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Role of ionizing radiation in the natural history of the Earth

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Abstract

A role of ionizing radiation in some global processes and events in geological history of the Earth is considered. In particular, we discuss: (1) the influence of ionizing radiation from radioactive nuclei disseminated in sedimentary rocks on the transformation of terrestrial organic matter into stone coals and oil; (2) the effect of cosmic rays from Supernova stars as a common cause of quasi-regular global geological processes and biocatastrophes. © 2001 Elsevier Science Ltd. All rights reserved.

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Taking a look back in time on the history of the Earth we would like to discuss two problems where the role of ionizing radiation was, probably, very significant: (1) the transformation of terrestrial organic matter (TOM) to stone coal and oil and (2) planetary biocatastrophes accompanied by global environmental changes.

1. Natural ionizing radiation and transformation of TOM into coal and oil

From a chemical point of view TOM is a complicated mixture of high-molecular-weight compounds composed mainly from four elements — C, H, O, N. With time TOM undergoes alterations accompanied by an increase of the carbon atom fraction. This process is often called carbonization or coalification. Only beds of organic matter (OM) form coals, while oil and natural gas are by-products of carbonization of dispersed OM.

One usually attributes the formation of coal and oil to the action of heat flux from depth of the Earth. The effect of ionizing radiation from radioactive elements dispersed in small amounts (several g/ton) in matter itself, although discussed in the literature (Mazor et al., 1984), has never been considered as a basic factor in the carbonization of TOM. Here we present arguments in favor of the hypothesis that formation of the main power resources on the Earth is a radiation-chemical process.

Laboratory experiments and some natural phenomena offer impressive examples of the transforming role of ionizing radiation. If we examine a brown coal microsample with zircon grains containing radioactive atoms, emitting α-rays, one may observe that carbonization of the surrounding OM is spatially inhomogeneous even though temperature and pressure had been the same throughout the sample. Far from the grain, at distances greater than the α-particle range, OM is only weakly carbonized, but it is strongly carbonized close to the radioactive grain (Christoph, 1965).

It was demonstrated experimentally that irradiation of coals with various types of ionizing radiation (γ-^{60}Co, α-^{210}Po, neutrons) leads to marked coalification (Byakov et al., 1987; Stach and Depirieux, 1965). However, all these data do not enable us to estimate the overall contribution of ionizing radiation under natural conditions. For this purpose we suggested a simplified mechanism of carbonization of OM, and derived the following equation describing stages of coalification of deposits (Byakov et al., 1987):

$$\ln\frac{C_0^{-1}-1}{C^{-1}-1}=(1.85U^{1/6}t^{1/2}+8)\exp\left(-\frac{1400}{T_\mathrm{m}}\right). \qquad (1)$$

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Here $C_0 = 0.6\,\mathrm{g/g}$ determines the starting point of physico-chemical transformations of TOM (at lower carbon content the process has a microbiological character); C (g/g) is the current content of carbon; U (g/ton) is the concentration of uranium disseminated in matter, t (Myr) is the deposit age and T_m (K) is the maximum paleotemperature (i.e. maximal temperature which was ever reached in a given deposit in the past; typical values of T_m are 300–500 K). All variety of radioactive elements enter Eq. (1) through uranium, because other radioactive elements (Th, ^{40}K) are virtually absent in plant residues. In most cases, the first ("uranium") term in the pre-exponential factor predominates over the second. This means that besides T_m the carbonization process is governed by U and t. Fig. 1 shows a striking correlation between carbon contents in TOM taken from bore-holes all over the Earth and contents calculated by means of Eq. (1).

It is worth noting that Eq. (1) significantly simplifies the rather complicated geological problem of the determination of the maximum paleotemperature of sedimentary rocks. Estimations of T_m based on Eq. (1) are in a good agreement with reconstructions made by geologists (Byakov et al., 1990).

