Chemical Evolution in Big History

Leonid E. Grinin
National Research University Higher School of Economics,
Moscow; Institute for Oriental Studies of the Russian Academy
of Sciences, Moscow

Correspondence | **Leonid E. Grinin** leonid.grinin@gmail.com

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Abstract: Unfortunately, there is insufficient research on the course of chemical evolution within the framework of the study of both Big History and evolution. The lack of attention to chemical evolution is all the more disappointing since it is a very important part of megaevolution and Big History, which at some of its stages even act as the leading line (in particular, in the formation of pre-life on the Earth five billion years ago). The paper presents a brief history of chemical evolution: from the formation of the first atoms in the Universe to abiogenesis on the Earth, that is, the stage of pre-life and the formation of prerequisites for the emergence of the first living organisms. The history of chemical evolution before life's origin can be divided into three stages: the formation of atoms (pre-evolution); history before the start of the abiogenic phase on the Earth; and abiogenic chemical evolution. However, the author aims to elaborate a more detailed periodization of chemical evolution before life's origin. One should also pay attention to the important feature of chemical evolution which distinguishes it from other lines of evolution, namely, its co-evolutionary nature. The author demonstrates that chemical evolution at all its stages acted as a part of a co-evolutionary tandem: first, as a part of cosmic and stellar-galactic evolution, then as a part of planetary evolution since it is on planets (where temperature parameters are much more comfortable for chemical reactions) that a new qualitative stage in the development of chemical evolution begins. Finally, on the Earth, it developed first as a part of geochemical evolution, and then as a part of bio-chemical evolution, and this development continues until now.

Keywords: chemical evolution, megaevolution, Big History, cosmochemical evolution, co-evolution, bio-chemical evolution, geochemical evolution, star-galaxy era.

Introductory Notes

It is strange, but there is little, if any, research on chemical evolution in the framework of the study of Big History. Why? This is a difficult question. Perhaps, no one knows the answer. I do not know it either but I have an idea, which will be presented below. One way or another, considering the chemical line of Big History can significantly enrich our ideas and understanding about the general course of Big History and about the path to increasing complexity. Moreover, without understanding the history of chemical evolution, one can hardly grasp either the mystery of the origin of life and development of life in the early periods.[*]

However, the question of the formation of the chemical elements has always been among the most important questions and remains so today. Among seminal works is the 'The Origin of Chemical Elements' by R. A. Alpher, H. Bethe, and G. Gamow (1948). The Alpher–Bethe–Gamow theory explained correctly the relative abundances of the isotopes of hydrogen and helium. The mistake was in the idea, that all atomic nuclei are produced by the successive capture of neutrons, one mass unit at a time. Later it was recognized that most of the origin of heavy elements was the result of stellar nucleosynthesis in stars. The stellar nucleosynthesis theory supported it with astronomical and laboratory data first suggested by E. M. Burbidge *et al.* (1957). The authors identified nucleosynthesis processes that are responsible for producing the elements heavier than iron. The paper became highly influential in both astronomy and nuclear physics.

The process of formation of elements up to and including iron took place mainly in the cores of stars. But the cosmic origin of elements heavier than iron has long been uncertain (Kasen *et al.,* 2017). At present this process has become clearer. Two types of processes are distinguished: s-

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[*] See Bernal, 1969; Betekhtin, 2007; Galimov, 2008; Glyantsev, 2019; Guotmi & Cunningham, 1960; Degens & Reuter, 1967; Dickerson, 1981; Dobretsov, 2005; Zavarzin, 2003; Zaguskin, 2014; Calvin, 1971; Kamshilov, 1970, 1979; Lima de Faria, 1991; Rudenko, 1969; Spiridonov, 2019; Haldane, 1949; Lyons *et al,*. 2014; Grinin, 2013, 2017, 2018, 2020; Grinin & Grinin, 2019.

process (the slow neutron-capture process) and r-process (the rapid neutron-capture process).

S-process. Previously it was known that processes that create elements heavier than iron occur as a result of supernovae explosions, when some stars become supernovae at their demise and spew those s-process isotopes into interstellar gas. And both explosions and results of s-process were observed due to astronomical observations. They believe that the s-process is responsible for the creation (nucleosynthesis) of approximately half the atomic nuclei heavier than iron. However, it was unclear how very heavy elements were formed.

