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1. From the Arrow of Time to the Arrow of Life

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Abstract. Astrobiology, like many (but not all) sciences, must take into account questions of the "Why?", "Where?", "How?" and "When?" type. In this introductory chapter, we explain why, in this book, we will only consider two of these questions that are, moreover, deeply interrelated. Chronology is by definition related to the "when?" question but as soon as we are interested in the history of Earth or the history of life, it is impossible to treat these questions and their answers without explicit references to the "how?" questions. We also present in this chapter the genesis and the aim of the book.

Keywords: Time, dating

1.1. The Notion of Time in Astrobiology

Scientists are trained to ask questions about Nature. As is well known in dialectics, the quality of the question determines the quality of the answer. Questions that remain unanswered for a long time are probably questions that must be formulated in a different way.

Each chapter (from the "Dating methods and corresponding chronometers in astrobiology" chapter 2 to the final "Life on Earth and elsewhere" chapter 9) has been submitted to a very severe internal refereeing, each author having read many, if not all, contributions to make comments, criticisms and advice. As a general rule these comments/remarks were discussed amongst the authors and were included in the original text. Ideally, all the authors could have signed together all the contributions but we have preferred to "render to Caesar the things which are Caesar's" and the specialist who first wrote it signed each subchapter. For further information on the contributing authors, please refer to CVs', included at the end of this volume. All subchapters devoted to the same general field have been gathered together as a chapter under a general title. Consequently, each chapter is alphabetically co-signed by all the authors of the subchapters, and the first author is the coordinator who supervised its homogeneity and completeness. In all cases, each author did his (or her) best to give to the reader the most accurate and recent data, along with the evidence, but also assumptions, on which the data is founded and, when necessary, the caution required for its interpretation. A glossary of terminology used in all chapters is available at the end of this volume.

Among the numerous questions scientists are interested in, those related to time are probably the most fascinating because time is a very peculiar dimension. From Einstein's work, we learnt that, for physics, time is "just" the fourth dimension but, on the other hand, we are also aware that the time dimension, as we perceive it, is qualitatively different from the space dimensions. Time "flows"; time is irreversible and associated with past, present and future.

"Why is time different from the other dimensions?" remains an open question, and this is one major reason why many scientists are fascinated by problems related to time. Of course, not all sciences are historical, i.e. not all sciences focus their study on similarities or differences occurring between past, present and future events. For example, a chemist studying the evolution of a reaction as a function of time certainly knows that if pressure, temperature and all other experimental conditions are kept the same, the reaction will evolve tomorrow in a deterministic way, exactly as it does today. For this chemist, time is a parameter easily measurable with a chronometer. Even if the reaction under study is irreversible, chemists (as all scientists) know that the physical laws do not change with time. As Noether showed, this time translation independence is related to the energy conservation law (Zee, 1986)

The situation is completely different for a geologist or a biologist interested in evolutionary problems. They must take into account the historical time and, therefore, the irreversible flow of time, the so-called "arrow of time" (e.g. Klein and Spiro, 1997). For these scientists, a chronometer is useless: they need to measure time with respect to a conventional reference time. Their situation can be compared to that of a historian who, in Western countries, uses as reference time the birth of Christ, even though its date is still debated among historians, being uncertain by several years. All of them, historians, geologists or biologists have in common their need to apply to a time reference chosen by convention.

Cosmologists are the only scientists who could claim to use a time scale based on an absolute zero even if, today, it is discussed whether the Big Bang itself could be considered as the origin of our time. Planetologists and geologists use different reference times depending on the problem they are interested in. They know from cosmologists and astronomers that the Universe is probably 13.7 billion years old, but they do not use the Big Bang as reference time: they use the age of the oldest meteorites instead. Frequently, but not always, they use a time scale that takes as reference time the "present time" defined as 1950 AD[1], which is the reference used for ^{14}C dating. Any time is thus expressed in "years before present" (yr BP). On this scale and just as examples, the accretion of the solar system took place approximately

[1] AD = Anno Domini = After Jesus-Christ.

4.6×10^9 yrs BP while the extinction of dinosaurs took place approximately 65×10^6 yrs BP. As explained in Chapter 2 on chronometers, for various reasons different communities have to use different time scales, both forward and backwards, even for events that are a common subject of study.

