SECTION IV

UNIVERSAL ASPECTS OF BIOLOGICAL EVOLUTION

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INTRODUCTION

This Section deals with the origin and evolution of life on Earth, and from this only known example of life in our Galaxy we try to extract any general characteristics that might be applicable to other cosmic cases. The Co-Chairmen of the corresponding Session of the Symposium were: Lynn Margulis of Boston University and John Billingham of the NASA-Ames Research Center.

Three important characteristics of life on Earth are the following:

I. It appeared quite early in the history of our planet.
II. The biological evolution that led life from primitive bacteria to an advanced technological civilization was excruciatingly slow.
III. In the process of its own evolution life transformed also our planet changing its atmosphere from non-oxidizing to oxidizing. In a sense life has been acting like a long-term tenant who is remodeling the house he is staying to make it more to its liking.

We now have substantial microfossil evidence that life in the form of procaryotic algae and bacteria was present on Earth close to 3.5 billion years ago. There are only few known rock formations, such as the Isua region in West Greenland, that are a little older but still no older than 3.8 billion years, and in addition are severely metamorphosed by geological activity which prevents us from getting a clear reading on the presence of life.

For life to have been present on Earth 3.5 billion years ago, it implies that it must have originated some time earlier, probably 3.6 to 3.9 billion years ago, which brings it very close to the time that the Earth had finally settled down and was capable of holding life. Our planet was formed about 4.5 billion years ago, but then it underwent heating, melting, chemical differentiation, and it outgassed its secondary atmosphere. Later on it began to cool off, formed a solid crust, water vapor in the atmosphere condensed to form the oceans, and finally the severe meteoritic bombardment, as deduced from lunar data, ended around 3.9 billion years ago. It is fair to say, therefore, that life began on our planet almost as soon as the Earth was able to hold it.

The evolution of life, on the other hand was a very slow process that took almost 4 billion years to evolve to a technological civilization. This is a very long period even on a cosmic time scale since the entire Universe is only about 15 billion years old, and there are no Population I stars like our Sun in our Galaxy with 1-3% of heavy elements that are older than about 10 billion years. It must be

M. D. Papagiannis (ed.), The Search for Extraterrestrial Life: Recent Developments, 179–183.

emphasized, however, that most of this time life was just digging and setting the foundation for its imposing building, which, as in the case of construction takes a long time without much to show. Still, during the first 3 billion years life accomplished several important tasks. It developed the process of oxygen producing photosynthesis (~3 b.y.a.) which began slowly to convert the primitive atmosphere of the Earth into one of free oxygen. This allowed the replacement of anaerobic metabolism with the far more efficient aerobic metrobolism. Life also evolved from primitive procaryotic microrganisms to the far more complex eucaryotic organisms (~ 2 b.y.a.), and finally life produced the first multicellular organisms (~1 b.y.a.) which were without skeletons and looked like jelly-fish.

The foundation was finally in place with an adequate, but still much less than today, amount of oxygen in the atmosphere. The first metazoans with skeletons appear (~600 m.y.a) leaving behind a fossilized evidence of their existence, and life moves from the sea to the land (~400 m.y.a.) protected from the ultraviolet radiation of the Sun by an early ozone layer in the stratosphere. Mammals replace the reptiles as the reigning land animals (65 m.y.a.), the apes appear (~35 m.y.a.), the austrolopithecus emerges (~3.5 m.y.a.), and finally modern man, the so called Cro-Magnon man, comes to the scene just ~40,000 years ago. Once the foundation was completed the building has gone up at a much faster pace, becoming finally the imposing edifice of today's technological civilization in a very short period.

The evidence, therefore, is that life appeared on our planet very soon (probably only a few hundred million years) after the Earth became capable of holding life, while it took life nearly four billion years to evolve to a technological civilization. The only available data then say that given the appropriate conditions (most likely a planet with liquid water), getting life started appears to be a much easier task than its subsequent evolution to an advanced technological civilization, which in our case took about 10 times longer. The question then becomes what is the likelihood that a planet with liquid water will be able to maintain this hospitable environment for billions of years so that the painfully slow process of biological evolution may run its full course?

