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ENTROPY SEISMOLOGY AND THE VIEW OF COSMOLOGY: SEISMIC FORMALISM AND ALPHABET OF EVOLUTION

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ABSTRACT

The theory of entropy seismology based on the seismostatistics is presented and a certain analogy between the statistical seismology and cosmology is drawn. The key points of entropy seismology are described in terms of cosmology for transferring the knowledge from the first field of science to the second one. In particular, the concepts of `dark matter' and `dark energy' for the Earth are introduced. The alphabet of entropy seismology is created, in the scope of which the statement of the problem is presented, the analogs of the first and second laws of thermodynamics are formulated, and the entropy funnels for the open dissipative seismic systems are described in the new terms of matter. The key role of the continuous energy inflow into the system in the violation of time symmetry and formation of complicated structures is noted. The real environment is simplified in such a way as to allow the description and tracking the main stages in the formation of tectonic structures at the plate boundaries capable of radiating seismic energy. This approach enabled the problem to be subdivided into two stages: the first stage consists in considering the emergence of the primary heterogeneities and structures of `dark matter' from `dark energy'; and at the second stage, the formation of the structure of `white matter' which can emit seismic energy is described. In the scope of the seismic formalism, the formula describing the evolution of matter in the Universe was derived and the simplified theory of quantum entropy formulated.

Key words: *Theoretical seismology, Statistical seismology, Geopotential theory, Instability analysis, Self-organization, Spatial analysis*

INTRODUCTION

Seismology as a science studying the earthquakes can be conditionally subdivided into two branches. The first branch, which includes recording the seismic events and studying the earthquake source and propagation of seismic waves, has been studied fairly well [1]. In contrast, the second branch which addresses the seismicity and seismic processes, is as of now incipient since a unified theory for describing the seismic processes based on seismostatistics (earthquake catalogues) is absent. By analogy with classical physics, let us refer to these two branches as wave seismology and statistical seismology, respectively. The Gutenberg-Richter (GR) empirical law of earthquake recurrence [19] is best known relationship in the statistical seismology. Let us refer to the theory developed in the present work as entropy seismology, which relies on the parameters calculated from seismostatistics. In the previous works [2, 3, 6] it was shown that introducing of the parameters of cumulative energy and entropy into the statistical seismology enables us to reveal the specific volumes of the geological medium, referred to as *seismic systems* (SSs), where the strong earthquakes in certain energy range form the ensemble [5, 8, 12]. The regularities linking the relatively weak seismicity in the seismic cycles with strong earthquakes, ending the cycles, have been tested by the author on the numerous examples of the SSs revealed in the different regions of the world [4-7, 10, 14]. The established regularities enable us to describe the behaviour of seismic processes leading to the development of seismic instability in the real medium. These regularities bear a relation to the problem of earthquake prediction and seismic hazard assessment as well as to the distributions of elastic and inelastic energy during the preparation and occurrence of the strong earthquakes.

There is certain similarity between seismology studying the Earth's interior and cosmology studying remote objects of the Universe. Both seismology and cosmology are based on the information obtained from the remote energy sources within the Earth and far beyond it, which are inaccessible for direct measurements. In the first case, the information is carried by seismic waves from earthquake sources, rock bumps, and explosions; in the second case, this is the electromagnetic waves from the stars, galaxies, and other space objects. The state of maturity of these sciences depends on the sensitivity and accuracy of measurement instruments and on the organization of observations and processing. *Fig. 1* shows the fragments of distribution of microseismic sources at the different depths beneath the Earth's surface and the sources of energy radiation in the sky. At first sight, the images are barely distinguishable. However, these seemingly simple pictures have a profound meaning: both images are virtual, i.e. they do not exist in the shown form at the current time moment. These pictures depict both the present and the past, i.e. they show the aggregated image of the objects located at the different distances from the observer over a certain (long) period of time. In the case of the Earth, the aggregated visual image of the real objects was obtained by the seismologist, whereas in the case of the stellar sky the image was produced by the light beams. The structure of the images in this figure suggests that the theory describing these media should be based on the physical parameters that contain cumulative spatiotemporal and energetic information about the sources.

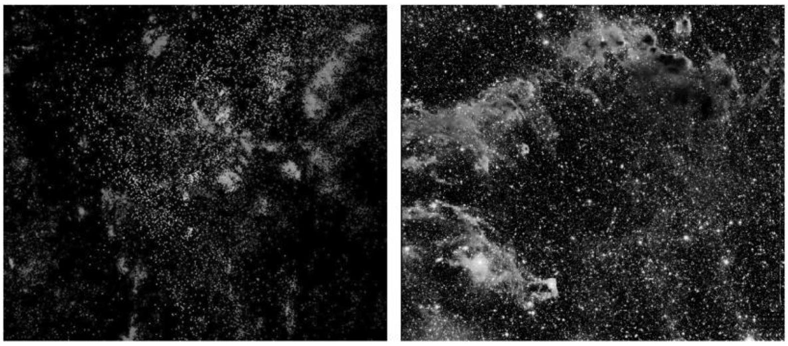


Fig. 1. Left: the microseismic energy sources in the Earth's lithosphere (the tomography image from the surface into the interior for the region of Honshu Island, Japan); right: the energy radiation sources in the stellar sky (the fragment of the sky view from the Earth).

Our experience in seismology shows that it is the ways of information accumulation with time rather than simple retrieval or gathering the information with time that can explain the observed regularities and their nature. For example, in the theory of entropy seismology, the evolution of SS is analysed through cumulative parameters within the seismic cycles. In SSs, seismicity follows the periodically repeated pattern: a long-term stage of energy accumulation is changed by a short-term stage of equilibrium when a catastrophe occurs. The strong earthquakes periodically restore the order from the chaotic state. The similarity between the images in *Fig. 1* indicates that a certain approach can be found for describing the seismicity in such a way that the developed seismic formalism be as close as possible to cosmology. The seismic formalism is understood here as the theory of entropy seismology expanded to other forms of energy. This would allow the knowledge about the origin and evolution of seismicity to be rendered in terms of cosmology. The method of analogy and knowledge transfer from one scientific field to another can become a prototype for modeling the systems having complex behaviour for which the laws of evolution with time are not known with sufficient detail [31]. Entropy theory which describes evolution of dynamic processes in the geological medium and relies on the records of seismic waves can serve, in a certain sense, as a simplified laboratory for cosmological studies aimed at describing the origin and evolution of the Universe. If we maximally simplify the problem, we can see that the statistics in the both cases is unusual and essentially distinct from that in classical physics. In the classical statistics a system consists of a set of generally peer particles (mass points, atoms, molecules). In seismology and cosmology we are dealing with nonuniform statistics of the objects that are not statistically identical: the 'particles' of the system (earthquakes or stars) have a broad scatter in energy. It is not accidental that energy in seismology is measured on the logarithmic magnitude scale and in cosmology on the logarithmic scale of stellar magnitudes [44]. In the both cases, the number (the statistics) of particles in a system decreases at the transition to energetically significant events (large earthquakes or giant stars), therefore the methods of conventional statistics become inapplicable. Seismology and cosmology consider large mechanic systems (macrosystems). For describing the systems with uncommon statistic in seismology, instead of the number of earthquakes we introduced the metrics that quantifies the cumulative parameters of energy and entropy. This allowed us to pass from the statistics of the number of earthquakes, which is used in the GR law, to the number of energy levels and to describe the behaviour of the system in the cases when there are relatively few events but energies are very high [2]. The statistics is gained by quantifying the total energy. This approach resulted in the theory of open dissipative SSs that describes the processes of instability formation in the virtual space with time, energy and entropy coordinates [8]. Such parameters as 'time arrow', 'seismic temperature', 'seismic time', dissipation function, coefficient of operation efficiency of a system, inelastic energy, and dynamic probability of the loss of stability, which are calculated based on seismostatistics, enable the transfer of knowledge from the theory of dissipative dynamical systems to seismology. Describing the macroscopic processes of self-organization by analogy with thermodynamic theory of irreversible phenomena for different classes of systems is a topical problem of the present-day physics [31]. Based on the energy and entropy production balance between the system and its environment, we established the analogues of the laws of thermodynamics for open dissipative SSs and revealed their peculiarities [11]. The rigour and universality of the theory of entropy seismology are achieved through the maximal simplifications. Simulation of the real processes yields the spatiotemporal scales for transferring these models beyond seismology. For example, the models of the preparation of catastrophic earthquakes in the form of spiral diagrams and information entropy funnels [6, 8] help to look at the matter from a different standpoint and can form a new image among the existing notions of the origin and evolution of the Universe. As energy sources, the earthquakes and the stars (*Fig. 1*) have a fundamental difference: the earthquakes are prepared within the SS and only release energy during a short time interval upon the external impact on the system, whereas the stars are initially formed due to the external impact and after their formation radiate energy for a long time due to the internal processes supporting the radiation. (A protostar is a very young star that is still gathering mass from its parent molecular cloud). A protostar becomes a star when a nuclear reactor transforming hydrogen into helium begins operating inside them. Thus, the time of action of seismic sources is short (incommensurably small) compared to their preparation period, whereas in the case of the stars it is much longer.

Seismicity of the Earth is related to active plate tectonics which is supported by the convection in the Earth's mantle. The structure and evolution of the Earth as well as the mantle convection have been explored quite thoroughly [30, 42, 46, 48]. The theory of entropy seismology enables the evolution of plate boundaries in their contact zones to be described on the longer time intervals. Description of the Earth's evolution and dynamical processes in relation to seismicity and the appropriate transfer of this knowledge to cosmology can provide a novel insight into the theory of evolution of the Universe. The paper develops the seismic formalism and alphabet of evolution in order to apply the methods of entropy seismology as an instrument for theoretical modeling the incipient (embryo) stage in the formation of spatiotemporal structure of the Universe, the origin of the gravitational field and matter.

ENTROPY SEISMOLOGY

Statement of the Problem. For describing the dynamics of strong earthquake preparation within large volume of geological medium, the concept of SS was introduced [2, 6, 12]. The SS is characterised by a threshold magnitudes M_h and M_{th} subdividing all earthquakes within the system volume into (a) microearthquakes with $M < M_h$, (b) indicator earthquakes with $M_h \le M < M_{th}$, and (c) strong earthquakes with $M \ge M_{th}$. In the entropy-energy approach the terms of macroscopic and microscopic states, strong and indicator earthquakes are relative: they depend on the SS size (configuration L on the surface and depth H) and the threshold parameters, M_h and M_{th}. The SS is a large-scale formation in the Earth's lithosphere having an enclosed volume V and including the contact areas A_r on the surfaces of active faults [41] that can potentially generate strong earthquakes.

The main causes of earthquakes are located beyond the SS and associated with thermal convection in the upper mantle of the Earth [46, 48]. Therefore, we will consider the SS as an open dissipative system that exchanges energy, mass and heat with the environment. Since the dynamical processes of earthquake preparation in the SS are relatively short term, such thermodynamic changes in the medium state as mass and heat exchanges will be neglected. The tectonic forces caused by plate motions lead to tension and deformations in the lithosphere and, in some local volumes of the geological medium, to rupturing with the release of elastic and inelastic energies. However, stresses and deformations in large volumes of the lithosphere are not the parameters that can be reliably recorded for solving the problems of dynamics and instability origination.

The SS volume is considered as a 'black box', whose configurations L on the surface and in the depth are known, whereas the internal structure is either unknown or known in general. The parameters of cumulative seismic energy and entropy enable to describe the energy state of such a 'black box' in whole and the evolution of this state in time. Under the action of external compression, the main information about a 'black box' state is provided by the indicator earthquakes, seismic waves which are recorded by seismic networks and then processed (*Fig. 2a*). By analogy with cosmology, we call the geological environment between seismic sources 'dark matter' (this term is in quotes in order to avoid confusing with the dark matter in the Universe) because it does not manifest itself in the form of radiating the seismic waves (*Fig. 1*). In this sense, the predominant part of the Earth's volume can be considered as 'dark matter'. The external forces, affecting in the geological medium of system, lead to the formation of elastic strains, which may result in faulting, and residual deformations such as compaction, plastic flows, creep, etc. We cannot describe all of these complex processes in detail, but can indirectly consider them from their effect on seismic processes. The approach based on seismostatistics (point seismic sources) allows us to considerably simplify modeling of the real medium and consider it as combination of 'dark matter' and 'white matter'. In fact, we subdivide the medium into two categories: capable and incapable of radiating seismic waves.