R-proccess. Another – rapid – process for the formation of elements heavier than iron (the r-process) has also been described theoretically. In fact, to create elements heavier than iron, such as strontium, an even hotter environment with a large number of free neutrons is required. Rapid neutron capture occurs in nature only under extreme conditions and environments, where atoms are bombarded by huge numbers of neutrons. This is observed in very rare cases. When two neutron stars merge, an explosion occurs. This event is called kilonova. As a result, conditions are created for the synthesis of a large number of elements heavier than iron. This event was observed in 2017, resulting in the identification of strontium in the spectral analysis. In addition, during the observations, a large amount of new data was collected. In particular, it has been recorded that heavy elements, such as gold, platinum and uranium are formed during neutron star mergers. The observational results and theoretical conclusions have been published in *Nature* (Kasen *et al,.* 2017; see also Yamazaki *et al.,* 2022; Arcones & Thielemann, 2022; Curtis, 2023).

Thus, about half of the abundance of elements heavier than iron originates in some of the most violent explosions in the cosmos (Curtis, 2023). Note that the very important rule of evolution – the Rule of coincidence of unique conditions for the emergence of qualitatively new phenomena – is clearly manifested here (for more details see Grinin, 2017). Supernova is a rare event. But kilonova is an exceptionally rare event, where the colossal energy is concentrated, and only this amount of energy can produce such a result.

So the formation of hydrogen, helium and a small amount of lithium atoms (Johnson, 2019: 474) in the first period after the Big Bang, and the accumulation of heavy element atoms as a result of the star collapses were the most important events in chemical evolution. However, the formation of atoms cannot be yet considered as a chemical evolution in the full sense of the word. Chemical evolution is *the emergence and development of different and more complex types of molecules and substances.* One should realize that such evolution could hardly begin in a very hot universe, nor could it take place in the depths of stars.

Thus, it is important to realize that chemical reactions:

a) can occur when the temperature drops to 5,000 degrees Kelvin, but in fact the most favourable condition for them is at relatively low plus temperatures[1];
b) take place constantly in space, even at deep sub-zero temperatures; some of the characteristics of such chemical reactions are known from the studies of gas and dust clouds;
c) should be even more active within the framework of evolution of planets and other bodies (including comets), as can be inferred from studies of the bodies of the Solar system.

Chemical Evolution as a Peripheral and Parallel Line of Big History

Chemical evolution can be regarded as a peripheral and parallel line of Big History. Why? From the argument above, one can make the following important conclusions: firstly, the chemical evolution could only begin after the cooling of the Universe. Secondly, it always evolved not in the main sequence, that is, not in stars and galaxies, but at the periphery of the Universe. It developed mainly in gas and dust clouds and on peripheral celestial bodies, especially on planets. And consequently, for many billions of years, the ‘achievements’ of chemical evolution have been somewhat invisible (see Figs 1, 2). Thirdly, since the formation of the Solar System the planets can no longer be considered as peripheral bodies, because the planet Earth played a significant role in the further course of evolution and Big History. However, the peripheral character of chemical evolution was preserved. As shown below, chemical evolution only in one case appeared in the center of the mega-evolution development, namely, during the abiogenic phase of Big History. This phase turned out to be very important, but nevertheless, it was transitional one. Fourthly, later, the role of chemical evolution was important,

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[1] Therefore, chemical compounds cannot form in stars, but only on the surface of not hot or cooling stars. It is also possible after the collapse of stars, when a significant amount of matter is ejected into space and rapidly cools down.

but it was supplementary rather than central, so it can be considered as peripheral, sometimes approaching the central line of Big History and mega-evolution. The question may arise: If life is not peripheral and is only known to us on a planet, how can we argue that chemical evolution is peripheral just because it occurs on planets? Of course, life is the most important phase of Big History and mega-evolution. And life would be impossible without the powerful development of chemical and biochemical evolution. But here one should take into account the additive nature of chemical evolution. It is extremely important, but it does not play a central role, it only has an additional or co-evolutionary role. At the same time, the role of chemical evolution in the biosocial and social phases, although still significant, decreases compared to the biological phase.