Our two neighboring planets, Mars and Venus, might have had brief periods with liquid water on them but now they are without it. They have several physical similarities with the Earth, but also many differences in their mass (much smaller for Mars), spinning rate (much slower for Venus), tilt of spinning axis (very small for Venus), eccentricity of the orbit (considerably larger for Mars), magnetic field which provides a protecting shield against cosmic rays (Mars and Venus lack one), moons (Venus none, Mars two very small moons) and of course in their respective distances from the Sun. A planet with liquid water on its surface lives continuously in a precarious balance between a run-away greenhouse effect, as on Venus, where all available water evaporates and ultimately through photodissociation becomes lost, and a run-away glaciation, as on Mars, where all the water freezes into ice. In either case the planet becomes inhospitable to life.

It is clear that different periodic or accidental perturbations that occur in the life of a planet have a tendency to disrupt this delicate equilibrium between run-away glaciation and a run-away greenhouse effect. Such perturbations include the precession and nutation of the spinning axis (in the case of the Earth with respective periods of 26,000 and 42,000 years), variations in the eccentricity of the orbit (in the case of the Earth with a cycle of about 102,000 years that has been associated with expansions and retreats of glaciation), continental drifts which are believed to be the cause of the major ice-ages, reversals of the magnetic field, etc. The Earth has been rather lucky that all these fluctuations have been quite modest, in some of these cases thanks to the stabilizing influence of our large moon. It is doubtful that the Earth would have been able to retain its liquid water if it had to experience the fluctuations in orbital eccentricity and tilt of the axis that Mars has been undergoing.

It is important to note also that all these changes (modification of the chemical composition of the atmosphere, continental drifts, ice ages, volcanic eruptions, seasons, tides, and even the day-night cycle) seem to have had a stimulating effect on the biological evolution. Without them life would have adjusted to a perfectly stable environment and the biological evolution would have probably become hopelessly stagnant. Characteristic of the effects of external perturbations on the biological evolution are the mass extinctions of species which have occurred repeatedly on Earth and probably have been caused by catastrophic impacts of comets and large meteorites. These impacts produce drastic changes in the environment of the Earth, with which many species are not able to cope. Their extinction, however, makes room for the appearance of new species in the crowded ecosystem of the Earth and thus these catastrophes, which are also blessings in disguise, fuel the process of biological evolution.

What levels of fluctuations may a planet be able to tolerate without losing its water and hence its ability to hold life, and to what extent the lessenings or even the absence of such fluctuations would slow down the process of biological evolution, are two important problems that we are now beginning to address. It appears that changes are a welcome incentive for biological evolution provided that they do not get so large as to disrupt the delicate temperature balance required to maintain liquid water on a planet. The limits of tolerance, however, are not yet known.

This Sections consists of nine papers. It starts with a review paper on Chemical Evolution by Cyril Ponnamperuma of the University of Maryland. He discusses the synthesis of complex prebiological compounds from simple molecules such as methane, ammonia, water vapor, etc. under a variety of natural and laboratory conditions and energy sources that simulate conditions that might have existed on the primitive Earth. The first such experiment was conducted in 1953 by Stanley Miller and Harold Urey. Tremendous progress has been made since then, and today there is even a large and very active International Society for the Study of the Origin of Life (ISSOL), with Cyril Ponnamperuma as its current President. There are still, however, many problems that remain to be answered. Still, from the fact that complex organic compounds are also synthesized in a variety of extraterrestrial environments (Ponnamperuma and his colleagues, e.g., have detected several alpha-aminoacids and all of the five bases of DNA and RNA in samples of the Murchison meteorite), it appears that chemical evolution is a universal process which given a planet with liquid water it is likely to lead to life.

Leslie E. Orgel of the Salk Institute for Biological Studies discusses the next step in the process leading to life, namely the ability of certain products of the chemical evolution to replicate. Replication, he also notes, must be a common property of all forms of life in the Universe. In a summary article Orgel reports on recent work in his laboratory where they have been working for many years on the template-directed, non-enzymatic synthesis of oligonucleotides that are complementary to the template. They have already succeeded in obtaining a sequence of seven Guanine (G) nucleotides from a template of seven Cytosine (C) nucleotides without any proteins acting as enzymatic catalysts. They have also managed to use mixed sequences, such as a CCGCC template to produce a GGCGG oligonucleotide with a 20% yield.