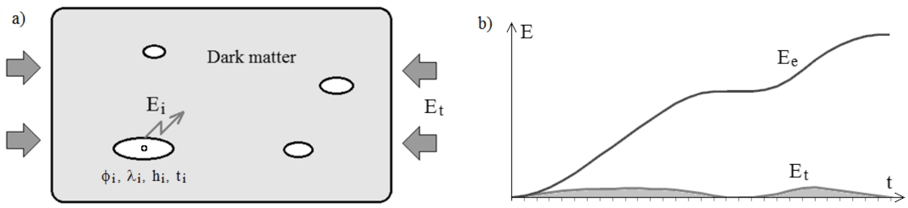


Fig 2. (a) SS as a 'black box' with sources of seismic energy E_i under compression setting. (b) The current and cumulative inflows of tectonic energy (E_t and E_e, respectively) into the system.

Let us now proceed to the qualitative analysis of the emergence of an earthquake in our statement of the problem. Let the 'dark matter' within volume V be initially ideally homogeneous, i.e. contain microcracks with the lengths l_i which do not exceed a certain length l_0, such that $l_i \le l_0$, and l_0 is much smaller than the characteristic size L of the system ($l_0 \ll L$). Let the forces of interaction between the cracks be very small and their influence captures the distances of the order of crack size. Therefore for the large SS volume, we assume, that the radius of action of these forces to be zero. The total resulting force **F**, acting on a certain volume V of the lithosphere, can be written as a volume integral and converted into the integral over the surface of this volume [25]:

$$F_i = \int f_i \, dV = \int \frac{\partial \sigma_{ik}}{\partial x_k} dV = \oint \sigma_{ik} d s_k \tag{1}$$

where **f** is the force acting on the unit volume of a body. One can easily write out the stress tensor in the case of a uniform confining pressure on a system. Under this compression, each element of the body surface is affected by pressure, which has equal value and everywhere is directed toward the interior of the system along the normal to the surface. If to denote this pressure p, then the surface element ds_i will be affected by the force pds_i (the negative sign here indicates that the force is directed inwards the system). At equilibrium, this force should be compensated by the force $\sigma_{ik}ds_k$ acting on the same element of the surface from the internal stresses. The stress tensor for this case can be written out in the following form: $\sigma_{ik} = -p\delta_{ik}$. Shifting the boundary surface by value δu_i, the external forces do the work $\delta\mathfrak{R} = pds_i\delta u_i$. We denote the energy equal to this work for the entire surface per time unit by E_t and call it inflow of tectonic energy into the system at the current time step δt. Let us write it as follows:

$$E_t = \oint \delta\mathcal{R} = -p_t \oint \delta u \, ds = -\, p_t \, \delta V \tag{2}$$

In the case of compression, $\delta V < 0$ and $E_t > 0$. The tectonic energy inflow into the system is equal to the work of tectonic forces on the system surface. In the case of a SS, we typically deal with the three-dimensional (3-D) (x, y, z) flat extensive plates that are subjected to lateral compression. The horizontal dimensions of SS are much larger than the depth. We consider a simple case of the SS schematically shown in *Fig. 3*. The system is immobile on three sides and is compressed on the side face which is perpendicular to a given horizontal velocity **v** of plate motion. This situation is similar to the work done on gas placed into a vessel with a piston [37].

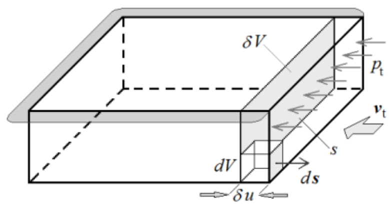


Fig. 3. Schematic representation of changes in the system volume due to the lateral pressure (see designations in the text).

Elementary volume dV of a body can be represented by the product of the elementary area ds and length element of the body δu along the velocity direction, $dV = \delta u ds$, and the system volume change can be written as $\delta V = s\delta l$. Since per unit time step $\delta t = 1$ the lateral side is shifted by a velocity unit $\delta u = vt$, we can write formula (2) in the following form

$$E_t = -F_t v_t = -p_t \, s \, v_t, \tag{3}$$

The inflow of tectonic energy into the system at constant pressure and velocity depends on the area s, through which the energy is supplied to the system. Just as the tectonic plate motion, the energy inflow into the system is a continuous quantity. Since the average velocities of tectonic plates are small, ($\bar{v}_t$= 2 cm/yr), then the quantity (3) mainly depends on the unknown tectonic forces. The external forces acting at the system boundaries do the work, that causes the internal deformations within the SS volume, $d\mathfrak{R} = \sigma_{ik} \, du_{ik}$, which are also unknown. This external compression can result in the emergence of non-diagonal components σ_{ik} in the stress tensor within a certain small domain (with the characteristic size $l > l_0$) of the volume V (*Fig. 4*). This means, that within this small domain a surface is formed, which is not only is affected by the normal forces, but also by the tangential forces, tending to shift the parallel elements along this surface.

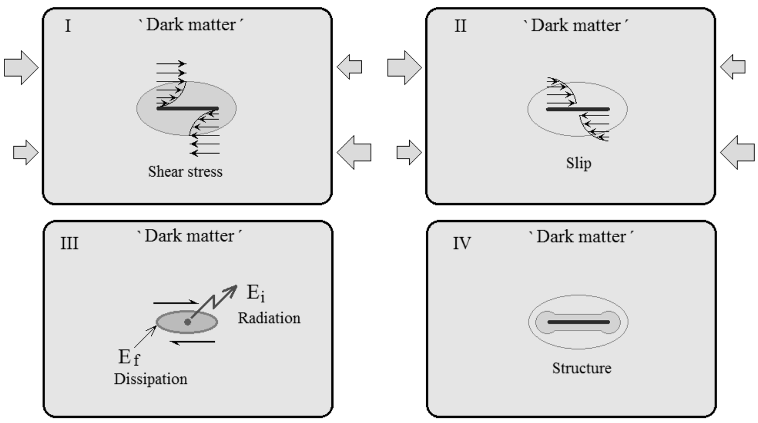


Fig. 4. Schematic representation the formation stages of seismic radiation E_i, dissipative energy E_f, and residual (newly formed) structure in the initially homogeneous ‘dark matter’. The description of stages I - IV is presented in the text.

If stresses appear within a certain interior domain, then also the forces which can do the work δR_r also appear. The necessary condition of an earthquake occurrence is the formation of a sliding plane A_r within the ‘dark matter’. As result of the work done, δR_r, inelastic energy E_f (for simplicity, we assume it to be purely thermal) and elastic energy of seismic radiation E_s are released on the sliding plane A_r

$$\delta R_r = E_f + E_s \tag{4}$$

We introduce the formal definitions: the part of energy E_f, which is released within a local volume of the system, is referred to as 'structure-forming', and the remaining E_s, as the 'radiation energy'. *Fig. 4* schematically illustrates the four stages of the formation of seismic radiation and the 'structure' in the 'dark matter'. Stage I accommodates the accumulation of elastic stresses. Stage II corresponds to the nucleation of local instability. Stage III reflects the formation of the internal sliding surface and radiation. Finally, stage IV is marked by the emergence of a local structure (residual dislocation). In this model, the emergence of the primary elementary source of seismic radiation and the 'structure' within the system is governed by the necessary condition of the continuous external energy inflow into the system and the formation of a random sliding plane. The initial homogeneous state (I) is less structured than the final state (IV). We denote the time integral of the energy inflow into the system (2) by E_e

$$\mathrm{E_e(T)} = \int_0^{\mathrm{T}} \mathrm{E_t\, dt} \tag{5}$$

and refer to this integral as the cumulative inflow of tectonic energy into the system during the time T. The tectonic energy inflow into the system, E_t, can increase or decrease with time; however, the cumulative inflow of tectonic energy, E_e, always increases with time (*Fig. 2b*). The cumulative inflow of tectonic energy allows us to describe a new type of the ordered behaviour: a dissipative structure characterised by the violation of symmetry [8, 31].
Each earthquake within the 'black box' can be described by a vector $r = r(\varphi_i, \lambda_i, h_i, t_i, E_i)$ in the 5-D space, where φ_i, λ_i and h_i are the latitude, the longitude, and the focal depth, respectively; t_i is the time in the source, and E_i is the elastic seismic energy radiated by i-th earthquake. The radiated seismic energy E_i is determined by the earthquake magnitude M_i [36]:

$$\log E_i\ (J) = 4.8 + 1.5\, M_i, \tag{6}$$

The accepted model of the point source of earthquake in the 5-D space simplifies the problem. Among five coordinates of the source point vector, four coordinates are the spatial dimensions and time in the physical world familiar to us. The fifth coordinate of the point is energetic. While mathematicians and physicians difficult to imagine a 4-D or 5-D space, this is quite straightforward for the seismologist, who is aware of the fact that earthquake forecasting requires an approximate knowledge of five parameters ('coordinates') of the expected earthquake: three spatial coordinates, time, and magnitude. Therefore, drawing the analogy and describing the 5-D spaces in the Universe in terms of the earthquake science simplifies the perception. If we replace the energy of the earthquake at a spatiotemporal point by another form of energy (electromagnetic, gravitational, mechanical, thermal, etc.), we can formulate a new problem and transfer the obtained results into the other fields of physics.

Discrete energetic states and SS scales. For describing the state of the 'black box' (*Fig. 2a*), we introduce the cumulative energy parameter E_c and the number of energy states S [2, 3, 12]:

$$E_c(t) = \sum_{i=1}^{\tilde{N}(t)} E_i, \tag{7}$$

$$S_N(t) = (t - t_{N-1})\, E_c - \sum_{i=1}^{\tilde{N}(t)} (t_i - t_{N-1}) E_i \tag{8}$$

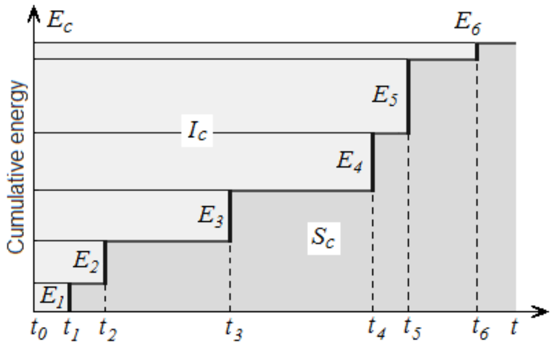


Fig. 5. A schematic picture of a stepwise increase of the cumulative energy $E_c(t)$ function versus time within the first seismic cycle for six indicator earthquakes with energies E_i and times t_i ($i = 1 \div 6$). The parameters S_c and I_c are equal to the total (integral) area below and above the function $E_c(t)$.

where t_i and E_i are the indicator earthquakes occurrence time and radiated seismic energy, respectively, $\tilde{N}$ is the number all indicator earthquakes with energies $E_i \geq E_h$, recorded in a volume V of system after the last strong earthquake t_{N-1}. The scheme of calculation $E_c(t)$ is shown in *Fig. 5* after the occurrence of a hypothetical strong earthquake at time t_0.
The time interval δt for actual calculations is taken as a single unit of time, that is, a second, minute, hour, month and so on. Seismic parameter $SN(t)$ is analogue to action in Newtonian mechanics. The equation (8) at current time $T = t - t_{j-1}$ within any cycle j can be reduced to the more compact form

$$S = TE_c - \sum_{i=1}^{\tilde{N}} T_i E_i \tag{9}$$

At the constant cumulative energy E_c, we find

$$S_{max} = T\,E_c, \quad S_{min} = E_c. \tag{10}$$

These cases are illustrated in *Fig. 6* by the example of a single earthquake with energy E_1. The maximal value of (10) corresponds to the case when an earthquake occurred at the beginning of the cycle at $T_1 = 0$ (*Fig. 6*, case A). The minimal value is observed when the earthquake occurred at the end of cycle at $T_1 = T - 1$ (*Fig. 6*, case B). These cases show that parameter S contains (remembers') information about the time of event and about the time interval when there no events. In case A, the trajectory deviates from the equilibrium state and comes into the state (E_1, S_{max}). The equilibrium state for the case A is indicated by point C in the equilibrium diagonal (*Fig. 6*). The bottom graphs in *Fig. 6* show that the shortest way to achieve the equilibrium state C is, when one hypothetical earthquake with energy $E_2 = S_{max} = E_1 T$ occurs at the end of the period.