All this gives reason to regard it as a peripheral and parallel line of Big History. However, since the terms 'peripheral and parallel lines of Big History' are new and are first introduced in this paper, the distinctions between parallelism, peripherality and co-evolution need to be clarified for a better understanding. We hope to do this in our future works.

Let us now return to the question of why so little attention is paid to the chemical evolution. I believe that one of the main reasons is the parallel development of chemical evolution within Big History. Other reasons are its co-evolution with geological and biological evolution and the fact that we know very little about the abiogenic chemical evolution. This, however, in no way diminishes the role of chemical evolution; but, on the contrary, it makes its study really relevant.

Chemical evolution began even before the star-galaxy era, that is, already in the first millions of years after the Big Bang, in gaseous hydrogen-helium clouds. This is where the first molecules were formed. But, of course, this evolution could not proceed actively without the formation of a sufficient variety of chemical elements. Thus, chemical evolution progressed in parallel with the star-galaxy evolution. At the same time, (in clouds, on planets, in comets and meteorites, etc.) there are many dozens of different not only inorganic but also many organic substances, including water, alcohols, acids, monosaccharides and even amino acids, in particular glycine. The synthesis of simple organic substances constantly occurs in various cosmic environments.

We do not know when the first planets formed, but with their emergence, the rate of chemical evolution increased considerably due to the variety of chemical processes on the planets, including in different gaseous and liquid media.

The scheme (see Fig. 1) demonstrates the unfolding of Big History, the structure of which consists of ten phases – five major phases and five transitional ones. On the left one can see the line of chemical evolution.

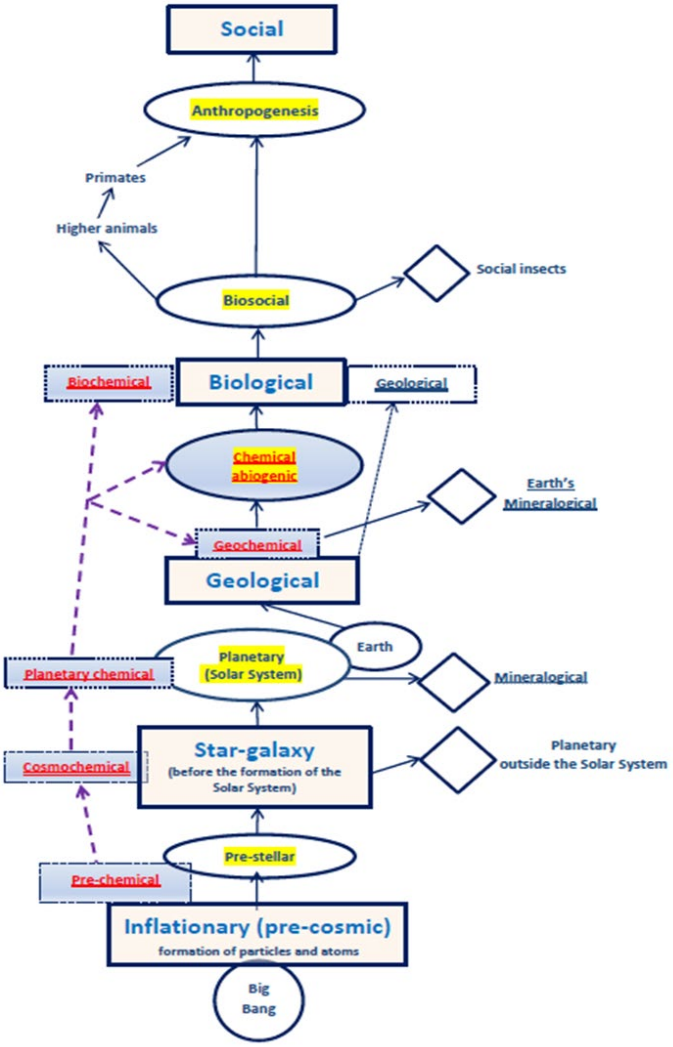

Fig. 1. *Unfolding of Big History (Megaevolution). Phases and lines of Big History*

Periodization of Chemical Evolution

We distinguish the following sequence of stages of chemical evolution before the origin of life:

