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IS OUR UNIVERSE TYPICAL?

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Վ.Գ. ԳՈՒՐԶԱԴՅԱՆ

ՏԻՊԱԿԱ՞Ն Է ԱՐԴՅՈՔ ՄԵՐ ՏԻԵԶԵՐՔԸ*

Արծարծված է Տիեզերքի, որպես կանոնավոր և քաոսային փուլային տարածության դրական չափի տիրույթներով դինամիկական համակարգի, տիպականության հարցը: Հետազոտված են երկու դինամիկական համակարգեր. 1. Դիտվող նյութական Տիեզերքը, որպես փոխազդող ձգող N մարմինների համակարգերի դասակարգություն /հիերարխիա/. 2. /3+1/-չափանի՝ նյութական դաշտեր ընդգրկող բազմաձևություն, որի էվոլյուցիան գերտարածությունում բնորոշվում է Ուիլեր-Դե Վիտի հավասարմամբ՝ Հոկինգի պարփակ /կոմպակտ/ չափողությունների սահմանային պայմանի առկայությամբ: Ցույց է տրված, որ մեր դիտվող Տիեզերքը տիպական է: Երկրորդ համակարգի համար միարժեք պատասխան դեռ չկա: Տիպական լինելու դեպքում այժմյան Տիեզերքը կարող է իր սկիզբը առնել անվերջ քանակի տարբեր սկզբնական վիճակներից, որոնց վերականգնումը ներկայումս կլինի գործնականորեն անհնար:

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Երևան 1988

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Препринт ЕФИ-1066(29)-88

В.Г.ГУРЗАДЯН

ТИПИЧНА ЛИ НАША ВСЕЛЕННАЯ? *

Ставится и обсуждается вопрос о типичности Вселенной,как о динамической системе, обладающей как регулярными, так и хаотическими областями положительной меры фазового пространства. Рассмотрены две динамические системы - наблюдаемая материальная Вселенная, как иерархия систем N - гравитирующих тел и (3+1) - мерное многообразие с материей, эволюционировавшее в соответствии с уравнением Уилера-де Витта в суперпространстве с хоукинговским граничным условием компактности метрик. Как показано, наш материальный мир является типичным. Однозначного ответа для второй системы пока нет. В случае типичности современная Вселенная могла иметь свое начало из бесконечного множества разных начальных данных, восстановление которых в настоящее время практически невозможно.

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V.G. GURZADYAN

IS OUR UNIVERSE TYPICAL?*

The problem of typicalness of the Universe - as a dynamical system possessing both regular and chaotic regions of positive measure of phase space, is raised and discussed. Two dynamical systems are considered: 1) The observed Universe as a hierarchy of systems of N gravitating bodies ; 2) (3+1)-manifold with matter evolving according to Wheeler-DeWitt equation in superspace with Hawking boundary condition of compact metrics. It is shown that the observed Universe is typical. There is no unambiguous answer for the second system yet. If it is typical too, then the same present state of the Universe could have been originated from an infinite number of different initial conditions, the restoration of which is practically impossible at present.

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Yerevan 1988

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Why there is no infinite number of
Worlds?
YEZNIK (Armenian phylosopher,
5th century A.D.)*

1. The Statement of the Problem

The investigation of the Universe in the framework of modern cosmology includes the construction of mathematical models explaining the available observational data based on introduced mathematical concepts and physical variables. The concept of typicalness is one of the important ones for the mathematics. In many formulations of the theory of dynamical systems, the concepts of typicalness and typical systems are the central ones. Just the typical systems or the systems of general state, according to D.V. Anosov, "are worthy of paramount attention", the question of typicalness being a "clearly formulated question, requiring answers "yes" or "no" " [1].

In what sense can one speak of the typicalness of the Universe? and what dynamical systems can be considered first?

Below we shall discuss two possible answers to these questions:

1. The structure of the present Universe is characterized

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*Yeznik Koghbatzi, Refutation of Religions, Yerevan, 1970.

by a hierarchy of systems of N gravitating bodies - from planetary systems to clusters of galaxies and superclusters. Therefore, adopt a 6N-dimensional Hamiltonian system with Newtonian potential - as a dynamical system mostly determining the observed features of the Universe.

2. One can consider the Universe as a dynamical system evolving from one state at time t_0 (in some coordinates) to another - at moment t_1. The dynamics of the Universe (evolution) is described by, say, Einstein equations and the energy-momentum tensor of matter.

Evidently, these problems affect, on one hand, the classical N-body problem, on the other - the problem of solutions of cosmological equations.

Before we pass to the discussion of typical properties of those dynamical systems, let us briefly elucidate the concept of typicalness itself.

2. Typicalness of Dynamical Systems

Consider the space $\Gamma^r(TM,\mu)$ of all smooth, preserving the measure μ, dynamical systems of class C^r on n-dimensional manifold M (here and below see, e.g., [1]). A property possessed by a dynamical system is called typical if it is fulfilled for the elements of subspace of $\Gamma^r(TM,\mu)$ with complete measure. Within the categorial approach* the typical property

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*The categorial definitions though mostly coincide with the metrical ones, also enable to handle with spaces for which is possessed by the open set of second category - intersection of a countable number of everywhere dense sets; *non-typical* property - by a set of first category - unification of a countable number of nowhere dense sets. A dynamical system possessing a typical (non-typical) property is considered a *typical* (*non-typical*) one.

Many typical properties of dynamical systems are studied within the theory of dynamical systems, the corresponding criteria for their fulfillment are found; the systems of lower dimensions are investigated in special details. Thus, it is proved that a typical dynamical system is a system with a "shared phase space", i.e. containing both regular and irregular (chaotic) regions of positive measure. This result directly follows from the Kolmogorov-Arnold-Moser (KAM) theory (see [2]).