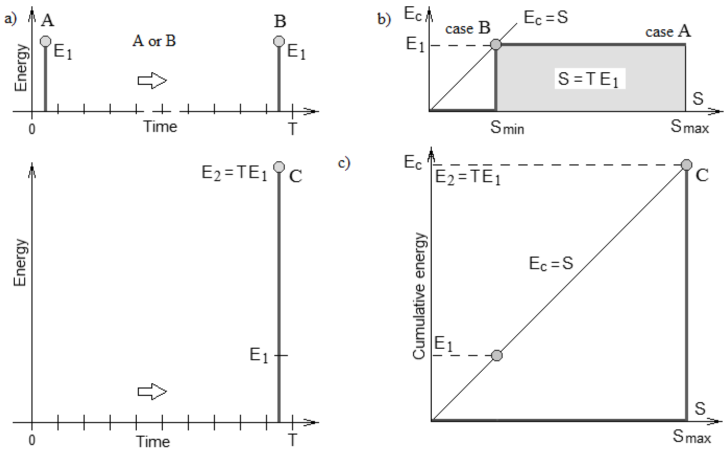


Fig. 6. a) Two versions (A and B) of the implementation of an earthquake with energy E_1 on the time interval 0, T; b) the trajectories and extreme values of the parameter S for the two versions (A or B): case A corresponds to the maximum and case B, to the minimum; c) the bottom graphs show the same as the graphs at the top but for one event with energy $E_2 = TE_1$.

Formula (9) can be recast in the following form:

$$S = S_{max} - I_c, \quad \text{where} \quad I_c = \sum_{i=1}^{\tilde{N}} T_i E_i \tag{11}$$

Parameter I_c contains the information about the seismic events that occurred within the volume V, and parameter S characterises the uncertainty (deficiency) of the amount of seismic information at the time T. As shown in *Fig. 5*, parameter $S(t)$ describes the area under the curve of cumulative energy $E_c(t)$ (the dark zone), and parameter $I_c(t)$ describes the area above this curve (the light zone). For convenience and in order to avoid the complications caused by large numbers in seismology, let us apply the respective decimal logarithmic scales for (7) and (8)

$$K_c = \log E_c \quad W(t) = \log S(t) \tag{12}$$

where K_c is the cumulative energy class of indicator earthquakes and W is the seismic entropy, analogous to physical entropy in thermodynamics. In the work [8] the analogy was drawn between the parameter (8) and the action in classical mechanics [24]. The idea is following. In classical mechanics, the system consists of N material points in the space. Simultaneously assignment of all generalised coordinates q_i and velocities $\dot{q}_i$ determines the position of the system and allow predicting future movement of the system in time based on the principle of least action. The movement of the system is mathematically described by differential equations of the second order including the functions $q(t)$, whose integration allow the trajectory of mechanical system motion to be defined. Such an approach, however, complicates the problem. The action of mechanical system (in terms of Hamiltonian) for the conservation of energy (E = const) along the path from t_0 to t can be written as follows

$$S = -E(t - t_0) + S_0 \text{ where } S_0 = \int_{t_0}^{t} \sum_{i=1}^{N} p_i dq_i \,, \tag{13}$$

where p_i and q_i are the canonical momenta and the coordinates of the material points, respectively; S_0 is referred to as abbreviated action. It has a minimum relative to all trajectories satisfying the energy conservation law and passing through the canonical point at the arbitrary time instant. By analogy with (13), we refer to the parameter I_c in (11) as the abbreviated seismic action. In a conservative mechanical system energy is conserves (is a integral of motion) because of the uniformity of time, whereas in the SS, time is generally nonuniform and the energy conservation law is obeyed only locally, at the end of seismic cycles. In contrast to the classical physics where canonical coordinates describe the motion, parameters (7) and (8) describe the number of probable states for the system overall (instead of its individual particles) at the current time, with the entire previous evolution of the SS taken into account. Holistic behaviour of the system as a selective volume of the lithosphere significantly simplifies the problem and alters the meanings of space and time. There are some similarities between our approach and the definition of a statistical system [26]. The statistical state of an entire closed system at rest (in the absence of translational and rotational movements) depends only on energy. From the seven additive independent integrals of motion (the energy, three components of the impulse vector and three components of the angular momentum), which completely determine the statistical properties of the closed system, only the energy remains.

In our approach, the system is open hence the internal energy is not the integral of motion (it does not constant), and it becomes dependent on time. In other words both the time and the energy becomes the independent parameters describing the state of the system, likewise temperature in thermodynamics [8]. Statistical physics studies the regularities governing the behaviour and properties of the macroscopic bodies composed of a huge number of individual particles (atoms and molecules). In contrast, entropy seismology deals with the properties of macroscopic systems with many discrete states of cumulative energy. It is the quantised total energy (rather than the number of the earthquakes as, e.g., in the GR law) that is the statistics in our approach. The quantum constraints of energy and the resulting discreteness of the system states form the basis of entropy seismology. Quantum mechanics is a microscopic theory which was mainly intended for describing atoms and molecules [27]. The theory of entropy seismology is macroscopic; at the same time, it is described by certain elements of quantum mechanics. Like atoms and molecules, the SS has a discrete energy levels. However, in contrast to quantum mechanics where the energy levels ensue from the quantum constraints and are determined from the eigenvalue problem with Hamiltonian operator, the problem in entropy seismology is maximally simplified. The discrete energy levels E_{c1}, E_{c2}, ..., E_{cn} of the system appear as a result of 'quantising' the cumulative energy parameter (7) and are determined from the records of the earthquakes. Let us show that the necessity of 'quantising' the cumulative energy parameter in seismology follows from constraining the maximal energy density ϵ in the rock. It is known [45] that the maximal density of the potential energy that can be accumulated within a unit rock volume is

$$\epsilon_m = 10^{-4}\ \mathrm{J\ cm^{-3}}, \tag{14}$$

While the energy density ϵ for rocks in the Earth's interior is below the critical value ϵ_m ($\epsilon \le \epsilon_m$), the rock accumulates stresses. Having reached the critical energy density, the rock begins to radiate seismic waves. In entropy seismology, according to the necessary accuracy of recording time and energy of the earthquakes, the quantum h_s of seismic radiation (seismic action) was introduced [2]:

$$h_s = E_h \delta t_h = 1\ \mathrm{J\ s}, \tag{15}$$

where E_h is the quantum of seismic energy radiation (E_h = 1 J). It corresponds to a microearthquake with the minimal source volume $V_h \approx 10^4$ cm^3. For this quantum of energy, a smaller volume of the source is impossible due to the limitation of the radiation energy density. The magnitude of a microearthquake calculated by formula (6) is $M_h = 3.2$ and the linear size of rupture in the source will be $l_h \simeq 22$ cm ($l_h = V_h^{1/3}$). For this microearthquake, the characteristic times in the source (τ_{s1} and τ_{s2}) are determined by the rupture propagation velocity, i.e. ~ 3 km/s ($\tau_{s1} \approx 10^{-4}$ s), and particles displacement velocity along the rupture, i.e. ~ 100 cm/s ($\tau_{s2} = 0.2$ s). Hence, the time scale in (15) was selected by $\delta t_h = 1$ s (longer than the characteristic times). If we assume $\tau_{s1} = 10^{-4}$ s as the minimal time of seismic information propagation by distance l_h in the homogeneous 'dark matter' of the Earth's interior, the maximal possible mean velocity will be $\bar{v} = 10^5$ cm/s. This is 10^{12} times as high as the average plate motion velocity ($\bar{v}_t$ = 3 cm/yr). Velocity $\bar{v}_t$ provides continuous energy inflow into the system (5), leading to the increase in density ϵ of the energy accumulated in the 'dark matter'. This 'dark matter' brought to the critical values of energy density begins to radiate seismic waves and eventually leads to the formation of the structure.

The entropy as a measure of disorder is the fundamental concept for characterising the complexity of the dynamics of natural processes. Entropy W for statistical seismology was defined by the formula [2]:

$$W = \log\frac{S}{h_s} \tag{16}$$

where S is determined through the cumulative parameters (7) and (8). Looking ahead, we note that this (non-thermodynamic) definition of entropy allowed us to develop seismic formalism and apply it for description the dark energy and dark matter at the initial stage of the Universe formation, when the very notion of temperature and a thermal form of energy were absent. The quantisation of the parameter S makes it possible to describe the behavior of the system at high energies but with relatively few strong events. The dimensionless parameter S/h_s determines the total number of the discrete energy states of the system [12]. Seismic entropy determines the entropy as a measure of the total number of options. Each number of the states S/h_s corresponds to the decimal measure 10^W, showing how many times ten should be multiplied by itself to give the number of options. At $h_s \to 0$, entropy (16) tends to infinity indicating that entropy of the continuous distribution is meaningless. Only the 'quantisation' of action (i.e., the discard of simultaneous continuity in the distributions

- the 'quantum' of action $h_s = 1$ J s;

- the cumulative energy of radiation E_c ranging from 1 to 10^{19} J;
- the number of the states S ranging from 1 to 10^{22} (J s);
- the dimensionless entropy W ranging from 0 to 22;
- the linear sizes of the sources l_s ranging from 20 to 10^8 cm.

From the standpoint of quantum mechanics, the 'quantum' of seismic action (15) is huge. For comparison, the Planck's constant is $h_p = 6.6 \times 10^{-34}$ J s. However, in the context of the SS, the value of (15) is extremely small and has the meaning of the uncertainty principle for entropy seismology. We recall that the Planck units of length and time are $l_{pl} = 5.1 \times 10^{-33}$ cm and $t_{pl} = 1.7\times10^{-43}$ s, respectively. The system of 'natural measurement units', which is based on five universal physical constants was suggested by Max Planck [32, 33]. It is believed that the Planck units are extremely important for the theoretical physics as the limits of applicability of the modern physical theories. The characteristic size of a quantum microearthquake falls in the centimetre interval, whereas the characteristic spatial scale of the intermolecular forces is of the order of angstroms (10^{-8} cm). In other words, the volume of the elementary microearthquake contains about $(10^9)^3 \sim 10^{27}$ molecules. The emergence of a 'complex' from such a huge number of particles in thermodynamics, created a macrostructural volume unit, which is a characteristic (microscopic) ordering scale for the description of SS.

The entropy law of gravity in seismicity. The function S is equal to the total number of energy states E_{ci} in the seismic cycles. Any current state of the SS can be presented by a point $q_i = q(S_i, E_{ci})$ on a trajectory diagram $\{S, E_c\}$, and the evolution of SS state is determined by the moving point $q(t) = q(S, E_c)$ (*Fig. 7a*). Each jump of the trajectory corresponds to an indicator earthquake. In our formalism, the system in *Fig. 7a* is shown in the form of the three-dimensional volume V of geological medium. We recall that the point of trajectory describes the state of this volume in 5-D space and contains the total energy information about the SS state at the time t. The total (cumulative) density of the indicator earthquakes within the system volume increases with time (at the time T_1, T_2, T_3 in *Fig. 7a*). Here, the total (cumulative) density should not be confused with the instantaneous density which may decrease with time. The cumulative density includes the sources many of which have undergone activation before the current time instant T (or, in the cosmological terms, have been extinguished to this time). The motion of the point along the trajectory in the 5-D space in *Fig. 7a* describes the energy evolution of the volume of system which is immobile (at rest) in the conventional 3-D space. Of course, when the SS is described on the time scales of hundreds and thousands of years and longer, its volume changes; however, the seismostatistic data for such a description are absent. The trajectory does not depend on the locations of energy sources (indicator earthquakes) within the system. Considering this, we may assume that the uncertainty in the layout of the sources is determined by the characteristic size L of the system, which is much larger than the characteristic size l_i of the sources ($L \gg l_i$). At the beginning of seismic cycle, the trajectory evolves chaotically. However, with the lapse of time (at $S > S_{th}$), parameters S and E_c begin to interact and the trajectory is gravitated to the most probable state of the cumulative energy, i.e. to the power law [12]:

$$E_c = \beta S^a, \tag{17}$$

where constants a and β are determined based on the events that have already occurred. When the law (17) is satisfied with the same constants a and β in all seismic cycles, the strong earthquakes clump into the ensemble and form the statistically independent cycles. In the logarithmic coordinates (12) this law has a more convenient linear form

$$K_c(t) = aW(t) + b, \qquad b = \log\beta, \tag{18}$$

Constants a and b reflect the properties of structural inhomogeneities in the system (the faults), which are formed during many years. In the trajectory diagram $\{K_c, W\}$ the current of time along the trajectory is nonuniform (*Fig. 7b*).