Now we will illustrate the role of uranium radiation in the formation of oil. It was found that intense separation of petroleum hydrocarbons from disseminated OM begins at a certain stage of its maturation, when the content of carbon in it increases to $C \approx 0.74\,\mathrm{g/g}$. Inserting this value in Eq. (1) we obtain the temperature of the intense oil formation:

$$T_f(t,\,U) \equiv T_m(C_0 = 0.6,\,C = 0.74,\,t,\,U) \approx 1400/\ln[3(Ut^3)^{1/6} + 13]. \tag{2}$$

For the first time it becomes possible to understand why this temperature is not a completely defined value. Eq. (2) demonstrates that T_f is a decreasing function of age of petroleogenetic rocks and uranium concentration in it. Eq. (2) is in good agreement with the measured values of T_f in many bore holes of the Russian platform (Byakov, 1991).

It should be mentioned that ionizing radiation plays an important role in the genesis of a remarkable physical property of oil, its optical activity. We have suggested the following empirical relationship for the mean optical activity α (grad/dm) of oils formed in a deposit of the age t (Myr) and uranium content U (g/ton) in it (Byakov et al., 1991):

$$\alpha(t,\,U) = 0.85U(t)/\sqrt{t}. \tag{3}$$

This equation (Fig. 2, dashed line) describes well the puzzling non-monotonic variation of α of crude oils vs. their ages, provided the average uranium concentration of clay rocks for different geological periods (solid line) is taken into account. Eq. (3) successfully predicts an extremely high optical activity of crude oils from uraniferous black shales as well (Byakov et al., 1991). Proportionality between α and U indicates on biogenetic origin of oil and could be of special importance for the problem of origin of life (Goldanskii, 1997).

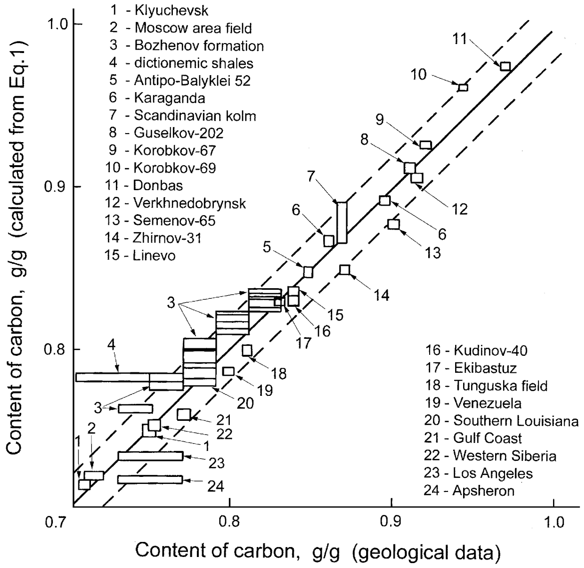

Fig. 1. Comparison of measured and calculated contents of carbon in organic matter (Byakov et al., 1987).

2. Extraterrestrial ionizing radiation in the natural history of the Earth

Now we shall discuss phenomena related to the action of extra-terrestrial ionizing radiation, i.e. cosmic rays (ultrarelativistic protons, heavy nuclei and electrons), bombarding the surface of the Earth. Since Cuvier, more and more facts have accumulated which demonstrate that calm periods of evolution of living organisms were interrupted by numerous planetary biocatastrophes, accompanied or initiated by global physico-chemical effects. We attempt to demonstrate that the cause of all these phenomena is also related to the action of cosmic rays, originating in Supernova (SN) remnants (Byakov et al., 1997).

It is well known that stars in the Universe are distributed inhomogeneously. They form disk-like associations, galaxies. The inner part of our Galaxy, close to the Galactic midplane, is occupied by massive short-living stars. Extremely powerful explosions (SN flashes) terminate their life. The average frequency of such explosions in our Galaxy is approximately $0.05\,\mathrm{yr}^{-1}$. An expanding gas nebula and a neutron star appear as a