As mentioned above, not all sciences are historical. Yet many scientists, if not all of them, are concerned by the history of the solar system, of the Earth, and of life on it. Naturally, many of them also wonder about the existence of extraterrestrial living systems, whose emergence and survival would depend on various physico-chemical parameters, including time. Some of these scientists investigate specific aspects of these broad topics and, from their collaboration, a new scientific field, called Astrobiology, has emerged. Interestingly enough, although Astrobiology is a scientific field in itself, scientists tend to avoid describing themselves as astrobiologists. In any case, Astrobiology (exobiology or bioastronomy are also used as synonyms) is probably one of the best examples of a truly interdisciplinary field. By putting together pieces of a huge puzzle, astronomers, geologists, physicists, chemists, and biologists try to bring to the fore scenarios that led to the emergence of life on Earth and, eventually, to see if these scenarios could apply to other planets. The collaboration between these scientists from different horizons does certainly contribute to our understanding of the Earth's remote past and to better apprehend the conditions that allowed the emergence of life. Astrobiology is, today, a well-identified science. Of course, we are still far from having definitive answers to the countless questions related to events that took place billions of years ago. We should even consider the possibility that some of these answers will never be found. This may be perturbing for an experimental scientist who is able to test his hypotheses by performing experiments in his laboratory. However, this situation is absolutely normal if we consider the nature of all the historical sciences, including history itself. Nobody knows with absolute certainty how and when language did originate in human populations. A few hypotheses exist, but compelling evidence proving one of them while disproving the others is still missing. It might be found tomorrow, in one century or never!

If one considers Astrobiology as a good example of a historical natural science, the types of questions that can be formulated may then be classified into four families: "why", "when", "where" and "how"

1.2. Why, Where, When and How: Here are the Questions

1.2.1. Why?

Although we will not discuss here the qualitative differences between all these families, we would like to highlight the peculiarity of any question of the "why" family. Whatever the answer to a question of this type may be, another "why" question immediately arises. We can argue that this is a never-ending course, even if science reaches some day the "theory of everything" that some theoretical physicists are looking for. Even if that is the case and the four forces of physics eventually become unified, someone might ask: "Why four forces and not five or seven?" " Why the Planck constant is what it is and not 1", etc.? The series of "why?" is thus infinite. It is interesting to observe how difficult it is for many people to accept this situation. This is probably one of the reasons why some people are searching, outside the field of science, what they consider as the ultimate response.

In this review dedicated to chronology (and for obvious scientific reasons) we have kept away the "why" questions.

1.2.2. Where?

"Where" questions are sometimes asked in Astrobiology. Did life arise somewhere else in the Universe? Does it exist on other planets? Was it born in another planet and did the young Earth seed in some way, as postulates the panspermia theory? From Kelvin to Arrhenius, from Hoyle to Crick, the panspermia theory finds advocates. Nevertheless, this hypothesis, lacking any kind of observational support, will not be discussed in this review. Today, the expression "molecular panspermia" is sometimes used to describe post-accretion processes during which pre-formed organic and water molecules were brought onto the young Earth. This kind of panspermia, on the contrary, may have played an important role in the transition from non-living to living matter and, as such, will be obviously discussed.

1.2.3. When (and how)?

In any historical science, determining a date requires a clear-cut definition of the event for which we want to get a dating, i.e. it must correspond to a point on a continuous time scale. It usually corresponds to a singularity, i.e. a transition from a previous state to a new one that took place within a very short time. However, this condition is seldom fulfilled. In most cases, conventional, somehow, arbitrary discontinuities are defined just because these discontinuities are used to obtain a dating. A most paradigmatic example concerns the origin of life itself. It is hard to believe that the transition from "non-living" to "living" took place in a very short period of time. Furthermore, any attempt to date this transition requires an agreement about the nature of "living" and "pre-living" systems. A microfossil may be unambiguous evidence that life was present when the sedimentary process started, but its occurrence at a given time point does not preclude the existence of life hundreds, thousands or millions of years before. Strictly speaking, it is possible to determine the age of the oldest sediment containing microorganisms but it is impossible to ascertain the age of the first microorganisms. A similar situation applies to the age of the Earth or that of the first oceans. We can establish the age of the oldest refractory inclusions in a particular type of chondrite or the age of the oldest zircons, but we are unable to measure directly the age of the Earth or that of the first oceans. Nevertheless, by fascinating "language shifts", we tend to speak about the age of the Earth or about the age of the first oceans. Moreover, these ages are considered to be known with great accuracy whereas, in fact, what we know accurately is the age of what was measured i.e. the age of pieces of rocks or even of single minerals within rocks (e.g. Jack Hills zircons are 4.4 billion years old, but the rocks they were extracted from are much younger). All these ages are strongly dependent on the validity of theoretical models describing the accretion of the solar system or the formation of a hydrosphere on the surface of the young Earth as very rapid processes. Therefore, "when" questions are often dependent on answers to "how" questions.