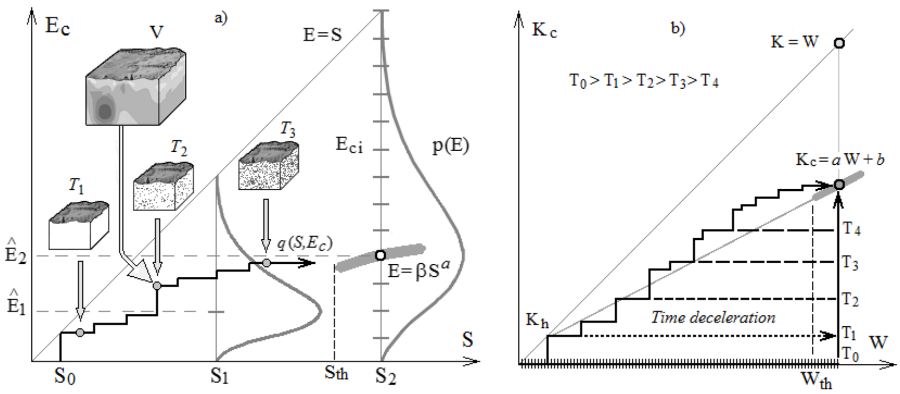


Fig. 7. (a) Schematic presentation of the evolution in the trajectory diagram. $\hat{E}_1$ and $\hat{E}_2$ are the most probable values of the cumulative energy for the states S_1 and S_2, respectively. E_{ci} is the number of discrete levels of cumulative energy at S_2; $p(E)$ is the function of probability distribution in the interval $E \in [1, S_2]$. Thick arc shows the instability region after the threshold S_{th}. (b) Illustration of the deceleration of seismic time on the approach of the linear zone of instability in the plane $\{W, K_c\}$. The other notations are presented in the text.

The 'seismic time' decelerates in the SS compared to the ordinary clock [8]. However, the higher position of the trajectory ensures the faster approach of the point of instability. The frequency of the dashed lines indicates the distance on the track diagram, by which the trajectory gets shifted per unit time on the ordinary clock. The slowest motion is that experienced by the point on the bottom trajectory (the dashed line in *Fig. 7b*). Reaching the instability area (18) by this trajectory takes the longest time. This situation is characteristic of the strong earthquakes that occur within plate boundaries, regions called intraplate zones, where their preparation mainly occurs through the weak seismicity. For example, the preparation of strong earthquakes with $M \geq 7.2$ in the New Madrid Seismic Zone in the Central U.S. lasts for 250-500 years [47]. The latest cycle of the strong earthquake preparation has started here from the time of strong earthquake of 07.02.1812, $M = 7.4$, and it will take as long as 2060 for the trajectory to approach the instability area [9]. Thus, the duration of earthquake preparation depends on the path on which the system approaches the point of instability. The instability points $\{K_j, W_j\}$ for the ensemble of strong earthquakes obey the Gaussian distribution and determine the lower limit of entropy W_{th} ($W_{th} = \min\{W_j\}$, *Fig. 7b*), above which the trajectories are attracted to Eq. (18). This attraction is caused by the fact that the real states of SS, which are described by Eqs. (17) and (18), become degenerate, i.e. most probable. In course of time, the uncertainties deflecting the system from entropy (16) are accumulated in it. These uncertainties are described by the probability function p_i through the information entropy [2, 12]:

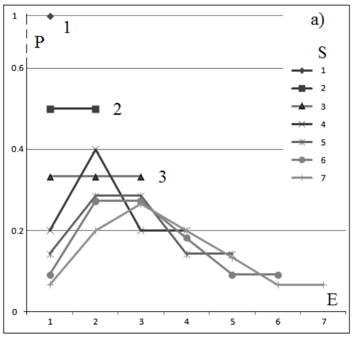
$$\langle W \rangle = -\sum_{i=1}^{S} p_i \log(p_i), \qquad p_i = \frac{m_i}{n} \tag{19}$$

Here, n is the number of all possible paths (trajectories) to the state S ($n > S$) and m_i is the degree of degeneration for the each energy state E_{ci}. The degeneration of the energy states occurs because of the increase m_i of their 'attendance' which makes these states more probable. The attraction of the trajectories to the power law (17) is the manifestation of the fundamental entropy-probability law of gravitation in seismology. The trajectories governed by the cumulative (remarkably, exactly cumulative) seismic parameters (7) and (8) are attracted to these inhomogeneities (17) in seismic cycle as to zones that are most probable for the implementation of the strong earthquakes. The probability distribution function $p(E)$ for a given S, being defined for any limited interval $E \in [1, S]$ (*Fig. 7a*), is close to the Poisson distribution

$$p(E) = \frac{1}{E!}\left(\hat{E}\right)^{E} e^{-\hat{E}}, \tag{20}$$

where $\hat{E}$ is the most probable value of the cumulative energy.

Information entropy and ground energy states. Let us now discuss the ground energy states of the system. *Fig. 8a* shows the probability distributions (20) with energies E_{ci} at the fixed $S = 1 \div 7$. The states at $S = 1, 2, 3$ are not degenerate. The probability distributions in these three states are uniform, $p_i = \tilde{p} = 1/S$. From formula (19) it follows that in the case of uniform distribution, the amount of information required for the full definition of the SS state is maximal and equal to $\langle W \rangle_{max} = \log S$. *Fig. 8b* shows the combined diagram of the energy entropy W (16) and information entropy $\langle W \rangle$ (19) versus the dimensionless S in the interval from 1 to 10. The energy and information entropies (the upper and lower curves, respectively) coincide in the states at $S = 1, 2, 3$ corresponding to the uniform distribution of energy probabilities. We will refer to these non-degenerate states as the 'ground energy states'. The degeneration of the energy states begins at $S = 4$ and entails the divergence of these curves. This leads to the priority energy states, increases the accuracy of the prediction and, with the increase in S, brings about the formation of structures. It is the information entropy (19) that is responsible for the formation of structures (Section 2.1).



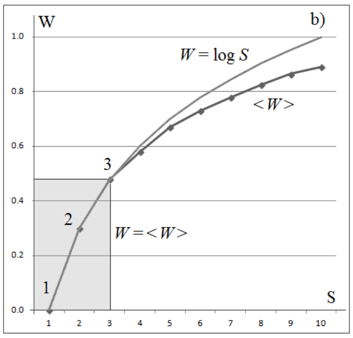


Fig. 8. (a) The calculated distribution of cumulative energy probability for the system states with $S = 1 \div 7$; (b) the calculated graphs of entropy and informational entropy. States 1, 2 and 3 are stable (non-degenerate).

For the three ground states, the entropy and information entropy are indistinguishable and the state of system is stable. The systems that are only in these initial states are 'germinal', and a fluctuation may cause early formation of structures. By using probability p_i of energy E_{ci}, we define the mean cumulative energy $\langle E_c \rangle$ [23]:

$$< E_c > = \sum_{i=1}^{S} p_i E_{ci}. \tag{21}$$

For the first three states with S = 1, 2, 3, the probabilities are 1, 0.5, and 0.33, and the average cumulative energy is $\langle E_c \rangle$ = 1, 1.5, and 2, respectively. *Fig. 9a* shows three independent equilibrium portions of energy which are not summed up in the ground state. In the track diagram (*Fig. 9b*) they occupy the first three points on the equilibrium diagonal. At each time step any of these three portions of energy is implemented with equal probability and the system immediately passes into the equilibrium state so that the track does not leave the initial domain. It can be said that the time interval in the first three ground states is frozen (the time does not grow, and ticks only on 1 s). If the time asymmetry (fluctuation) takes place, the trajectory deviates from equilibrium and begins to grow with time. Depending on the activation of the different (one among the three) portions of energy, the trajectory spreads and fills the oblong zones. This evolution of the trajectory under the violation of time symmetry by the fluctuating portion of energy by four units during the first four seconds is shown in the *Fig. 9c*. The colours in *Fig. 9c* correspond to the three portions of energy. Ultimately, this leads to the formation of elliptical attractors with the most probable middle area (the light squares). Here we are interested in the qualitative pattern whereas the further evolution of the trajectory can be calculated on the computer.

Let us dwell on one important issue concerning entropy and information. When describing the black holes, the physicists sometimes use the information in terms of *bits* (mathematically, the logarithm to the base 2 is used in the entropy formulas). The bit means that the information is coded by two symbols (binary system). In formulas (16) and (19) we used a decimal logarithm. If there is no deep physical meaning in the definitions, then, in terms of pure mathematics, we can easily change between the definitions. For example, the conversion from the dimensionless seismic entropy to Shannon's dimensionless information entropy (in bits) can be implemented through the conversion factor $\log_2 10$ = 3.322 *bit* (1 *bit* = $\log_2 2$). It can be seen that the decimal logarithm is more than thrice as large as the binary logarithm.

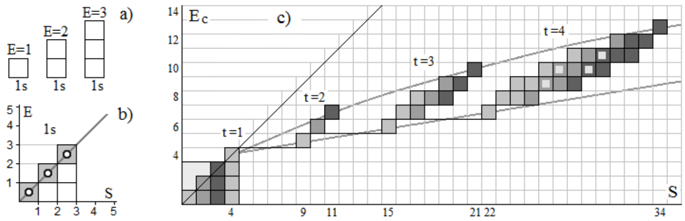
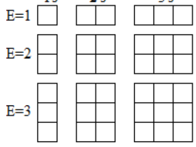


Fig. 9. (a) Three independent portions of energy in the ground state. (b) These energy portions fill the first three equilibrium points (circles) in the trajectory diagram. (c) The areas on the track diagram that are filled during the first four second when time asymmetry takes place.

In the case of seismology, decimal logarithm is used because the first three energy states of the system, $E_k = kE_h$ (k = 1, 2, 3), are not degenerate. The specified quantum of action $h_s = E_h\delta t_h$ determines what problem will be considered: the physical one (reflecting the real world) or virtual (speculated by a human). In the case of seismology, the three ground energy states enlarge the quantum of action threefold. However, strictly speaking, the time step δt_h should also be enlarged threefold: $\delta t_k = k\delta t_h$. The reason why it is necessary to do this is illustrated in *Fig. 10*. If the energy portions repeat two or three times in a row at 1 s interval, the equilibrium pattern in *Fig. 9b* will not change. As a result, we obtain a matrix $(h_s)_{ij}$ consisting of nine portions of the quantum of action (15) (*Fig. 10*). I.e., the quantum of action in the ground state (15) is nine times as large $(h_s' = 9h_s)$. Hence, in the description of the evolution of physical systems it is reasonable to use decimal logarithm of action because the fluctuation begins at the minimal value $S_0 = 10h_s$ and, correspondingly, at the dimensionless entropy $W_0 = \log 10 = 1$.

Between the physical (material) and virtual definitions of information there is a thin borderline, important for understanding the laws of Nature. If we describe the remote cosmological objects, then we should exclude all the living things (i.e., related to biological organisms, humans and everything created by humans) from the notion of matter, except for the virtual measuring instruments that do not affect the Nature. In particular, we assume that the life does not affect the evolution on the cosmological scales. It is in this understanding that we will discuss the matter in Section 4. (However, we should remember that our knowledge about the Universe relies on the measurements which, as is known from quantum mechanics, slightly alter the behaviour of the microcosm [18, 26]). Books, computers, binary code and everything else that human has created are the virtual information that should be excluded from the cosmological theory. The Shannon information entropy (19) can be both physical and virtual. We note that the entropy defined by formulas (16), (7) and (8) is seismic, it is determined from the data on the real events (earthquakes).



$$\begin{Bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{Bmatrix}$$

Fig. 10. The illustration of enlargement of the action quantum in the ground state with increasing the step of time.

Just as the thermodynamic entropy, it is a physical quantity describing the macroscopic Nature. Physical information is objective and material; it can be measured and then stored. However, the storage alone does not make the information material in the sense described above. For example, the binary '*bit*' is the virtual information introduced by humans.

The possibility of storing this information on the material carriers does not make this information physical. Moreover, an attempt to make bits the most fundamental building block smaller than an atom, quark, or neutrino for studying the black holes cannot be physically justified. Therefore, the application of binary information and the closely related concept of entropy to the problem of black holes is a mathematical technique [39] that is not quite justified from the physical standpoint. If we expand these results to the other forms of energy, we can state that the ground (zero) state of the material world (in the *energy* × *time* dimension), as shown in *Fig. 10*, is somewhat more complicated and the terms of the simplified binary system (*bits*) are insufficient for its adequate description. In other words, the assertion that the maximal amount of information that can be contained within the infinitesimal spatial domain is equal to the area (rather than to the volume) of this domain is a great simplification. The elementary cells of the space should encode the main properties of the observed Universe, for example, gravitation (just as an elementary microearthquake encodes the properties of entropy seismology). The energy-time matrix (*Fig. 10*) contains the necessary components for creating 3-D space (columns) and matter (rows). In the future, this matrix can give the answer to the questions, why the observed space-time has 3+1 dimensions? Why the observable properties of matter are such as they are? These issues will be discussed in the next paper.

