3-10.

Javaux, E. J. (2006). Extreme life on Earth - Past, present and possibly beyond. Res. Microbiol. 157, 37-48.

Joseph, R., Wickramasinghe, N. C. (2011). Genetics indicates extra-terrestrial origins for life: The first gene. Journal of Cosmology, in press.

Kminek, G., Botta, O., Glavin, D. P., Bada, J. L. (2002). Amino acids in the Tagish lake meteorite. Meteorit. Planet. Sci. 37, 697-701.

Knoll, A. H., Walter, M. R., Narbonne, G. M., Christie-Blick, N. (2006). The Ediacaran Period: A new addition to the geologic time scale. Lethaia 39, 13-30.

Kuhn, T. S. (1962). The Structure of Scientific Revolutions. University of Chicago Press, Chicago.

Kurland, C. G., Collins, L. J., Penny, D. (2006). Genomics and the irreducible nature of eukaryote cells. Science 312, 1011-1014.

Luisi, P. L. (2006). The Emergence of Life - From Chemical Origins to Synthetic Biology. Cambridge University Press, New York.

Manning, C. E., Mojzsis, S. J., Harrison, T. M. (2006). Geology, age and origin, of supracrustral rocks at Akilia, West Greenland. Am. J. Sci. 306, 303-366.

Mayr, E. (1982). The Growth of Biological Thought. Harvard University Press, Cambridge.

Miller, S. L. (1953). A production of amino acids under possible primitive Earth conditions. Science 117, 528-9.

Nemchin, A. A., Whitehouse, M. J., Menneken, M., Geisler, T., Pidgeon, R. T., Wilde, S. A. (2008). A light carbon reservoir recorded in zircon-hosted diamond from the Jack Hills. Nature 454, 92-95.

Nisbet, E. G., Sleep, N. H. (2001). The habitat and nature of early life. Nature 409, 1083-1091.

O'Neil, J., Carlson, R. W., Francis, E., Stevenson, R. K. (2008). Neodymium-142 evidence for Hadean mafic crust. Science 321, 1828 - 1831.

Oparin, A. I. (1924). The Origin of Life. Moscow Worker Publisher, Moscow. (*in Russian*).

Penny, D. (2005). An interpretive review of the origin of life research. Biol. Phil. 20, 633-671.

Pizzarello, S. (2006). The chemistry of life's origin: A carbonaceous meteorite perspective. Acc. Chem. Res. 39, 231-237.

Pross, A. (2004). Causation and the origin of life. Metabolism or replication first? Orig. Life Evol. Biosph. 34, 307-321.

Rampelotto, P. H. (2009). Are we descendants of extraterrestrials? Journal of Cosmology 1, 86-88.

Rampelotto, P. H. (2010a). The search for life on other planets: Sulfur-based, silicon-based, ammonia-based life. Journal of Cosmology 5. 818-827.

Rampelotto, P. H. (2010b). Resistance of microorganisms to extreme environmental conditions and its contribution to Astrobiology. Sustainability 2, 1602-1623.

Rauchfuss, H. (2008). Chemical Evolution and the Origin of Life. Springer-Verlag, Berlin.

Rosing, M. T., Frei, R. (2004). U-rich Archaean sea-floor sediments from Greenland - indications of > 3700 Ma oxygenic photosynthesis. Earth Planet. Sci. Lett. 217, 237-244.

Ryder, G. (2002). Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth. J. Geophys. Res. 107, 5022.

Sayer, R. M. P. (2007). Self-organizing proto-replicators and the origin of life. Biosystems 90, 121-138.

Schopf, J. W. (2006). Fossil evidence of Archaean life. Philos. Trans. R. Soc. B 361, 869-885.

Schopf, J. W., Kudryavtsev, A. B., Czaja, A. D., Tripathi, A. B. (2007). Evidence of Archean life: Stromatolites and microfossils:. Precambrian Res. 158, 141-155.

Seufferheld, M. J., Kim, K. M., Whitfield, J., Valerio, A., Caetano-Anolles, G. Evolution of vacuolar proton pyrophosphatase domains and volutin granules: clues into the early evolutionary origin of the acidocalcisome. Biol. Direct, in press.

Sharov, A. A. (2006). Genome increase as a clock for the origin and evolution of life. Biol. Direct, 1, 17.

Sharov, A. A., (2010). Genetic gradualism and the extra-terrestrial origin of life. Journal of Cosmology 5, 833-842.