Andrew H. Knoll of Harvard University presents a fine review paper on the Precambrian Evolution of life on Earth. This is the 3 billion year period from the first evidence of primitive life that we have discovered in ancient cratonic areas (stable portion of the Earth's crust) in South Africa and Western Australia dated at 3.4 to 3.5 billion years ago, to the beginning of the Cambrian era about 570 million years ago when fossils of multicellular organisms finally became abundant. Knoll says that a universal aspect of biological evolution is the tendency of life "to organize metabolically disparate populations into a biogeochemical system capable of transferring energy and cycling biologically important elements".

Misia Landau of Boston University discusses the Human Evolution. She takes a critical view of theories that try to interpret different steps that are considered as landmarks in human evolution such as bipedalism, tool making, fire, language, etc. Landau warns us that "scientists tend to make sense of the past by telling stories in which everything leads up to, or away from, being human." To reinforce the need for scientific measurements rather than interpretive stories she says that bipedalism ought to be defined according to the distance covered on the ground rather than along some road to humanity.

J. John Sepkoski Jr. of the University of Chicago discusses the implication of Mass Extinctions for the evolution of complex life. Raup and Sepkoski established that mass extinctions tend to occur in periodic intervals of about 26.2± 1 million years. Ecosystems have limited resources and therefore the number of lineages they can support is also limited. When they become saturated, the introduction of a substantial number of new lineages becomes possible only by eliminating a large number of competing lineages through mass extinctions. The most impressive of these extinctions was the one that occurred 65 million years ago at the end of the Cretaceous period which brought to an end the age of reptiles and ushered in the age of mammals. It is clear, therefore, that these externally induced mass extinctions are not only great disasters but also blessings in disguise because they help the biological evolution to march on.

Richard A. Muller of the University of California-Berkeley advances the thesis that these periodic extinctions may be explained by the presence of a red dwarf companion star of our Sun, with a period of about 27 million years on an eccentric orbit with a major axis of about 2.8 light years. Such a companion star could perturb the Oort cloud of comets at periodic intervals of about 27 million years and send a large number of comets toward the Sun where some of them would collide with the Earth. This theory is in agreement with the discovery of thin geological layers with an enhanced content of Iridium that have been found to coincide chronologically with some of these extinctions. Also with a periodicity of 28±1 million years which seems to exist in the occurrence of large impact craters on Earth, the peaks of which tend to coincide with the times of the extinctions. Muller and his colleagues, who are now searching for this companion star, have proposed to name it "Nemesis", if found, after the ancient Greek goddess for disaster and divine retribution. It is interesting, by the way, that disaster comes from two Greek words that mean "bad star". Harlan Smith of the University of Texas proposed at the Symposium that a better name for such a star might be Siva, the Indian god who stands for both destruction and rebirth, since these mass extinctions play actually such a double role in the process of biological evolutions. Some have questioned the periodicity of these events, but the fact remains that they do indeed occur, periodically or not, and become an important factor that accelerates the process biological evolution

This Section ends with three short papers that speculate on properties of extraterrestrial life on the basis of some general principles. In the first, Minas Kafatos of the George Mason University uses what he calls "Universal Diagrams" in which he plots different quantities, such as luminosity vs. mass, of all known objects in the Universe and tries to extract form them the position that extraterrestrial life might occupy. In the second, John A. Ball of Harvard University argues that genes are biological, and memes are intellectual units of information that can be replicated or altered. Progress, he says, is the increase of information (measured in bits) and that successful replicators (genes or memes) are those that promote successfully their own survival and propagation in the prevailing environment and occasionally they even alter the environment to promote their own perpetuation. Those he concludes must also be properties of all extraterrestrial life. In the final paper G. Bodiffee and C. deLoore of the Free University of Brussels, Belgium, follow the thermodynamic approach introduced by Ilya Prigogine, and suggest that extraterrestrial life, like all forms of life, must be macroscopic, open with regard to the rest of the Universe, and far from thermodynamic equilibrium. Biological organisms and their collective organizations are dissipative structures with a high production of entropy which is efficiently removed from the system. These thermodynamic properties, they say, could be of help in our search for extraterrestrial life.

THE EDITOR