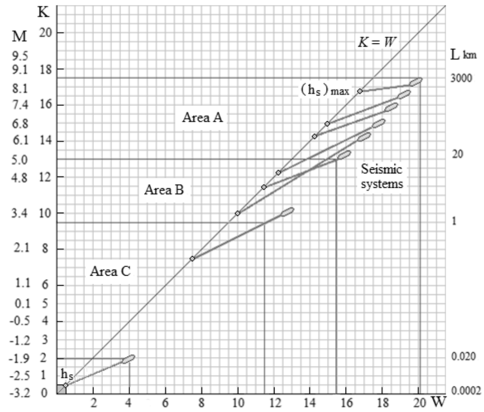


Fig. 11. Schematic illustration of the hierarchy of attractors with the increase in the SS size L and threshold magnitudes. The increase in the minimal parameter of action h_s (enlargement of the minimum quantum of energy E_h) is shown by the dots on the equilibrium diagonal. A is the area of dangerous earthquakes that cause damage, destruction and human losses; B is the dangerous area for the technical constructions and industrial objects; C is the area of microseismicity.

In [3, 5, 7, 11, 12-14] the regularities (17), (18), and the numerous SSs revealed in the different seismically active regions with strong and weak seismicity in the world were described. *Fig. 11* illustrates the schematic generalisation of the attractor area for these SSs on the trajectory diagram [9]. The characteristic sizes of SS are indicated on the right. It was empirically established that for the microscopic SSs with the threshold magnitudes M_{th} = -1.8 which are at the lowest energy level E = 1 J, the first structural instability of the type of Eq. (17) has the form $E = 10^{-1.8} S$ and appears starting from $S = (8.0 \div 9.5) \times 10^3 h_s$. Hence, the first critical values of cumulative energy in the microscopic systems will be $E = 125 \div 137$. This energy corresponds to a microearthquake with the magnitude M = -1.8, i.e. the weak microearthquakes in the magnitude interval of $-3.2 \le M < -1.8$ prepare the relatively strong microearthquakes with $M \ge -1.8$). In terms of the rupture length in the sources of earthquake this means that in the smallest SS (with characteristic dimensions of $\sim 10 \div 30$ m) the activation of the indicator microearthquakes with the source ruptures of $\sim 22 \div 150$ cm can lead to fractures of 2 to 4 m.

As seen in *Fig. 11*, the parameter of action h_s increases with the enlargement of the threshold energy of the earthquakes E_h and the time step δt_h when we pass from the small to the large SSs. The threshold energy characterises the minimal energy level of the homogeneity in the system. Thus, the size of the quantum of radiated energy (the indicator earthquake) is not identical for the hierarchy of the SS that include the faults of the different scales. These quanta are extremely small for the small SSs with the threshold magnitudes M_{th} of 'strong' earthquakes ranging from -1.8 to 3.3 (the microseismicity area in *Fig. 11*), medium for the small SSs with $M_{th} = 3.4 \div 5.0$ (area B, danger for technical constructions), and large for the SSs with $M_{th} = 5.1 \div 9.0$ (area A of the widely perceptible and destructive earthquakes). Perhaps, the primary heterogeneity at the earliest stage of the lithosphere evolution originated in the very small systems (fine 'graininess'); then, with the laps of time, they gradually rose in the hierarchy (become larger, medium 'graininess'), etc. Importantly, the period of the instrumental observations for the real SSs is negligibly small compared to the history of their evolution lasting up to hundreds thousands and millions of years. However, the simultaneous existence of the SSs in the different seismotectonic situations enables reconstruction of the SS evolutions on the geological time intervals. During such a long evolution, the SSs inherited the main primary heterogeneities and accumulated the newly acquired ones [22, 40].

The analogues of the first and second laws of thermodynamics. The cumulative energy inflow into the system (5), just as the parameter S, has the dimension of action (*energy* × *time*), whereas its logarithm has the meaning of entropy $W_e = \log E_e$. We formally introduce one strong earthquake with energy $ET = E_e(T)$ at the (T - 1)-th unit time step (by analogy with the case C in *Fig. 6*). Then, by the formula (9), we find $S_{min} = ET$ or

$$E_e(T) = 10^{W_e(T)} = 10^{-W(T)} \tag{22}$$

The minus sign appears because the entropy inflow into the system W_e is assumed to be negative, whereas the outflow W is positive. The right-hand side of this expression describes the abbreviated action. This formula establishes the relationship between the cumulative inflow of energy into the system (5) and entropy (16). Formula (22) reads that the cumulative inflow of energy into the SS is equal to the abbreviated seismic action determined from seismic entropy. Thus, we obtain an important law: the seismic entropy controls the flow of tectonic energy into the system. Formula

$$W = -\lg E_e = \lg\left(\frac{1}{E_e}\right) \tag{23}$$

is the definition of entropy for the energy flow into the system per time T. The first law of thermodynamics is the energy conservation law [37]. The parameter of cumulative seismic energy (7) contains the total 'memory' about the seismic energy radiated by the previous events during time T and therefore differs from the instantaneous energy. Information is understood as instantaneous if it is obtained within the current discrete time step δt_h which depends on the duration τs of faulting in the sources ($\delta t_h \geq \tau_s$). The duration of the strong earthquakes is short; however, it increases if we include the aftershock process in the source effect. Nevertheless, the duration of the seismic cycles T is much longer than δt_h ($T \gg \delta_{th}$). In entropy seismology, we consider alternation between the energy parameters on two time scales: long T and short δ_{th}. In the conservative mechanical system the energy is conserved (is the integral of motion) due to the uniformity of time, whereas in the SS time is, generally speaking, nonuniform and the energy conservation law is satisfied only locally, on the short time scale at the ends of seismic cycles. Hence, the law of the energy sources and the energy conservation law in seismic cycles are united: the change in the internal energy during the seismic cycle is equal to the inflow of tectonic energy (5).

The further analysis will be conducted in the scope of seismic formalism, i.e. when the theory is based on seismic information alone. In this approach it should be taken into account that the energy inflow into the system is much larger than the energy that manifests itself through seismicity. The energy supplied to the system is the result of the mechanical work done by the moving plates over the system. In turn, the energy of plate motion is the result of the thermal convection in the Earth's mantle which is maintained by the energy generated in the Earth's core, etc. In seismic formalism, we assume that the SS activity is only maintained by the external energy sources (which do not have seismic nature). The duration of action of these sources is constrained by the age of the formed Earth ($\sim$4 Gy). For any SS, these energy sources can be thought of as inexhaustible because the lifetime of the SS is much shorter than the age of the Earth.

The description of the macroscopic self-organization processes by analogy with the thermodynamic theory of irreversible phenomena for various classes of system is a topical problem of modern physics [31]. Let us formulate the analogues of the laws of thermodynamics in entropy seismology. The change in entropy in an open SS can be written as

$$dW = d_iW + d_eW. \tag{24}$$

where d_iW is related to the internal production (outflow) of entropy due to the earthquakes (this value is always positive, $d_iW > 0$), and d_eW is related to the inflow and outflow of tectonic entropy in the SS (subscripts near the differential should not be confused with the summation index). Of course, the mathematical notation d_iW is somewhat arbitrary, as it means continuity and differentiability of the function W. Since the entropy is an additive quantity, piecewise differentiable with the first-order discontinuities [34], the value of $W(T)$, calculated in the seismic cycle, is the change of entropy from the beginning of the seismic cycle, $W(T) = \Delta W = \int_0^T dW$, because $W(0) = 0$. Therefore, the behaviour of infinitesimal dW reflects the nature of processes within the entire seismic cycle described by the entropy W. In this sense, dW is equivalent to W, ($dW \equiv W$). For the SSs without internal sources of tectonic energy, the inflow d_eW is always negative, $d_eW \leq 0$, and $|d_eW| \geq d_iW$. Taking into account (22), we can represent the inflow of tectonic energy into the system in the form $d_eW = -W$, where W is equivalent to the change in energy since the beginning of the seismic cycle at time T. With the allowance for (12), the internal production of entropy in each unit time step can be cast as $d_iW = \Delta W_i = \log \Delta S_i = K_c$. This is illustrated by the example in *Fig. 12* which shows the diagrams of seismic entropy production calculated for the three seismic cycles of the ensemble of strong earthquakes ($M \geq 8.4$) of the Mega Japan SS described in [5].

The upper curve in *Fig. 12* depicts the logarithm of total elastic energy radiated in the sources of the indicator earthquakes and the lower curve corresponds to the logarithm of tectonic energy flow in the Mega Japan SS. The middle curve is the sum of the upper and lower ones. Once the modulus $|dW| = W$ reaches the maximal critical value W_k, a strong earthquake occurs within the short time interval Δt and restores the energy equilibrium in the system [8]:

$$10^{W_e} = E_s + E_f + E_c \tag{25}$$

Here $E_s = \beta_s S^{a_s}$ is the radiation energy of a strong earthquake (a_s and β_s are the characteristics of the newly formed structures, i.e. the faults); $E_f = \ln 10\ S \log S$ is the total inelastic energy released in the source of the strong earthquake and in the sources of all the indicator earthquakes (typically, $E_s \cong E_f 10^{-2}$). Equation (25) is the energy conservation law in the scope of seismic formalism where all the parameters are determined based on seismostatistics. This is an analogue of the first law of thermodynamics for the open dissipative SS. It states that on a short time scale, the entire energy supplied into the system is equal to the sum of the entire radiated energy and the dissipation energy in the earthquake sources. Of course, we somewhat idealise the system in the seismic formalism and assume that the residual deformations are absent.

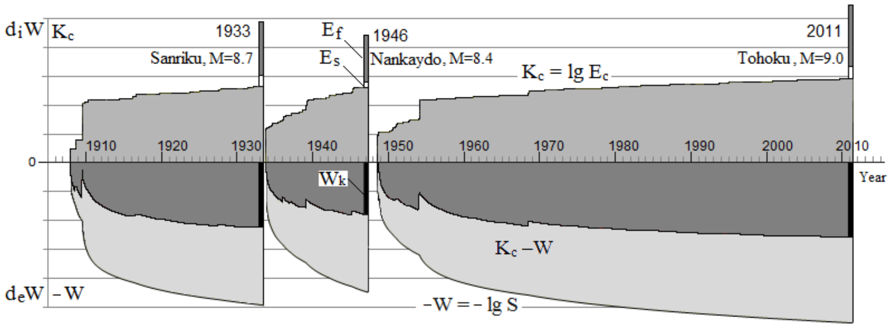


Fig. 12. The graph of entropy production in the seismic cycles of the Mega Japan SS. The upper graph illustrates the outflow of entropy; the lower graph shows the inflow of entropy; and the middle graph is their sum. The graph shows elastic E_s (withe lines) and inelastic E_f (gray lines) energies of the strong earthquakes in 1933, 1946 and 2011, which restored the balance of energy deficit W_k at the ends of seismic cycles (dark lines). The scale of the upper graph is increased by two orders.

The analogue of the second law of thermodynamics for the open dissipative SS can be formulated in the following way: the total production of entropy on the long time scale increases by the absolute values up to the critical value W_k. The case $d_iW = 0$ corresponds to the reversible process in thermodynamics, and the case $d_eW = 0$ refers to the closed systems because Eq. (24) is reduced to $dW = d_iW > 0$, i.e. to the conventional formulation of the second law of thermodynamics. In this case the entropy increases and the system tend to the ultimate equilibrium state. The analogues of the laws of thermodynamics allow the complex self-organization processes in the SSs to be jointly described on the different time scales within a seismic cycle. Another important feature is that on a short time scale, the restoration of equilibrium is achieved through the intense internal production of entropy within a local domain of the source of the expected strong earthquake rather than in the entire volume of the system. As a result, in the j-th local internal fragment of volume V, the sliding surface A_{rj} appears on which the work is done:

$$\delta R_j = \ln 10\, S \lg S + \beta_s S^{a_s} = (\mu_s \sigma_n u A_r)^j \qquad (26),$$

where μ_s is the coefficient of static friction, σ_n is the local normal stresses, A_r is the area of the contact surface of the fault, and u is the expected length of the slip. The formation of the sliding surface is the necessary condition for the radiation of seismic energy. The source area V_j of a strong earthquake is the zone of restoration of local equilibrium within volume V of the SS. As time goes by, the sources of the strong earthquakes fill the main heterogeneity within the SS volume thus completing the large seismic cycles.