1.3. Our Modest Contributions to the "When" (and "How"?) Answers

1.3.1. The "when and where" making-of

This project started in September 2003 during an exobiology summer school (Exobio'03) we (M. Gargaud and D. Despois) organise in Propriano (Corsica) every two years since 1999 and where 80 researchers working in astronomy, geology, chemistry and biology try, year after year, to reconstitute the story of the emergence and evolution of life on Earth and its possible distribution elsewhere in the Universe.

1.3.2. The "why" making-of

At that time, two of us (M. Gargaud and D. Despois) had the modest ambition to put on a sheet of paper some chronological data relevant to the origins of life and to understand what was the exact meaning of numbers in sentences like "the solar system is 4.569 Ga old", "the first proto-ocean appeared around 4.4 Ga", "the first undisputable evidence of life is dated around 2.7 Ga, but oldest traces of life could be dated as soon as 3.5 Ga". In brief, their goal was simply to understand:

– What is the exact meaning of data read in the literature?

This aspect is particularly important for people, even scientist, who are not specialists of the field and have no other choice than to take for granted what specialists say. If specialists all agree, it's not really a problem but of course it's not often the case. The important secondary questions are then:

– What are the error bars associated with these numbers?
– What sort of chronometer each scientific field uses and what is the reliability of each of them?
– Which hypotheses (models, observations, experiments) are assumed or taken for granted to validate these data?

On the other hand, a number, as precise as could be, can rarely reflect a sudden event (the transition from ''non-living'' to ''living'' can certainly not be represented by a Dirac function) and some questions relative so these numbers are even more important. For instance:

– What has been exactly the duration of that event and how rigorous is it to speak about a ''beginning'' and an ''end'' of a given one (planetary disk formation, Moon formation, ocean formation, late heavy bombardment, etc... but also and much more difficult, prebiotic chemistry, early biochemistry, etc...)
– What is the time reference used by astronomers, chemists, geologists or biologists?

1.3.3. The ''how'' making-of

Of course the questions previously listed were not obvious ones, but we were enthusiastic enough to hope that one day of brainstorming with the whole community would allow us to order, at least sequentially if not absolutely, the main events having led to the emergence of life. At the time of Exobio'03 (September 2003), we didn't even think to publish anything on these topics; we just wanted to clarify our own ideas.

In fact, we rapidly realized that we wouldn't leave Propriano with the answers we were looking for, but we were far from thinking that we had put a finger in a terrible set of gear – wheels from which we could only escape more than two years later (and the story is probably not finished...), after two others specialized workshops on the subject and hours and hours of vivid and passionate discussions...

Of course we were aware of the difficulties for an astronomer (geologist, chemist, biologist) to think like a biologist (astronomer, geologist, chemist) but having organised several conferences and summer schools devoted to various aspects of astrobiology, we thought that a common language was now more or less acquired. In a sense, we were right: the language was common, but the culture and the ways of thinking were (still are?) completely different. Indeed, the nature of the problem each discipline can solve, the difficulties encountered, the tools used to solve them, the interpretation of theory/modelling/observations/experiments are by nature absolutely different. For example, physicists, and even more so astrophysicists, are used to extensive logical and deterministic constructions (mathematical models) spanning a bridge between facts and deduction. Indeed, and just as an example, many details of the nuclear reactions inside stars rely, *in fine*, on the measurements of only T and L on their surface, many thousands kilometres away from the centre. ...Of course it's far from being intellectually satisfying, but as nobody will never go inside a star nucleus to measure physical parameters, (even though, in the case of the Sun, which is the only star we know with great precision, we have access to deep layers via neutrinos and helioseismology), the only choice astrophysicists have is to built models not at variance with observations.

Concerning the chronometers each discipline can rely on, here again the situation is completely different from one field to another. For example, astronomers can collect a lot of information but the chronometers they have in hand are indirect and only of statistical nature (chapter 2.1). Geochemists have very efficient radioactivity chronometers (chapters 2.2 and 3.2) but the difficulty for them is to determine what is exactly dated and what they can infer from these data (the latest measurements of Calcium Aluminium Inclusion in Allende meteorite gives a very precise age of $4.5685 \pm 0.0004 \times 10^9$ yrs, but on what reliable hypotheses can we deduct that this gives also the age of the solar system with an error bar of less than 10^6 yrs?). Chemists have no chronometers (chapters 2.3 and 5.1) and it's even an impossible mission for them to reconstruct the prebiotic chemistry and biochemistry period (between 4.4 and 2.7 billion years) when absolute and even to some extents relative chronology remains totally unknown. Hopefully the situation gets better in biology where molecular clocks are invaluable tools for reconstructing evolutionary timescales (chapter 2.4), but biochemical and biological problems are so complex that of course the reliability of chronometers helps but doesn't solve everything in a definitive way...

