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Cosmic Rays as a Factor of Biospheric Evolution[1]

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Abstract. There are no doubts that the Earth's space environment in the past inevitably exerted direct and/or indirect influence [1–4] on the conditions of terrestrial life and biospheric evolution. Well-known cosmic factors are usually streams of cosmic dust and gas, comets and asteroids, cosmic rays (energetic particles of galactic and/or solar origin), interplanetary plasma (solar wind), and electromagnetic radiation of different energies, wavelengths, or frequencies. Of great interest are radiation conditions and their variations, especially in the remote past (over the geological time scales). The Sun, the most important and indispensable condition for the existence of the Earth's biosphere, is also a potential source of dangerous emissions. In continuation of (and in addition to) our review paper [3], below we summarize the observational data and results of theoretical works that have been carried out and/or published mainly after 2012. These studies are actually in the frontier region between the Astrobiology and Space Weather. Our main attention is paid to cosmic rays (CR) of galactic and solar origin (GCR and SCR, respectively).

Introduction. Cosmic Rays in the Past

Earlier [3] we have described a history of the problem "Cosmic Rays and Biosphere". Besides that, the main experimental data on CR influence on the biospheric evolution have been reviewed. In particular, we have considered regular variations of GCRs in the remote past of the Solar System (by meteoritic data), possible occurrence rate of some sporadic phenomena, namely, Supernova explosions and giant solar flares [4, 5]. As noted, in this region of investigations there are still quite a number of astrophysical and biological problems that require to study them from modern positions, taking into account new models of structure and evolution of the Galaxy as well as experimental evidences of important CR role in the evolution of the biosphere [3]. Space research programs that are currently fulfilled and/or planned for the nearest years enhance our hopes for the better understanding of the Astrobiology basis. In particular, contribution of the nearest dwarf stars to the GCR flux at the Earth's orbit seems to be revised in the light of the newest observational data [6].

[1]Talk presented at the Interdisciplinatory Colloquium on Cosmic Factors of Evolution of the Biosphere and Geosphere, Moscow, May 21–23, 2014.

When estimating the role and contribution of GCRs, one should take into account the real timescale for different stages of biospheric evolution under study. Indeed, the actual "age" of observed GCR fluxes near the Earth is limited by the values of 10–100 million years. It implies that, during the crossings of galactic arms in the process of Sun's rotation around the Galaxy center, terrestrial biosphere might be exposed to irradiation by GCRs of different intensity, age, and origin. Meanwhile, since the times of Darwin (and even earlier) the data appeared on that the development of the biosphere seems do not exclude some unconformities ("jumps"). One of them is the well-known "Cambrian explosion" (CE) – a sharp (by geological scales) and dramatic augmentation in the numbers of one-cell organisms inhabited the Earth about 540–480 million years ago. Charles Darwin himself in 1859 was compelled to admit this event to be the gravest single objection to his theory of evolution. On the other hand, since many cosmophysical factors have a random and/or sporadic character (e.g., comets, asteroids, Supernova explosions, and solar flares), it seems overwhelmingly likely that the development of the biosphere also was not uniform in time.

Until very recently, the CE was thought to be an anomaly [4] that cannot be compatible with the modern concepts of biospheric evolution. Sudden, nearly simultaneous appearance of many groups of animals in the Cambrian period was named a "Darwin dilemma", because such an anomaly could not arise within the process of natural selection. Up to now, one of the most common explanations of the CE is reduced to the fast transition of the animals to mineral exoskeleton due to enhancement of concentration of calcium salts. Recently, American geologists suggested their own explanation for this phenomenon [7]. In their opinion, the CE might happen due to the change of the ion composition of the sea water purely by geologic reasons, namely, due to eroding away surface rock to uncover fresh basement rock. Exposed to the surface environment for the first time, those crust rocks reacted with air (oxygen) and water in a chemical weathering process that released ions such as calcium, iron, potassium, and silica into the oceans, changing the seawater chemistry. These new materials were used by organisms for their own needs in the adaptation process, and as a result a phenomenon of biomineralization becomes a *fait accompli*.

However, up to now no reliable analysis of the speed proper of CE was carried out; the speed was simply considered as a very high one. In order to estimate this parameter of basic importance, Australian paleontologists [8] accomplished a numerical analysis of the evolution speed of arthropoda that separated into several large groups just in the Cambrian period. It was found that the evolution speed in the CE period was high, indeed, but it was not really anomalous. In fact, it was only 4.0–4.5 times higher in comparison with the evolution speed in the subsequent periods. Thus, the Cambrian explosion may be reasonably reconciled with Darwin's evolution theory. Note, by the way, that, according to meteoritic data (for details see [3]), the summary flux of GCRs in the CE epoch was about 3 times lower than the observed one at present... As to contribution of the hypothetical Supernova explosions to this flux, it remains still questionable.