SEISMIC FORMALISM

The alphabet of evolution. The aim of this section is to future expand the seismic formalism and to create the alphabet for describing the evolution of the Earth and the Universe. The Earth is the unique planet in the Solar System which has active plate tectonics. The maximum length of the largest revealed SS (the Chilean SS) is ∼ 3000 km which is by an order smaller than the length of the circumference of the Earth. We significantly simplify the problem and disregard all the elements that are not substantial for our purposes (the inner and outer core of the Earth). We also neglect the curvature of the Earth in a first approximation and only consider the mantle and the lithosphere, which we represent as horizontal layers (*Fig. 13a*). In order to draw an analogy with the Universe, we 'cut' the Earth and stitch it inside out (*Fig. 13b*) so that the Universe surrounded by SSs be located at the centre, followed by the mantle with the outer and inner cores above it. In terms of geometry, this means the inversion with respect to the Earth's surface. Each point located within the sphere of the Earth's interior passes into the exterior domain and vice versa. This inversion converts the centre of the Earth into the infinity and the infinity into the centre of the circle. The purpose of this representation will be clear when we will model the dark matter and dark energy in the early Universe.

The plates are permanently in motion; however, they cannot sink into the mantle to below 700 km without being destroyed. The seismic formalism implies that the deep layers of the mantle and the more so the layers of the outer and inner cores are 'inaccessible' for the SS. The seismically active volumes mainly exist in the upper mantle and decay with deepening into the mantle. The SSs are confined to the zones of plate interaction and make up less than 0.1% of the total volume of the Earth's crust and mantle; the volume of the lithosphere plates and the mantle beneath them make up ∼ 8% and ∼ 91.9%, respectively (*Fig. 13a*). At the geological stage of the Earth's evolution, starting from approximately between 4.0 and 3.8 billion years ago, the chemical density (gravitational) differentiation of the Earth's material has resulted in the layering of the Earth into the dense iron-oxide core and the residual silicate mantle [48]. This process was accompanied with the formation of the large-scale convective cells in the mantle. The bulk of the energy produced in the Earth's core is spent on uplifting the mantle material in the mid-ocean spreading zones. This energy forms the convective cells in the mantle (*Fig. 13a*) which drive the lithosphere plate motion [42, 46].

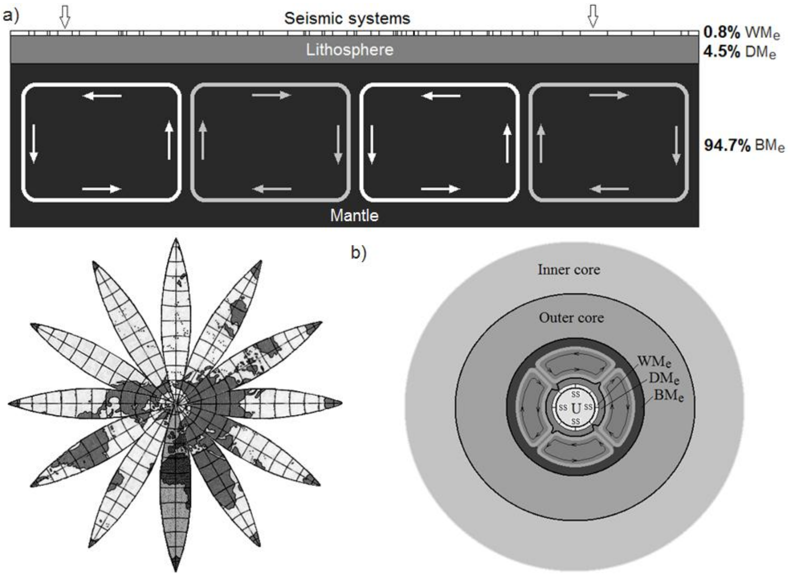


Fig. 13. (a) Schematic 2-D image of the convective cells in the mantle, lithosphere, and SSs. The ratios (in per cent) between the 'white', 'dark' and 'black' matter for the Earth are shown. (b) The Earth inside out. The Universe (U) located at the centre is followed by the lithosphere plates (SSs), the mantle, and the cores (outer and inner) of the Earth.

Let us introduce some definitions into the seismic formalism. In accordance with the ability of the environment to radiate seismic waves, the medium within the seismically active domains will be referred to as the white matter (WM_e). The seismically inactive material of the lithosphere (plates) which has nonuniform structure will be referred to as the dark matter DM_e, and the mantle of the Earth, as the black matter (BM_e). Index *e* indicates that these definitions apply to the Earth. Besides, considering the fact that the Earth's mantle supplies energy to the lithosphere, we will also use the term 'dark energy' (DE_e) for it. The DM_e is composed of the relatively cold rocks and have a thickness of 100 km on average. In contrast to the mantle BM_e, the plates DM_e are the 3-D structural formations (constructions) which are being constantly produced and swallowed by the mantle BM_e. While the Earth exists with its contemporary interior structure (with liquid outer core and solid inner core) and the dynamics and while there are no external impacts affecting this construction of the Earth, the plate tectonics will be continuously supplied with energy. In other words, BM_e will provide energy for DM_e for several billion years to come. For simplicity, we will avoid looking into the Earth below the mantle (or, in the scheme shown *Fig. 11b*, avoid moving off the mantle) and will assume that the plates are supplied with energy from BM_e. When the plates are spreading apart from each other, the hot mantle (magmatic) rocks are continuously uplifting along the oceanic ridges and forming the new fragments of plates on the divergent plate boundaries. These boundaries on which the accretion of the plate constructions takes place will be referred to as the boundaries of the primary DM_e formation. Since the surface area of the Earth (the surface of DM_e and WM_e) is almost constant, this means that also the reverse processes of plate destruction (i.e. transformations of DM_e and WM_e into the BM_e) take place. These processes occur on the convergent (in the zones of plate collision and subduction) or transform plate boundaries. As the plates move from the divergent to convergent boundaries, they become older and thicker and accumulate heterogeneities. The geological time is irreversible, and these natural evolutionary processes cannot be turned back. Only the biological objects (humans) can move across the Earth's surface 'back and forward' in the geological time and study the chronology of these objects.

The entropy theory of the open dissipative SSs describes the origin of seismic instability and the evolution of the lithosphere plates in the zones of their interaction. The analogues of the thermodynamic laws which were formulated in the previous section allow us to classify various plate-tectonic situations. Here we describe the classification of the plate boundaries in terms of the new alphabet. *Fig. 14* schematically shows an open dissipative system that includes a seismogenic structure (WM_e + DM_e) and the sources of the strong earthquakes surrounded by BM_e. We note one important factor that should be taken into account when modelling the Universe. The preparation of the strong earthquakes within the SS cannot occur simultaneously in two or more sources (V_1 and V_2 in the *Fig. 14*). The inflow and outflow of entropy production in *Fig.*

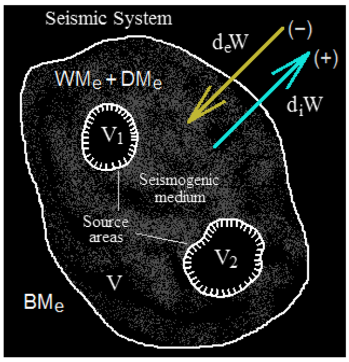


Fig. 14. Schematic representation of the open SS with the new terms of matter. The arrows indicate the (negative) inflow and (positive) outflow of entropy. V_1 and V_2 are the source zones of the strong earthquakes.

14 are shown by the negative and positive arrows. The characteristic tectonic conditions at the plate boundaries are mainly determined by the inflow of tectonic energy into the system (5).

Fig. 15a-e schematically shows the SSs in the different plate-tectonic situations. The mantle in these figures is indicated by BM_e; the relatively lighter material forming the plates is assumed to be *DMe*; the medium that includes seismogenic structures forms WM_e. In [8] the analysis of Eq. (24) and qualitative description of plate-tectonic situations were presented. The configurations of these boundaries with the indication of the type of matter in our formalism are presented in *Fig. 15*, right. In the seafloor spreading zones, where lithosphere plates diverge, the hot mantle composed of BM_e cools and creates the DM_e whose internal tension are the cause of the tectonic activity and earthquakes.

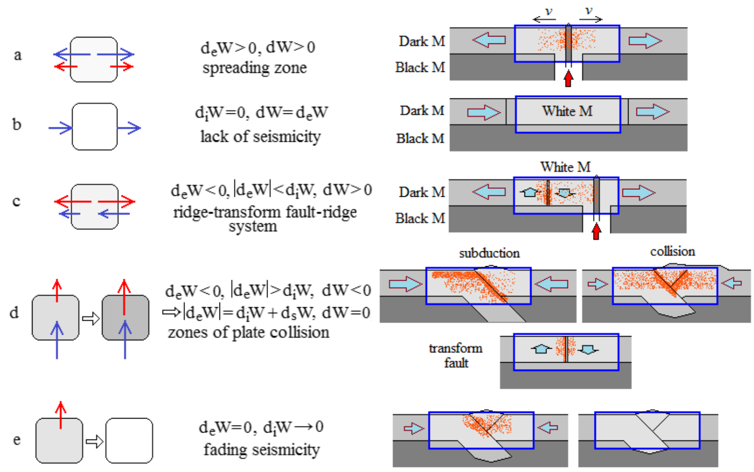


Fig. 15. Schematic representation of entropy balance in the open SS in the different seismotectonic settings. Squares (left) and rectangles (right) denote different seismic systems; dark arrow, internal entropy production; light arrow, inflow and outflow. In the right part, the mantle represents BM_e and the plates represent DM_e; the densely concentrated dots denote the seismically active zones WM_e. See the detailed explanations in the text.

Since the seismicity in these zones is weak, we assume that WM_e is not strongly pronounced here. The bulk of the volume of the lithosphere plates is seismically inactive. The property of stiffness enables the plates to transfer elastic stresses over large distances during the geological periods of time. Formally, the internal regions of the plate can also be considered as the SSs with nearly zero production of seismic entropy, $d_iW \approx 0$. In this case, from Eq. (24) it follows that $dW = d_eW$, i.e. the system, which remains seismically quiet inside, interact with the environment and transfer the tectonic entropy from one medium to another (*Fig. 15b*). The seismically quiet regions of the plates are relatively homogeneous DM_e domains. In the contact zones the plates behave as the WM_e containing seismic sources (indicator earthquakes) which are able to periodically radiate intense seismic waves. In the subduction and plate collision zones, DM_e partially sinks into BM_e, is destroyed, and again converts into BM_e. A certain (typically small) part of it forms the heterogeneous continental DM_e^c with the inclusions of white matter WM_e (*Fig. 15d*). It can be said that there are two types of DM_e for the Earth: oceanic DM_e^o (having higher density and more uniform) and continental DM_e^c (less dense and heterogeneous). *Fig. 16* illustrates the distribution of WM_e, DM_e^o and DM_e^c on the Earth's surface.

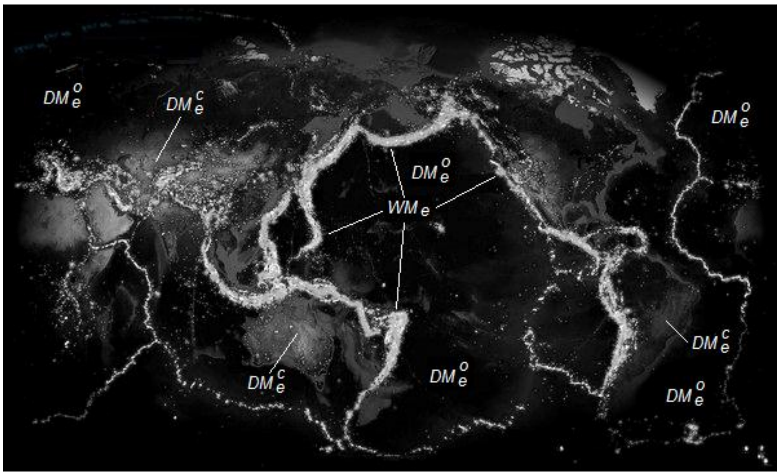


Fig. 16. Distribution of white matter WM_e (light dots) and two forms of dark matter, the oceanic DM_e^o (the black areas), and continental DM_e^c (the grey areas) on the Earth's surface.

