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Evolution of Circadian Clock Automation: How Long did it Take?

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Abstract

The paper expresses the opinion on possibilities of self-assembly of advanced clock-controlled system with feedback loops in the frames of time set by the evolutionary hypothesis, i.e. max. 400 million years. The main difficulty is that the circadian system of the oldest living cell (cyanobacteria) is dependent on gene expression and photosynthesis, both of them controlled by the circadian system. Moreover, without fully developed clock and functional machinery a cianobacterial cell is unable to switch from daytime to dark regime, which sets new limitations on the evolution time. Even though the process of automation in industry began ca. 60 years ago, it is widely recognized that a mechanical clock should be treated as a structurally complex cybernetic device even though its behavior is in principle simple [1,2]. In my opinion, this applies even more to the circadian clocks in biosystems of living organisms, since the researchers point out the features like auto-regulatory loops and programming [3,4]. Circadian clocks are found in organisms ranging in complexity from unicells to mammals, where they play important role to control daily rhythms in cellular activities and behavior [5]. Researchers found out that the "extensive circadian clock networks regulate almost every biological process in plants" [6]. It is a common view that the organisms "have developed the ability to measure time on a 24-hour basis" and thus to adapt their lives to cycles of light/dark and warm/cold [7]. The question rises, however, how they developed this kind of ability, and how long did it take to produce and to assemble the parts into the working circadian clock system?

Let us consider cyanobacteria with their clocks. These living beings are believed to be the Earth's architect who formed the oxygen atmosphere, they are thought to be the ancestors of plant chloroplast and they have been tremendously important in shaping the course of evolution and ecological change throughout the Earth's history [8]. First, the system of circadian clock is far from simple. To mention only the shape of three parts of cyanobacterial molecular clock mechanism, KaiA is a dimer of intertwined monomers, KaiB has a thioredoxin-like fold and forms dimers and tetramers, and KaiC is a "double-doughnut" hexamer [9]. At the level of the simplest eukaryotic, archaeal and bacterial common ancestor, complexity is of so high degree that the evolutionary researches can propose only a sort of "highly complex archaeal ancestor of eukaryotes that possessed certain signature eukaryotic features" [10]. To make the answer more difficult, cyanobacterial and eukaryotic clocks are so much different that it can be assumed that "oscillatory systems evolved independently at least twice, once in the cyanobacteria and once in the eukaryotes" [7]. The doubled question "how" remains unanswered. Next, the circadian control systems are completely self-dependent, which poses unsolvable problem on how they first get going. The most difficult is a question on gene expression, because without proper gene expression, there is no clock, and vice versa, without a clock, there is no proper gene expression. An assumption of long-term gradual development of such a system requires introduction of some sort of higher-degree system that would sustain an organism until the circadian automation system is fully developed.

The question becomes far more difficult when the time frames are considered. In case of the oldest fossils, they are c. 3.49-and 3.46-billion-year-old filamentous and coccoidal microbial remains [11]. It can be assumed that "cyanobacterium-like microorganisms were extant and morphologically diverse at least as early as approximately 3465 million years ago and suggests that oxygen-producing photoautotroph may have already evolved" [12]. Since the photosynthesis process is controlled by the circadian clock, it should be concluded that the clocks have evolved by this time, too. It is suggested also that some 3.5- to 3.0-billion-year-old fossils may belong to cyanobacteria, which is just a billion years later than a magma ocean started to cool (4.5 Ga) and 400 million years after heavy bombardments finished "preparing the Earth for the prebiotic chemical evolution" (3.9 Ga) [13,14].

The problem is, how many times during 400 million years the assembly process could have been interrupted before fully vital cell was ready to survive? From engineering perspective, time constraints of few hundred million years for circadian clock construction out of nothing are impossible to keep even theoretically. There is no reasonable model demonstrating how a cyanobacterial cell could survive without a clock. Moreover, we are unable even to imagine (leave alone imitating in a laboratory) a sort of conditions where life could "emerge" and how a cell could assemble itself using any set of prebiotic materials at any time.

However, the survival of cyanobacteria was threatened not after a long time of many years, but the very first night after its "emergence". In fact, both day and night include the redirection of central metabolism and sweeping changes in gene expression, so that if the clock is locked into a daytime transcriptional regime, that leads to metabolic imbalance, increased oxidative stress, and death [15]. To be sure, the entire system of cyanobacteria's cell, able to survive a daytime with its alarm clock able to recognize dark and to switch its subsystems to the night's regime in order to survive until the dawn, should be assembled before dusk. Otherwise, the very first Day-Night Cycle would kill the entire population of

cyanobacteria. To sum up, cyanobacteria being the oldest known living cell are able to respond to their environment, and this ability is provided by a circadian clock [16]. Circadian clocks are included into self-sustaining systems with numerous closed loops, sensors and feedbacks. There is no gene expression or photosynthesis without a circadian clock, and there is no circadian clock without gene expression and photosynthesis. Moreover, a Day-Night Cycle provides such a harsh environmental change that a cyanobacteria would not survive a single cycle, hadn't it fully assembled systems for both day and night functions, as well as the functional clock-controlled switch. The conclusion is, that the cyanobacteria as we know them must have emerged during 12 hours at longest, and after that short period of time it must have been fully prepared to face upcoming night or day.

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