1) the formation of atoms of the first elements (hydrogen, helium, and lithium);
2) the formation of atoms of heavier substances up to

iron, as a result of which a small number of the hydrogen and helium in the Universe has been transformed into the wide array of elements on the periodic table (Johnson 2019: 474);
3) the formation of atoms of elements heavier than iron[2];
4) the formation of simple compounds (inorganic and organic). [However, it is important that the second and third stages could take place in parallel with the fourth one, but in different environments: the second and third stages in stars, while the fourth one in less hot environment.]
5) the formation of compounds associated with the formation of minerals on planets;
6) synthesis of more complex organic compounds like nucleotides taking place already on the Earth;
7) synthesis of more complex substances and polymers, including proteins, not yet capable of replication; and
8) synthesis of replicators and substances associated with the origin of life.

Now let us consider the correlation between chemical evolution and Big History.

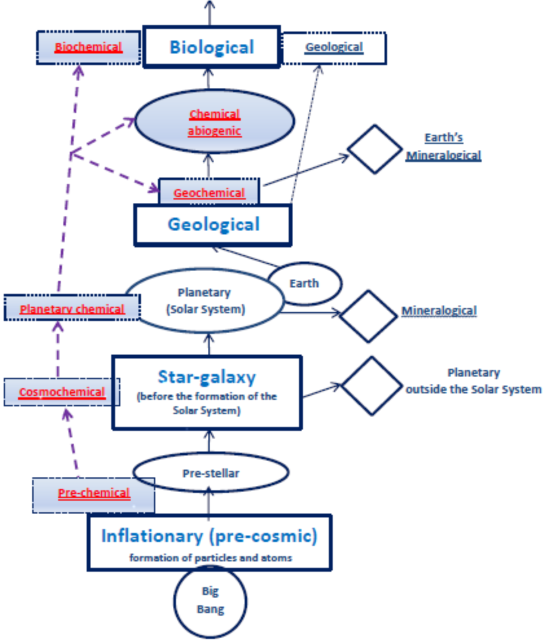

Fig. 2. Chemical evolution as a peripheral and parallel line of Big History

The Distinctive Features of Chemical Evolution from Other Forms of Evolution in Big History

Figs 1 and 2 show the important features of chemical evolution which distinguish it from other forms of evolution. These features are as follows:

1) All other forms of evolution are separate phases of Big History. Thus, one form of evolution, having been realized at a certain phase of Big History, is replaced by another form.
2) However, chemical evolution goes parallel to the course of Big History. More precisely, it co-evolves with different phases of Big History as a constituent part of each of them. Thus, one can see that chemical evolution acted as a part of a co-evolutionary tandem at all phases of Big History (see Fig. 3).

Let us now briefly consider the development of chemical evolution in its relation to the phases of Big History.

Chemical evolution after the Inflationary phase appears as a part of the Pre-stellar phase. I have pointed out above that chemical evolution began in pre-stellar clouds. But it was still pre-chemical evolution.

The star-galaxy phase, which includes the formation of planets outside the Solar System, corresponds to Cosmochemical evolution. It is during this phase that the first chemicals are formed. Thus, a new qualitative stage in the development of chemical evolution (where the temperature was much more favourable for chemical reactions than in stars), began on ancient planets. However, we know practically nothing about this evolution.

With the formation of the Solar System and the beginning of the Planetary phase, one can talk about the Planetary chemical evolution since we know quite a lot about chemical processes and substances on the planets of the Solar System.

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[2] But here, as we have seen above, the formation of the elements heavier than iron occurred in two ways. For more details about when and how the process of nucleosynthesis made elements in different ways, including dying low-mass stars and white dwarfs see Johnson, 2019.