On the other hand, in the course of natural processes a certain rhythmics is usually observed, and at large timescales different processes may be even synchronized on the principles of hierarchy, if a strong rhythm-setting source (for example, the Sun's activity) is in operation. In this light, a number of facts and findings from heliobiology research [1] may be adequately interpreted on the base of the concept of evolution-adaptation syndrome [2]. Hence, it appears that, side-by-side with the search for new data on cosmophysical factors, at least, two task remain urgent [4]: (1) construction and development of theoretical models taking into account possible intensities of radiations that exerted influence on the biosphere in the past; (2) studying the modern responses of the biosystems to cosmophysical factors as an atavistic reaction on the alteration of habitat conditions.

Ancient Flares at the Sun and the Biosphere

Radiation conditions near the Earth's orbit, ionospheric disturbances, state of the ozone layer, ionization state of the upper atmosphere, and other geophysical phenomena, to a large extent, are determined by variations of energetic particle fluxes [1] that are produced at/near the Sun (SCR). At the Earth's orbit these fluxes are manifested as Solar Proton Events (SPEs). The magnitudes and significance of such events (their geoefficiency) vary in dependence of the level of solar activity (SA). SPEs registration rate depends on the current stage of the 11-year activity cycle (ascent or descent phases) [2]. Of special interest are extreme solar flares and "ancient" proton events [3, 5], because their frequency and power could be different in different epochs of the Sun's evolution, in particular, during the epoch of the "young" Sun, at a different level of solar activity. The SPE power is usually estimated by summary values (fluences) of the SCR fluxes integrated over the entire duration of a given event. Our estimates [5] indicate a sharp fall of SPE distribution function in the range of small probabilities (i.e., in the range of large SCR fluences). It follows from the analysis of all data (indirect and direct) on SCR fluxes (fluences) available for the last ∼1200–1300 years [5, 9]. For reasonable extrapolation to the past and future, we need appropriate models of the "young" and "late" Sun.

Indirect data on SCR fluxes in the past may be obtained from some natural archives, e.g., nitrates in the ancient Antarctic and Arctic ices, radiocarbon ^{14}C in tree rings, ^{10}Be, ^{26}Al, and other cosmogenic isotopes in lake sediments, etc. [1, 3, 9]. At present, we have information about a few extreme SPEs for the period of the last 1200 years (since AD775). Amongst them, the most known is a flare of 1 September 1859 (so-called "Carrington Event", or CE) [10]. As to recently identified event of AD775 [9], our estimate of the proton fluence at the energy $\geq$30 MeV (2.96×10^9 cm^{-2}) is about one order of magnitude lower [1] than that for CE (1.88×10^{10} cm^{-2}). However, following the event model by the authors [11], we get a value of $(2.0–3.0) \times 10^{10}$ cm^{-2}. It is most likely that a summary fluence of AD775 was produced by a strong (but not extremely strong) SPE (or by a series of SPEs) [9]. On the other hand, available fluence estimates for a number of ancient SPEs (see, e.g., [12]), obtained by the scenario and spectrum of the event of 23 February 1956 (the largest one in the history of direct observations) seem to be not quite convincing to us.

In the whole, available data of observations and methods of investigations do not allow us, for the present, to resolve precisely the problem of spectrum break and to estimate maximum potentialities of the solar accelerator(s). This restricts considerably the extrapolation of the obtained results for the past and future, for the epochs with the levels of SA different from the modern one [5]. Nevertheless, data on SCRs and their geophysical effects allow us to understand better the mechanisms of solar-terrestrial relations [1]. In its turn, this is important for modeling the evolution of the terrestrial biosphere in the past and future [2] as well as for the quest of possible seats of life on Mars and other planets of the Solar System. Finally, with more realistic models of the Sun, it will become possible to discuss with more confidence a true role of the factors that have influenced the origin and evolution of the biosphere.

Search for Martian biosphere

As known, Mars has neither a dense atmosphere nor a strong magnetic field. Therefore, the particles of GCRs and SCRs can effectively bombard the Martian surface. This process results in the formation of radiation background near the Martian surface that can be nearly 100 times higher that that at the Earth's surface. Hence, a major interest to theoretical and experimental investigations of real CR background variations and their influence on the biological objects and biomarkers in the course of long-term Martian evolution becomes quite understandable [13]. If Martian life exists, or existed in the past, it is reasonable to assume that it is or it was based on organic molecules and that it will therefore share with terrestrial life the vulnerability to energetic particle radiation [13–17].