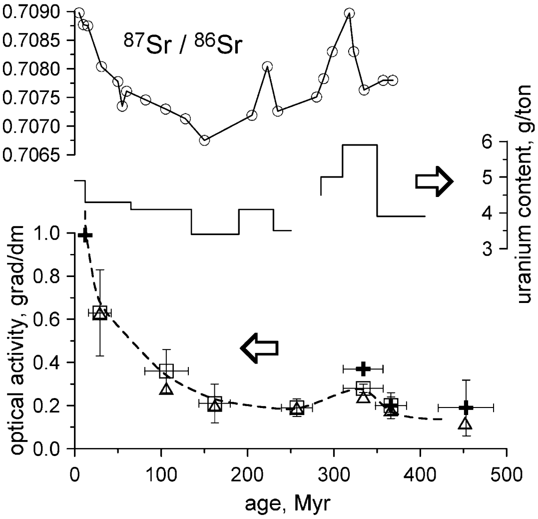

Fig. 2. $^{87}Sr/^{86}Sr$ ratio in sea water (Peterman et al., 1970), mean uranium concentration in clay rocks of the Russian platform (Baranov et al., 1956) and optical activity of oils (□) crudes of Russian platform; (+) American crudes; (△) average world values) vs. age of respective sediments (Byakov et al., 1991).

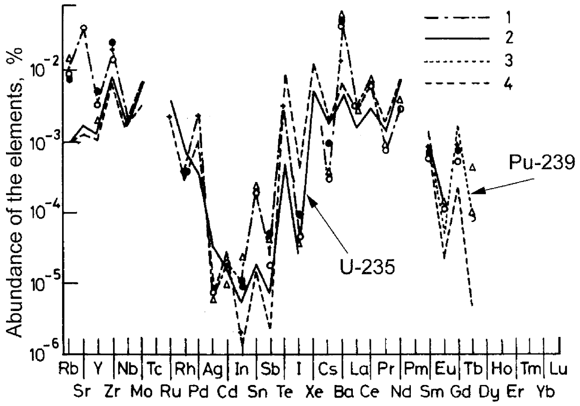

Fig. 3. Correlation between abundance of $40 < Z < 70$ elements in the Earth crust and their yields in the thermal neutron fission of ^{235}U and ^{239}Pu (Byakov, 1983): 1 — abundance of the elements in the Earth crust; 2 — relative yields of the elements as a result of fission of ^{235}U by thermal neutrons; 3 — the same as in 2, but for ^{239}Pu; 4 — relative amounts of elements accumulated during 1-year run of thermal nuclear reactor and after decay of radioactive isotopes.

result of a SN explosion. They both are possible sources of cosmic rays. High number of ultrarelativistic nuclei and electrons are kept by chaotic magnetic fields of SN gas remnant during tens thousands of years. In young SN remnants the cosmic ray energy density exceeds its current value ($\approx 1\,\mathrm{eV/cm^3}$) in the solar system by 4–5 orders of magnitude. Obviously, if one of the stars near the Sun had exploded as SN, many kinds of organisms would disappear from the face of the Earth.

The Solar system revolves around the center of our Galaxy and at the same time oscillates in a direction perpendicular to the Galactic midplane. The half-period T of these oscillations (time between successive crossings of the midplane) varies from 31 to 34 Myr. During the each passing through the layer of massive stars there is a probability of encountering young SN remnants. Knowing the parameters of the Sun's trajectory, the average frequency of SN explosions and critical level of radiation, which doubles the mutation rate for highest living organisms, we have estimated frequency of disastrous encounters of the Sun with SN remnants (Byakov et al., 1997). The calculation shows that it happens approximately *once per a half-period T*. Are there any experimental data which could support this estimation?

1. It is strongly suspected now that mass extinctions on the Earth were cyclical. If each passing through the Galactic disk would really be accompanied by a residence of the Earth within a SN remnant, the mean interval $T_{\mathrm{ex}} = \langle t_{\mathrm{ex}}^{(n+1)} - t_{\mathrm{ex}}^{(n)} \rangle_n$ between two successive extinctions should correlate with T as follows: $T_{\mathrm{ex}} \approx T \approx 31$–$34$ Myr.