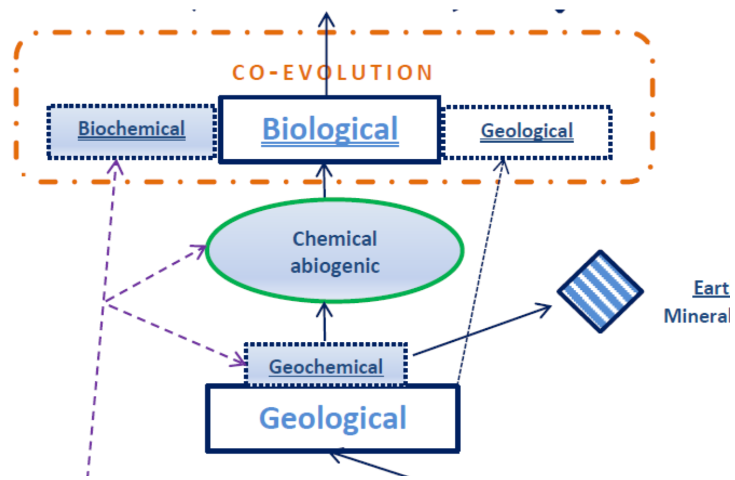

Fig. 3. *Chemical evolution on the Earth and its increasing evolutionary role. Phenomenon of co-evolutionism*

The formation of the Solar System means that the main line of Big History begins to focus on the Earth, where geological processes begin. Finally, on the Earth, chemical evolution developed first as a part of geological and then as a part of biological evolution. This development is still ongoing.

Thus, for the first time, chemical evolution moves to the center of evolutionary development at the level of chemical abiogenic phase (see Fig. 3). In this phase the role of chemical evolution rapidly increases to the level of a transitional phase.

The period between the formation of the Earth and the emergence of life was pivotal for the whole Big History, and at the same time, the least known and the most obscure. During this period chemical evolution was integral and interrelated with geological, mineralogical and biological evolution. It was the co-evolutionary tandem mentioned above.

From the Abiogenic Phase to the Origin of Life

Strengths and Weaknesses of Evolutionary Hypotheses about the Origin of Life

There are various hypotheses about abiogenic chemical evolution and the origin of life including the so-called RNA world. Although some progress has been made in many respects, especially in the last fifteen years, none of them seems to be completely satisfactory yet. This is mainly due to the extreme complexity of the problem itself. But from the point of view of evolutionary theory, the weaknesses of these approaches are in the following points:

1. They deliberately or involuntarily reduce evolution to one of its lines.
2. They take one evolutionary mechanism as the main one in all cases.
3. The achievements of later periods, already related to the biological phase, are extrapolated to the abiogenic phase.

We believe that the possibility of a major breakthrough exists only if there are a number of different development lines and paths. Moreover, each of these lines is limited and usually develops only one mechanism or innovation. But these lines compete and complement each other. As a result, there comes a time when the innovations of different lines are merged and formed into a fundamentally new system. This means the beginning of a powerful breakthrough to a new level of complexity. However, the beginning of such a breakthrough, after the formation and development of the new level is difficult or even impossible to detect. This corresponds to the important idea of Pierre Teilhard de Chardin (1987) that transitional forms leave no visible material traces. We have also formulated the rule of archaic character of primary systems. Systems do not emerge in the mature form. They usually require several transformations to reach maturity and sustainability, including cycles of destruction and reforming. Primary systems as a rule look archaic and are unlikely to survive.

Therefore, the first pre-living systems (the so-called protobionts) should not be considered as direct ancestors of the first living organisms, but as their analogues. These analogues were already comparable to the most primitive living systems in a number of functions. But in general they were organized differently (it is now extremely difficult to say how exactly). In addition, one should also take into account that the conditions on the young Earth were peculiar. Consequently, such structures could have formed, but modern scientists are unlikely to believe in their existence until concrete facts are available.

The Evolutionary Directions of Abiogenic Organic Substances

Thus, one can argue that the evolution of abiogenic organic substances occurred in the following different directions:

a) increasing complexity of chemical compounds and structures;
b) increase in energy output and reaction rate;

c) selection of elements and compounds according to certain parameters;
d) concentration of substances;
e) the ability of complex compounds and proto-organisms to expand and grow fast.
f) the selectivity and recognition of some substances by others, according to the important evolutionary pattern for self and non-self discrimination.

The Most Important Pre-Adaptations for the Beginning of Biological Evolution

The important pre-adaptations are worth special mentioning. The most important ones for the beginning of biological evolution are:

1) creation of a system isolated from the external environment, in which constant cycles of chemical and biochemical reactions could take place;
2) constant maintaining of conditions, concentrations, energy balance, the desired rate of reactions within this isolated environment, *etc.*;
3) effective responses to external conditions and stimuli;
4) replication (*i.e.*, the ability to reproduce);
5) preservation without major distortions of the initial code;
6) control of complex chemical processes through the use of increasingly advanced catalysts and substances;
7) autocatalysis and the ability to self-assemble.