Another problem we had to face was the relevance of an absolute t_0 time of reference. Of course it does not really matter to know that Ramses II lived 1250 years BC or 3200 years BP, but if historians want to compare the reign of Ramses II with those of Amenophys III or Cleopatra, they have first to agree on a unique reference time. And what is important in fact for Egyptian history is not so much that Ramses II reigned 1250 years C, but that he reigned during 66 years, after Amenophys III and before Cleopatra. Once again, duration is a very important parameter, and duration of course imply "a" beginning and "an" end.

As indicated in the previous paragraph we could have decided to choose the Big Bang as an absolute reference time. Nevertheless as we were interested in the history of life on Earth, we started our study from the formation of the solar system (we could have started from the formation of the Earth as well) and we defined an absolute and arbitrary time t_0* which corresponds to the start of the collapse of the molecular core cloud which precedes a time $t_0 = 4568.5 \times 10^6$ yrs corresponding to the oldest dated solids formed in the proto-solar nebula. This allowed us to describe the first million years by reference to t_0* (see section 2.5) and to introduce the different stages of protostar and T-Tauri star, necessary to form the Sun, which occurred before t_0. But, as explained in chapter 2, t_0 is the age of calcium aluminium inclusions in Allende meteorite, not the age of the solar system for which we'll never know "exactly" when it started to form. We could also have chosen different relative times (t_1 = impact of Theia on Earth, t_2 = formation of proto-ocean, t_3 = end of the Late Heavy Bombardment, etc...) and described the different following events by reference to these relative times. For practical reasons we finally agreed to take by convention a unique t_0 (whatever could it be) and to introduce sometimes time elapsed since t_0. Indeed it's by far easier to remember that Moon formed between 10 and 70 million years after the formation of the first solid in the solar system than remembering that Moon formed between 4.558 and 4.498 billion years ago.

After some very enriching discussions on the determination of t_0 (which we stress again is without real importance but is somewhere the emerged part of the time-iceberg problem), we had to choose "when" to stop this reconstitution of the history of life on Earth. Here again, and depending on the field of competence of each of us, opinions were different. We decided finally to stop approximately 0.5 billion years BP and we all agreed that between 100 millions years before the accretion of the Earth and 0.5 Ga BP, when multicellular life exploded at the beginning of the Cambrian, all kind of processes involved in the evolution of our planet took place. Of course macroscopic life diversified spectacularly during the last 0.5 billion years (and the literature on this period is very abundant) and the Earth itself continued to evolve, but the most important steps for the emergence of life had already occurred.

In the following six chapters astronomers, geologists, chemists and biologists will review what is known about the chronology of some key events (formation of the solar system, accretion and differentiation of the Earth, formation of the first oceans, late heavy bombardment, plate tectonics, appearance of prokaryotic life, evolution of the Earth atmosphere, origin of eukaryotic life) and how this chronology has been established. A general chronological frieze bringing to the fore the most important events relevant (at least to our opinion) to the emergence of life is presented in chapter 8, and final conclusions (chapter highlights and questions about the ubiquity of life in the Universe) are presented in Chapter 9.

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Writing a collegial paper with 25 researchers belonging to very different scientific fields is a challenge comparable to a "frog race"[2]. As we finally, all together, reach the finish, the editors would really like to thank all the authors who accepted to participate in this adventure and who accepted to stay on the "chronology wheelbarrow" whatever the difficulties could have been and the time needed to reach the goal. We would also like to warmly thank the «Château Monlot Capet», St Emilion, France http://www.belair-monlot.com/anglais/bienvenue.htm and the «Fondation Antoine d'Abbadie» of the French Academy of Sciences, Hendaye, France http://www.academie-sciences.fr/Abbadia.htm for their kind hospitality during the May and December 2004 «chronology workshops». The vivid and controversial ideas discussed during these workshops were at the origin of this review. Finally we are very grateful to Centre National de la Recherche Scientifique (CNRS), and especially to the Aquitaine and Limousin Delegation, to Centre National d'Etude Spatiale (CNES), to the GDR (Groupement de Recherche) Exobio, to the Conseil Régional d'Aquitaine, to the Université Bordeaux 1 and to the Observatoire Aquitain des Sciences de l'Univers, near Bordeaux, for their financial support in the course of this project.

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[2] The game consists in starting from a point A with N frogs you have to put on a wheelbarrow, and to reach a point B as quickly as possible with all the frogs still on the wheelbarrow. The story goes that you never reach the finish of the race because you spend all your time looking for frogs which, one after one, (and sometimes all together), jump outside the wheelbarrow.