2. Would the thickness of the layer of SN stars be extremely thin, the time moments of Sun's encounters with SN remnants (we identify these events with mass extinctions) should coincide with the time moments $t_{\mathrm{G}}^{(n)}$ of Sun's crossing of the Galactic midplane. Because of non-zero thickness of the SN layer $t_{\mathrm{ex}}^{(n)}$ deviates from the respective $t_{\mathrm{G}}^{(n)}$. It is very exciting that knowing $t_{\mathrm{ex}}^{(n)}$ from geological data, parameters $t_{\mathrm{G}}^{(n)}$ of Sun's midplane oscillations and adopting conventional function for spatial distribution of massive stars in our Galaxy, it is possible to estimate the width of this distribution. The obtained half-width (30–50 pc; $1\,\mathrm{pc} = 3.1 \times 10^{16}\,\mathrm{m}$) is in a good agreement with astrophysical data.

3. Inevitable consequence of the Earth stayings in SN remnants is an accretion of matter of the remnants, enriched in those elements, isotopes and chemical compounds, which are specific for SN. One believes that in the Universe SN stars are unique factories of heavy elements, from Fe to U. Enormous content of primitive organic matter in sedimentary deposits, which were formed during epochs when the Earth resided in SN remnants, accumulated a lot of uranium and other specific elements. That is why epochs of biocatastrophes are also known in geology as epochs of uranium accumulation (Neruchev, 1982). It is worth to note that bones of dinosaurs, which were perished during the Great Mesozoic Catastrophe 65 Myr ago, have abnormally high (100 times as large) concentration of U and

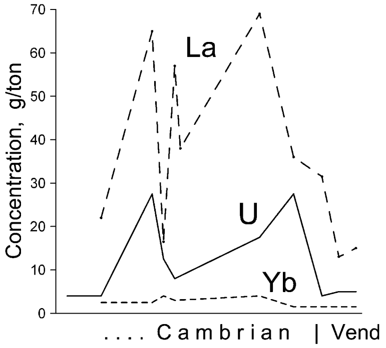

Fig. 4. Concentration of La, U, and Yb in boundary layers of Vend and Cambrian (Neruchev, 1986).

Th. So it is reasonable to link this extinction episode with a flash of close SN.

4. Surface layer of a neutron star consists of transuranium elements, which undergo repeated explosive nuclear fissions (Bisnovatyi-Kogan and Chechetkin, 1979). These events are accompanied by ejections of considerable quantities of a substance into the enclosing nebula. Distribution of chemical elements in these ejecta could resemble that of fission fragments in nuclear reactors (Fig. 3, Byakov, 1983). It is remarkable that the correlation exists between abundance of elements with atomic numbers from 40 to 70 in the Earth crust and their yields in the thermal neutron fission of ^{235}U and ^{239}Pu.

5. Uranium accumulations in sediments are accompanied by their enrichment also in those elements and isotopes, which are the most probable fragments of uranium fission. Fig. 4 shows U, La, Yb in sediments of uraniferous epochs. Correlated spikes of U and ^{87}Sr/^{86}Sr are stand out in Fig. 2. The last correlation is retraced during all Phanerozoic history. The reason is that under neutron-initiated fission of uranium the yield of ^{87}Sr is 3×10^5 times larger than that of ^{86}Sr. That is why increase of the uranium accretion on the Earth inevitably increases concentration ratio ^{87}Sr/^{86}Sr in the Earth crust.

3. Conclusion

The role of ionizing radiation in natural processes is still generally underestimated. The above data suggest a modification of the traditional view on formation mechanisms of main power resources, coal and oil, and indicates the important role of radiation from disseminated radioactive elements.

Numerous residences of the Earth within SN remnants with high level of ionizing radiation could trigger biotic catastrophes (mass extinctions of higher living forms and at the same time prosperity of the primitive organisms as manifested in black shales) and naturally explain some geological phenomena.

According to the evolution theory one of the necessary conditions, ensuring transformation of the simplest forms of life into higher ones, is a continuous time span about a billion years, during which the physical conditions on the Earth should be not too different from the modern ones. The data presented here imply that it could not be realized and restrict this time span by a few ten million years (about 30 Myr in average). Apparently, Darwin's selection of the fitness could only proceed between subsequent stayings in SN remnants. Because of these stayings, the evolution has been repeatedly stopped by the radiobiological damage done. Moreover, as the residences have short duration ($\leqslant 10^6$ yr), it is possible to explain the absence of the intermediate life forms between one kind and another among the fossil remains, which must exist according to Darwin's theory.

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