Recently, the first results of direct measurements of radiation conditions at the flight route of Mars Science Laboratory (MSL) to Mars have been published [18]. Of no less interest are the measurements by Radiation Assessment Detector (RAD) that registers radiation background directly at the Martian surface in the Gale Crater where the Curiosity Rover is since 7 August 2012 [19]. These measurements yielded a surface dose that may be extrapolated to subsurface layers (using transport models) with implications for estimating lethal depths and survival times for the microbiological objects [13–17]. The radiation environment on Mars may also play a key role in chemical alteration of the regolith and Martian rocks over the geologic scales of time, affecting the preservation of organics including potential organic biosignatures of the ancient Martian environment [14, 15]. At any rate, the RAD surface measurements provide a baseline for inferring the flux in these more shielded environments (by validating and anchoring transport models), and thus the foundation for understanding the limits to preservation of organic matter in the soil and rocks of Gale Crater.

Detection of the organic substance on Mars is one of the main goals of current and coming Martian landing missions. However, as noted in [17], degradation of organic molecules by cosmic ray irradiation on Mars is often ignored. The authors [17] calculated the accumulation rates of radiation dose from solar and galactic cosmic rays at various depths in the shallow Martian subsurface. It was shown that a 1 Gyr outcrop on Mars accumulates the dosage of $\sim$500 MGy (MegaGrey) in the top 0–2 cm and $\sim$50 MGy at 5–10 cm depths. It means that the preservation of ancient complex organic molecules in the shallow ($\sim$10 cm depth) subsurface of rocks could be highly problematic if the exposure age of a geologic outcrop would exceed 300 Myr. On the other hand, it was demonstrated that simpler organic molecules with masses $\sim$100 amu should have a good chance to survive in the shallow subsurface of rocks.

Several studies have modeled the expected subsurface radiation regime (e.g., [14, 15]), but the dose values depended until now on the modeled radiation environment on the surface. The authors [14, 15] suggested an absorbed dose of $\sim$150 mGy/year at the Martian surface, whereas in [13, 17] an absorbed dose of 50 ± 5 mGy/year was assumed. The actual absorbed dose measured by the RAD (76 mGy/year at the surface) allows for more accurate estimations of the subsurface dose. Differences may be in part due to differing assumptions in the models about the level of solar modulation compared with the actual level during the measurement period as well as the amount of atmospheric shielding above the surface. In its turn, the estimates of degradation of the organic matter at different depths may be very helpful for experimental detection of life on Mars [3] by observed signatures of vital activity of some microorganisms in the subsurface layers of the Martian soil (see, e.g., [20]).

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Космические лучи – фактор эволюции биосферы

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Резюме. Космическое окружение Земли прямо или косвенно влияет на условия земной жизни. Космические факторы включают повышенные потоки газа и пыли, кометы и астероиды, а также космические лучи (энергичные частицы галактического или солнечного происхождения), межпланетную плазму (солнечный ветер) и электромагнитные излучения различных энергий (частот). Большой интерес представляют радиационные условия и их вариации, особенно в отдалённом прошлом (на геологической шкале времени). Солнце, наиболее важное и непременное условие для существования земной биосферы, также рассматривается как потенциальный источник опасных излучений. Нами кратко суммируются наиболее современные данные наблюдений и результаты исследовательских работ, которые находятся в пограничной области между Астробиологией и Космической Погодой. В докладе основное внимание уделено космическим лучам галактического и солнечного происхождения (ГКЛ и СКЛ, соответственно). Детально рассматриваются регулярные вариации ГКЛ в далёком прошлом Солнечной системы, а также возможная частота спорадических событий, а именно, взрывов Сверхновых и гигантских солнечных вспышек. В этой области исследований всё ещё остаётся немало астрофизических и биологических проблем, требующих изучения с современных позиций, с учётом новых моделей эволюции Галактики и экспериментальных указаний о важной роли космических лучей в эволюции биосферы. Осуществляемые в настоящее время и планируемые на ближайшие годы программы космических исследований укрепляют наши надежды на лучшее понимание основ Астробиологии. В частности, вклад ближайших звёзд-карликов в поток КЛ на орбите Земли, по-видимому, должен быть пересмотрен в свете новейших наблюдательных данных. Имеющиеся данные наблюдений по СКЛ пока не позволяют точно оценить максимальные возможности солнечного ускорителя. Это существенно ограничивает экстраполяцию полученных результатов в прошлое и будущее, на периоды с уровнем солнечной активности, отличным от современного. Тем не менее, данные о солнечных космических лучах и их геофизических эффектах позволяют лучше понять механизмы солнечно-земных связей. В свою очередь, это важно для моделирования эволюции биосферы Земли в прошлом и будущем, а также для поиска возможных очагов жизни на Марсе и других телах Солнечной системы. В конечном счёте, при более реалистичной модели Солнца станет возможным более уверенное обсуждение роли факторов, влияющих на происхождение и эволюцию жизни на Земле.