If after the restoration of balance (25), the further activation in the plates gradually decays and ceases, the system reaches the equilibrium with the environment (*Fig. 15e*). The situation can be observed on the large time intervals at the stage of evolution of the convergent plate boundaries after their coalescence after the collision. The formerly active plate boundary slowly becomes locked and eventually loses seismic activity due to the restructuring of the convective cells in the mantle. The deceleration of the convective flows driving the seismic activity leads to $d_eW \to 0$, hence $d_iW \to 0$, i.e. the system 'dies'. In this case DM_e^o is completely eliminated and only DM_e^c remains. In the scope of the seismic formalism, the formula describing the evolution of the Earth's matter during the geological epochs can be cast in the following general form:

$$\mathrm{BM}_e(\text{or DE}_e) \to \mathrm{DM}_e^r \to \mathrm{DM}_e^o \to \begin{cases}\mathrm{DM}_e^c \\ \mathrm{DM}_e^o\end{cases} \to \begin{cases}\mathrm{DM}_e^c \\ \mathrm{WM}_e \\ \mathrm{DM}_e^o\end{cases} \to \begin{cases}\mathrm{DM}_e^c \\ \mathrm{BM}_e\end{cases} \quad (27),$$

where DM_e^r is the relic dark matter of the Earth. During the SS evolution the bulk of the matter returns to the mantle while the continental crust remains on the Earth's surface.

Thus, WM_e are the 'glowing' (i.e. radiating the seismic waves) volumes of the Earth's lithosphere. They are formed in the regions of interaction between DM_e^o and DM_e^c, which were initially formed from BM_e about 4 billion years ago. The plate motion velocities v_{pt}, supported by the convective cells in the mantle, are the necessary condition for the formation and evolution of the lithosphere plates. As was shown above, these velocities create the continuous energy flow E_t the logarithm of the integral of which is just the flow of entropy (23). The analysis described above shows that it is continuous inflow of entropy into the system that ensures the evolution and determines the dynamics of the plate tectonic situation. White matter WM_e (the seismic analogue of the Universe) is formed together with the lithosphere plates, then evolves, and fades out with them, being converted into DM_e^c or absorbed in BM_e. The age of the SS cannot be larger than the age of the lithosphere plates ($\sim 50 \div 150$ million years). At the stage of the nucleation of the plates, the spherical symmetry of the Earth has been violated. The relic matter DM_e^r (primary clusters of the horizontal inhomogeneities in the upper mantle) was formed from the mantle BM_e and then became a source of the formation of the oceanic matter DM_e^o. The continental matter DM_e^c has not yet existed at that time. This stage can be called a 'dark' stage in the Earth's evolution because there was no seismic radiation at that time. By analogy, the similar stage for the Universe can be called dark in the direct sense because there were no light sources. The white stage began with the emergence of the earthquakes, initially in the form of microseismicity (*Fig. 4*). Subsequently, with the accumulation of the heterogeneities, the earthquakes were gradually getting larger (*Fig. 11*). The continental type dark matter (DM_e^c) was accumulated and its fraction increased. At present all the three types of the dark matters of the Earth (DM_e^r, DM_e^o and DM_e^c) exist alongside with the black and white matters (BM_e and WM_e). This simplified treatment is fairly sufficient for analyzing the complex processes of the formation and evolution of the Earth's lithosphere in the scope of the seismic formalism.

Entropy funnels and turnover of `dark matter' and `white matter'. Formula (27) describing the evolution of Earth's material, i.e. its turnover, is implemented in the entropy funnels. It was shown [8] that the preparation of each strong earthquake in an ensemble can be represented in the form of a spatial spiral trajectory eventually tending to the local areas of generatrix (attractor) in the entropy funnel (cone-shaped annular structures) in the discrete points of which a seismic catastrophe occurs (*Fig. 17a*). *Fig. 17b* schematically illustrates the entropy funnels governing the dynamic processes of the described evolution (27). The funnels are calculated based on the systems revealed in the different plate-tectonic situations during the instrumental period.

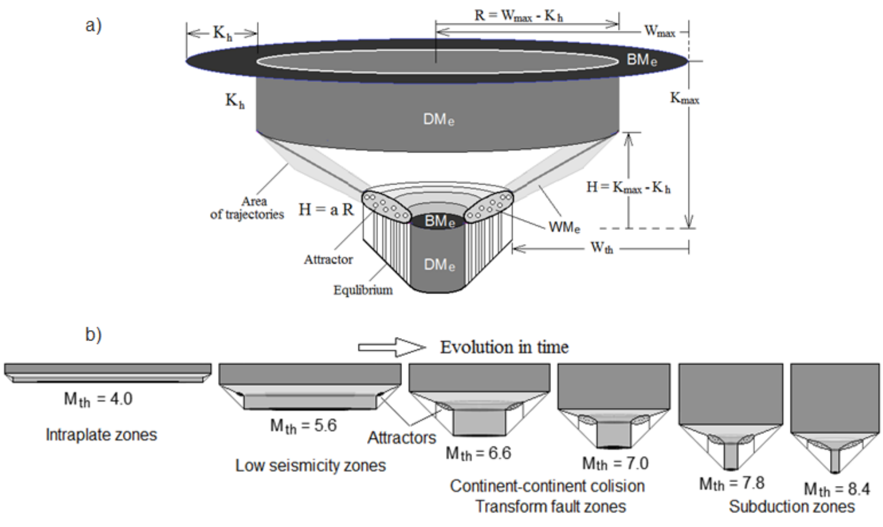


Fig. 17. (a) The scheme of entropy funnel (in the 3-D space of time, entropy and energy coordinates) and distribution of different forms of matter. The shaded surface of the truncated cone is a ring-like structure (attractor) near the generatrix $H = aR$. The spiral trajectory is drawn into the funnel and ends in the 'holes' within annular zones of the funnel. (b) Entropy funnels with increasing threshold magnitude for the SSs under different plate-tectonic situations.

These multi-scale funnels also exist within one large SS consisting of subsystems with hierarchically decreasing magnitudes. When the SS is split into the subsystems, the funnels fill the volume of the megasystem and evolve with time simultaneously with each other. These subsystems were revealed in the mega SS of Japan [5], in the SSs of Italy, Armenian Upland and Central California [6]. The walls of an entropy funnel (the attractor) store the information about the fragmented heterogeneous seismotectonic structure of the SS. As the threshold magnitudes grow, the entropy funnels become deeper and narrower, whereas the SSs, on the contrary, become expanded. Such multi-scale pattern of the funnels is observed in the transition areas from spreading to subduction zones. The funnels are form of the mantle material (DM_e) in the spreading zones, then evolve with time, decay in the subduction zones, and plunge into the mantle. The most clearly expressed and 'long-lived' entropy funnels are located in the subduction zones. The upper cylindrical part of the funnel corresponds to the lithosphere plate formed of DM_e. The areas of trajectories and the attractor form the walls of the funnel structures whose fine fabric is described by constants a_c, b_c, a_s and b_s of the laws (18) and (26). These constants are calculated based on the indicator earthquakes and strong earthquakes in the ensemble. The walls of the funnel (the region of trajectories and attractor) correspond to the structures of white matter (WM_e), which are able to radiate seismic waves. The definition of a structure for the seismicity was presented in Section 2.1. We note that constructing the entropy funnels requires the following transformations [8]:

$$\begin{cases} \Phi = T\,\Phi_0 \\ R(T) = W_{max} - W(T) \\ H(T) = K_{max} - K(T) \end{cases} \qquad (28),$$

where W and K are determined from (12), whereas W_{max} and K_{max} are their maximal values in the attractor. System (28) is defined in the non-equilibrium domain (*Fig. 17a*):

$$K_h \leq W \leq W_{max}, \qquad 0 \leq R \leq (W_{max} - K_h) \qquad 0 \leq H \leq (H_{max} - K_h) \qquad (29),$$

where K_h is the minimum threshold which specifies the time arrow. For the Earth overall as a planet, the maximum values W^e_{max} and K^e_{max} can be selected as the parameters of the world strongest earthquake. As the size of a hypothetical planet increases, the maximum values of the parameters can grow, hence the entropy funnels will become narrower and deeper. Theoretically, the entropy funnels of seismicity in the case of huge solid planets can cause the explosion and destruction of the entire planet. The analogue of the entropy funnels for the Universe is still to be comprehended.

The transformation of the time-entropy-energy space $\{T, W, K\}$ into the 3-D phase space $\{\phi, R, H\}$ has a deep physical meaning. Mathematically, this means that we, as an observer, move into the centre of a sphere (or, rather, to the vertex of the cone corresponding to the instability point of the strongest earthquake) and describe the trajectory in the spherical space. In this mode of observation, the trajectories are twisted into a spiral and attracted to the centre. This means that transformation (28) is an attempt to find a more suitable way of describing the observed processes of seismicity. Observation of a phenomenon not from an arbitrary point but from the state, to which the physical system tends, may turn out to be more importance under certain circumstances. In fact, this transformation allows the observer to move into the future of the system and enables him to look at the preceding states of the trajectory in time. Thus, if the events are predetermined, nothing prevents one from correctly restoring the past and from glancing into the future. However, this requires a ready (validated) construction of an entropy funnel in the space (beyond the time that is usual for us) with certain properties. If such a construction created by us will correctly describe natural phenomena (the earthquakes in the case of seismology, or the origin of matter and space in the case of cosmology) in the time domain, it will be the criterion of truth. We will apply this approach when describing the gravitational field, dark matter, and dark energy in the second part of the article.

The comparison and relationship between the black matter and dark matter. We also apply the evolution formula (27) for describing the evolution of matter in the Universe. What is known about the dark matter in the Universe is that (i) it is concentrated into clumps, likewise the ordinary matter; (ii) the clusters of the ordinary and dark matter generally spatially coincide; (iii) the dark matter is, to all appearances, non-relativistic; and (iv) the dark matter does not collide with ordinary matter. By analogy with the Earth, we assume that the dark matter in the Universe, DM_U, has also originated from the dark energy DE_U (hereinafter, index U denotes the Universe).We consider the ordinary matter in the Universe, which consists of the known particles, atoms and molecules, as an analogue of WM_e (seismogenic structures) and refer to it the white matter WM_U. Continuing the analogy, we assume that WM_U has originated from DM_U and is concentrated around the previously formed inhomogeneities of dark matter DM_U.

Fig. 18a,b shows the 3-D map of the dark matter distribution in the Universe [29] and the tomography image of the heterogeneities in the upper mantle of the Earth [68], respectively. In seismic formalism, the relic dark matter DM^r_e is understood as certain primary heterogeneities in the upper mantle (such as the ones shown in *Fig. 18b*, which have originated in the relatively homogeneous medium of the mantle) and become the progenitors for the subsequent formation of the lithosphere. By analogy, we will consider the bunches in *Fig. 18a* as the primary (relic) dark matter DM^r_U, which was formed from the dark energy. Importantly, these bunches are material; they can exist (in space and time) even without the ability of radiating the waves (seismic in the case of seismology and electromagnetic in the case of the Universe). Thus, from the standpoint of the astronomical observations and seismographs, dark matter in both the Universe and seismology is not directly visible. A virtual observer would not be able to detect relic dark matter because the sources of light have not existed at that time. It is known about the dark matter in the Universe that its spatial distribution is uniform and that it creates negative pressure leading to the accelerated cosmological expansion of the Universe [28, 35]. The ratio between the observed matter WM_U^{ob} : DM_U^{ob} : DE_U^{ob} (index *ob* means 'observed') in the Universe is 4% : 22% : 74% [20], that is, the dark energy is almost three times as large as the dark mass which, in turn, is six times as large as the ordinary mass. In the case of the Earth, the ratio $WM_e : DM_e : DE_e$ is 0.1% : 8.0% : 91.9%.

Hence, we may conjecture that there should actually be much more dark energy in the invisible Universe if we assume $DE_U^{ob} \equiv DE_U$. If we assume that it is only the upper 250-km layer of the mantle beneath the lithosphere plates (the low-velocity layer) that constitutes the dark matter, and specify it as DE_e^m, the ratio WM_e : DM_e : DE_e^m will approximately coincide with the observed ratio WM_U^o : DM_U^o : DE_U^o. However, what is meant by the observed values of dark energy and dark matter is still to be determined. The theory that describes dark energy and the origin dark matter from it should also describe the mechanism of formation of the usual white matter. As directly follows from seismology, the formation of white matter in cosmology should follow the succession $DE_U \rightarrow DM_U \rightarrow WM_U$.