These breakthroughs and pre-adaptations laid the foundation for biochemical synthesis and expansion. Especially important were the ability to store energy, and the ways to speed up reactions and to increase the concentration of a substance. Along with this, a new type of information (chemical and biochemical) emerged, which reached a very significant development later in biological evolution.

These and other achievements, of course, could not combine immediately and simultaneously. They combined much later when the basic mechanisms of life and the living cell were formed.

The primary conditions after the origin of the Earth were unique. Without them the transition to the emergence of pre-life and then life was impossible. Will these unique conditions ever be precisely known? Probably, they will not. But in any case, there must have been an abundance of available energy. Consequently, the fundamental difference between abiogenic chemical evolution and the previous stages of evolution was *the acquisition of the ability to store energy through chemical transformation during a system's lifespan and to use it for its own benefit.*

Protoviruses

There may have been one more intermediate phase between the abiogenic chemical and biological phases – the phase of protoviruses (see Fig. 4).

Below we will show the possible place of this phase in the megaevolutionary process. One should take into account that chemical reactions played a great role in the origin and development of protoviruses.

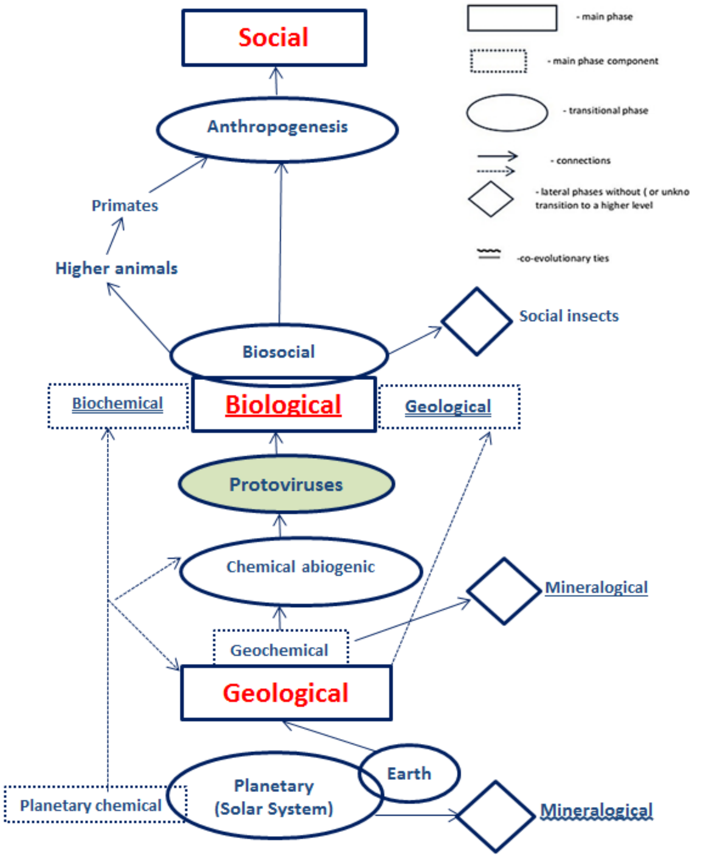

Fig. 4. *Evolutionary phases of Big History including the phase of protoviruses*

Conclusive Remarks

For a long time, the abiogenic organic chemical evolution was only lateral and marginal in the general flow of inorganic chemical evolution. Then it was able to advance to a new level of evolution, *i.e.,* to life, taking place in a complex co-evolutionary movement. Abiogenic chemical evolution was involved in a whole bundle of evolutionary developments: geological, mineralogical, and geochemical. Thus, one can assume that initially one of the most important directions of chemical evolution was the integration of protobionts into geochemical processes, such as sulphur springs, and the development of the ability to use these processes for one's own benefit.

Thus, gradually abiogenic chemical evolution gained momentum.