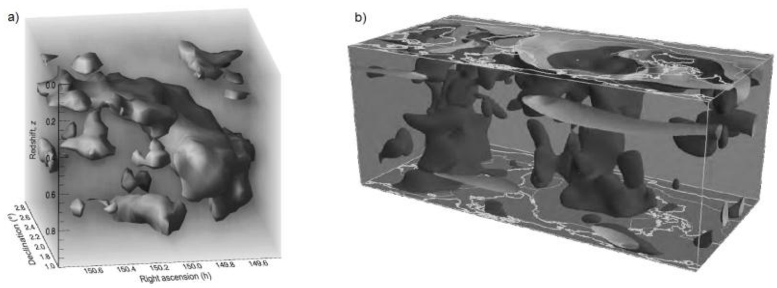


Fig. 18. (a) The mass distribution of the dark matter obtained by analyzing the gravitational lensing data. (b) The tomography images of the upper mantle.

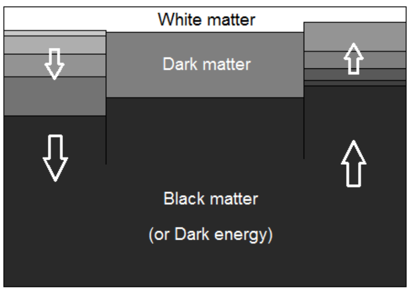


Fig. 19. The sequence of origin and the turnover dark and white matter.

Fig. 19 schematically illustrates the process of the formation and destruction of white matter in the course of the evolution with the formation and complication of the structures of dark matter. This scheme does not contradict the huge anomalous data which were accumulated in the observational astronomy and are related to so-called rotational curves of clusters of stars and galaxies and to gravitational lensing [18, 29, 36, 38]. Just as in the case of seismology, we distinguish two types of dark matter in the Universe: the primary relic dark matter (DM_e^r) whose carriers are yet unknown and the secondary dark matter which is formed of the known elementary particles after the stage of emergence of the radiation (the so called baryonic dark matter DM_U^{bar}). The secondary dark matter can also include the weakly glowing cosmic objects that are not 'visible' by means of the current astronomical equipment. These are, for example, massive planets, brown dwarfs, the galaxy dark matter haloes, etc. For developing the theory of dark energy and relic dark matter DM_r it will be sufficient for us to consider gravitational interactions, whereas when studying the stage of formation of white matter, we should also take into account other fundamental interactions (electromagnetic, strong and weak) in addition to gravitation; note, that their origin will be secondary. By the same reason, the elementary components of dark energy and the relic dark matter cannot consist of known particles. Gravitation is the only universal interaction: it manifests itself by the space and time warp. But what is the gravitational field, how has it come into existence, and what is its carrier? Or, to put a question broader, what do the dark energy and dark matter consist of and how do they interact with the gravitational field? All these questions have no answer yet. According to the current knowledge, it is assumed that dark energy has the properties of the physical vacuum in the Universe, i.e. is its 'zero-point oscillations' [15]. From this it is concluded that the physical nature of dark energy is quantum. We will look at these problems from the standpoint of entropy seismology and try to give some physical description of the observed substances of dark matter and dark energy. We will also consider the Universe by analogy with the SS as a specific quantum system having the least metric h_g.

Generalisation of the method and quantum nature of entropy seismology. The method of entropy seismology is based on the concept of an open dissipative SS. The problem of the system evolution becomes meaningful when the time symmetry is violated. Here the evolution is governed by the analogues of the law of thermodynamics on the long and short time scales, i.e. by the power law of entropy production (17) and energy conservation law (26), respectively. As a result of simplification, the SS state is described by fewer parameters, compared to classical mechanics, that is, in less detail. The statistical state of an entire closed system at rest (in the absence of translational and rotational movements) only depends on energy. From the seven additive independent integrals of motion (the energy, three components of the momentum vector and three components of angular momentum), which completely determine the statistical properties of the closed system, only the energy remains. The simplified consideration of the system consisting of the sources of energy radiation instead of the material particles avoids the common thermodynamic description of the system. The main physical quantities in the theory of entropy seismology are time, energy and entropy. The quantum constraints appearing in entropy seismology are unrelated to the corpuscular-wave property of the radiated energy; they rather result from the introduced of the system nucleation principle and the associated minimal quantum unit of action (metric) (15). The initial equilibrium state in thermodynamics is defined on the molecular level, whereas in seismology it is defined on the level of an elementary microearthquake. Since the theory of entropy seismology is based on seismostatistics (i.e. on the measurements), the choice of the metrics depends on the accuracy of measurements. To describe the evolution of nature on the huge spatia-temporal scales of the Universe, from the ultra microcosm to the clusters of galaxies and metagalaxies, we need to develop some universal basis. The universal basis for describing the evolution of nature on the huge range of spatiotemporal scales of the Universe can be provided by the approach, in which the problem is subdivided into the stages, the concept of a system is introduced on the different hierarchical levels of evolution, and then the results obtained at the individual stages of the evolution are stitched. Generalising the metrics of 'quantum of action' (15) to the other forms of energy defines the minimal size of the energy-time blocks for constructing the theory in the different fields of physics. The quantum of action can be unimaginably large or, on the contrary, incredibly small, but always finite. It is important to note that, depending on the stage of evolution of the Universe, with the enlargement of the quantum of action, the quantum of energy and unit time step also should be enlarged [8]. Time, likewise energy, has a quantum nature.

The law (17) governing seismic entropy in the system is probabilistic. Mathematically, it results from the degeneration of the SS energy states. However, (i) what is the physics of the probability and (ii) why should the system in the most probable states lose stability? For answering these questions, we should understand how the probability is defined. In the common events such as tossing a coin or the roulette game, the ordinary mathematical probability reflects the incompleteness of our knowledge. However, these probabilities say nothing about the fundamental physical properties. In contrast, the probability introduced on the basis of natural seismic events is more meaningful: it reflects the real physical processes of the emergence of instability in the geological medium. If there were the necessary information about the stress and strain distributions in the heterogeneous structures of the Earth and the detailed data about the deep structure, we would be able to find the exact solution of the problem of the origin of instability using powerful computers and to predict the time of the future earthquake. However, this information is unavailable and the exact solution cannot be obtained. As noted above, we significantly simplify the problem and describe the state of the system in terms of the parameters that are recorded in seismology. In other words, we do not solve the complicated equations of motion (the nature does it for us); instead, we describe the emergence of the catastrophes in the system based on the observations of the real behaviour of the nature. In our approach, the volume of the system is not arbitrary: it is specified based on the observations of the previous catastrophes and revealed regularities. Since the period of the observations is limited, the simplified approach leads to the loss of information, uncertainties, and probabilistic description of the medium state. Thus, the probability in entropy seismology ensues from the simplifications and limited period of the observations of earthquakes in the system.

The unavoidable loss of stability during a finite time interval is associated with the presence of the upper limit of the rock strength which is the necessary condition of the emergence and death of the system in entropy seismology and is taken into account through the 'quantum of action' (15). Methodologically, the law (17) was revealed experimentally. The theoretical substantiation of this law on the basis of probability only states the universality of the observed fact. Paradoxical as it may seem, the approach that is probabilistic due to the incompleteness of our knowledge can yield the exact mathematical laws. However, the philosophy lies in the fact that, in contrast to the exact outcome, the probabilistic approach expands our capabilities and allows the occurrence of the unordinary events which can strongly differ from our expectations. Remarkably, the similar principle also guides the quantum mechanics [27]; the fact that matter possesses the wave properties implies that the fundamental description of the matter should be probabilistic. An attempt of 'measuring' the parameters of a micro object is equivalent to an attempt to retrieve more information about the state of this micro object than is provided by the quantum mechanical description of its state [17]. In contrast to quantum mechanics which describes particles on the microscopic level, our theory is also applicable to the macroscopic objects. We reject the conventional absolute understanding of the micro- and macro-states and consider them as relative depending on the spatiotemporal scales of the system. For studying the system on a finer scale, we should split it into the smaller domains and to define the subsystems by the principle of a system. This means that macro states can exist even at the ultra microscopic level.

In our description of the systems, we retained some elements of quantum mechanics. Like atoms and molecules, the systems have discrete energy levels. In entropy seismology, just as in quantum mechanics, the notion of the particle motion trajectory is absent (the trajectory describes the state of the system overall in 5-D space). In quantum mechanics, this fact lies at the heart of the so-called Heisenbergs uncertainty principle [27]. At the preparatory stage of a catastrophe, we, in a certain sense, abandon locating the indicator earthquakes in space. The location of the indicator earthquake within the SS does not matter; it is only important that these earthquakes are within the system. However, the spatial localization of the catastrophe itself is the key important point of the theory. The typical statement of the problem in quantum mechanics consists in forecasting the result of the repeated measurement based on the known result of the previous measurements. In the SS the prediction of a new strong earthquake also relies on the data about the previous strong earthquakes of the ensemble. The systems approach in describing the evolution of nature by the analogy with entropy seismology can be referred to as *Simplified theory of quantum entropy* (STQE). Unlike quantum mechanics which describes microcosm, the quantum in entropy seismology can both be very small and large value, e.g., a seismic quantum. The universal quantum constant in quantum mechanics is connected with the radiation energy on the atomic scales, whereas the metrics in our approach is associated with the notion of the origin and death of the system and with the accuracy of measurements. The Planck's constant and the metric have the same dimension (*energy* × *time*) which is referred to as action. The laws of physics reformulated in terms of action and system seem to be more universal for the hierarchical description (within a huge scaling range) of the stages of the Universe evolution. This physics contains the elements of both quantum and classical mechanics. We will use this approach when describing dark matter and dark energy at the 'embryonic' stage of evolution of the Universe, in the absence of radiation.

The mechanical, thermal, electrical, nuclear, seismic, etc., are just some of the variety of the forms the energy can have. The main forms of energy in mechanics are potential and kinetic, which have fundamental importance for natural sciences. The emergence and division of energy into potential and kinetic is connected with the concepts of interaction, mass, and velocity of a point particle. By specifying the form of energy in the STQE, we can try to describe some fields of physics. Without going into the details of this approach, we can state that the new paradigm will significantly simplify the problem due to the emergence of uncertainties. In the new paradigm the concept of objective reality of the material structure for separate spatial points (pixels) in time disappears. The reality described by quantum entropy is much more subjective than we could imagine. The STQE describes the evolution of a system in the virtual space (time, energy, and entropy). All the spatial information of the system is accumulated within its volume and stored in these parameters. Under certain conditions, the system emerges from the environment, exists, evolves, and proliferates by interacting with the environment (it has the internal time of life), and eventually dies, leaving a certain imprint on the environment. For example, the SSs are now 'living' on the Earth; however, they have either not existed or already 'died' on the other planets. After 'dying', the SSs leave the 'scars' in the form of paleo-faults and newly formed complicated geological structures. This simplified theory of the SSs evolution in the geological environment, considered from the unusual standpoint of seismology, allows us to approach the description of the origin of the Universe, dark energy, dark matter, and gravitation without introducing initial singularity. The Big Bang (BB) and its experimental evidence (relic radiation and expansion of the Universe) could be produced from the primary relic dark matter, by analogy with the origin of stars and galaxies from gas-dust clouds under the action of gravitation.

In the second article, we will try to formulate the definition and to model DE_U and DM_U in the scope of seismic formalism and to develop the theory of transformation $DE_U \rightarrow DM_U$ at the time when WM_U (i.e. the known particles of the standard model) have not existed. We will distinguish the empirically observed values of dark energy (denoted by DE_U^{ob}) from DE_U. Looking ahead, we note that the contemporary cosmological theories are absolutely inconceivable without physics of elementary particles. From Sections 2.1 and 2.2 it follows that for describing the transition $DE_U \rightarrow DM_U$ in the Universe, we should consider the scale (except time) that are smaller than Planck constants: energy $\varepsilon < \varepsilon_p$, time $t \geq t_p$, metrics $h < h_p$, and structural heterogeneity $l < l_p$ (index p means 'Planck'); otherwise, the medium would radiate light waves.

CONCLUSIONS

The achievements in the field of the open dissipative SSs have enabled us to develop the seismic formalism based on seismostatistics and to elaborate basic elements (the 'alphabet') for transferring the knowledge from entropy seismology to cosmology and modeling the formation of primary structures in the Universe. The article addresses the study of the processes of the nucleation and evolution of seismicity with maximally simplified description of the geological processes in the Earth. It enabled us to model the geological environment and evolution of SS in terms of dark matter and dark energy and to transfer this unusual scheme to the modeling of the evolution of the Universe starting from the definition of dark energy. According to the suggested model, at the beginning there was only a dark energy where time and space were fused and frozen. The concepts of entropy and energy were equivalent. The mathematical space was without curvature and singularity. The notions of velocity and acceleration did not exist because there were no known particles.

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