However, the role of chemical evolution remained very important. It again becomes a part of a larger – the biological – phase. In the scheme of the phases of Big History, we do not trace a further development of chemical evolution, but one should remember that it has also become an important component of social evolution, which can be called sociochemical. At the same time, its importance begins to appear already in the phase of anthropogenesis, from the moment when humans learned how to control fire. It is widely known that there is no point in talking about the further role of chemical evolution in the social phase of Big History, it is widely known. Nevertheless, one can argue that neither technology nor ordinary life would be possible without continuous efforts to master new chemical substances and reactions.

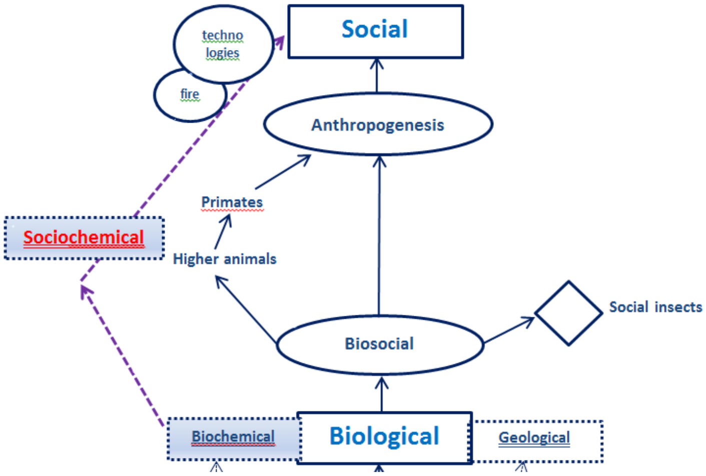

Fig. 5. *Sociochemical evolution*

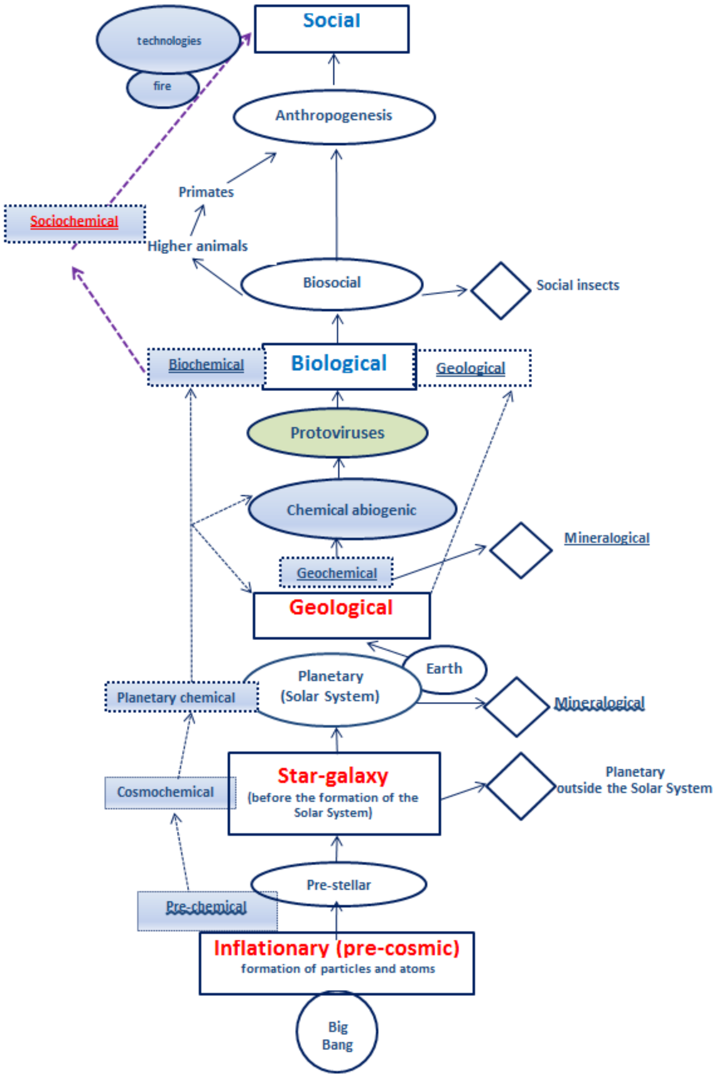

Fig. 6. *The complete line of chemical evolution from the Big Bang to social evolution*

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