In the regular region the system has zero Lyapunov characteristic exponents and can be integrable performing a winding of torus; in the chaotic region the situation is more complicated - the degree of chaos can be different. Within the ergodic theory the corresponding classification of systems is found: ergodic systems, systems with mixing of different degrees, Kolmogorov (K-systems), Anosov and Bernoulli systems [4,5]. The latter three systems are the most unstable ones.

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*the measure is not defined (cf. with difficulties of definition of measure for the space of cosmological solutions [3]). The independence of typical properties of these approaches once more demonstrates its universality.

Anosov systems (flows) are characterized by an exponential instability of trajectories, are isomorphous to the Bernoulli systems, are ergodic, possess mixing of all degrees and K-property [6]. A well known example of Anosov systems is the geodesical flow on a closed Riemann manifold of negative curvature; the two-dimensional curvature in the direction of the velocity of the geodesic u and the arbitrary vector v

$$K_{u,v}(x)=\frac{\langle R(u,v)u,v\rangle}{\|u\|^2\|v\|^2-\langle u,v\rangle^2},$$

is strongly negative at every point of the manifold x ($R(u,v)$ is the Riemann tensor).

One of the most important properties of these systems is their coarseness (structural stability). As it is proved [6], any Anosov system is coarse in the Andronov-Pontryagin sense, i.e. for any small perturbation there exists a phase space homemorphism, which transforms the trajectories of an unperturbed system into trajectories of a perturbed one. Therefore, Anosov systems can be schematically represented as "spheres" in the $\Gamma^r(TM,\mu)$ space (Fig.1). Integrable systems or the systems with chaotic regions of zero measure are

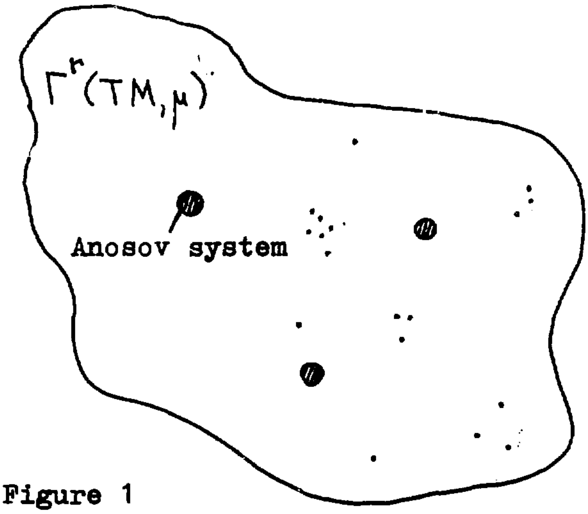


Figure 1

non-typical (have zero measure) and hence, in $\Gamma^r(TM,\mu)$ look like points; at small perturbation, when

$$\sum n_i \omega_i = 0 \ , \quad \sum (n_i)^2 \neq 0 \ ,$$

chaotic regions do appear between the KAM tori.

All the remaining space of $\Gamma^r(TM,\mu)$ is filled by systems with shared phase space.

Thus, at arbitrary choosing a dynamical system must be typical, the possibility of choosing a point, namely, a non-typical or integrable system, is zero.

3. Typicalness of the Observed Universe

As it had already been mentioned by Poincare (1982), the problem of N gravitating bodies is non-integrable when $N \geqslant 3$. Therefore, the only integrable case remains the problem of two bodies - the Kepler problem.

In 1962, using topological considerations, Arnold discovered a new mechanism of instability - (Arnold) diffusion, occuring for any small perturbations of systems, including integrable ones, when $N \geqslant 3$ [2]. Just due to Arnold diffusion the Solar system cannot be stable forever (irrespective whether it satisfies the conditions of KAM theorem at present or not). Some day the planets have to fall onto the Sun or fly away; however, the time of that instability, apparently, much exceeds the cosmological time scale (see [7,8]).

The dynamics of gravitating systems becomes rather complex when the particles' number N increases.

The investigation of statistical properties of systems of N gravitating bodies carried out in Yerevan Physics Institute, show that these systems can possess properties of the highly unstable systems described above [9-11] . So, it was shown that spherical and close systems (e.g., elliptical galaxies) are exponentially unstable ones, like K-systems, with the characteristic time of collective relaxation being much smaller than the binary relaxation time scale (cf. [12]): the former yields of $\sim 10^8-10^9$ years for globular clusters and elliptical galaxies, and $10^{10}-10^{12}$ years - for the galaxy clusters. These results solve the Zwicky paradox for these classes of objects.

As a result of strong instability several global properties of spherical systems (density run by radius, velocity distribution, etc), evidently, do not depend on the initial conditions of the system (coordinates and velocities of each star) and are determined by its dynamics. On the other hand, there exist properties strongly depending on the initial conditions; e.g., two now close stars could be highly departed at a small change in those conditions.

Disk systems (spiral galaxies) are more stable: the motion in the disk plane is mixing, while the velocity field is stable. In ref. [10] in hydrodynamical approximation, the characteristic time scale of that mixing was calculated, being equal to the $\frac{2}{\pi}$ part of the rotational period of the Galaxy or ~ 1.3 10^7 years for the Solar vicinity. It also removes the old contradiction between the observed picture of stellar motions and theoretical considerations.

Thus, spherical and disk systems being one and the same

6N-dimensional dynamical systems, are correspondingly staying in chaotic (with negative two-dimensional curvature) and more regular phase space regions. Hence, in ref. [10] a conclusion was made on different origins of elliptical and spiral galaxies following also from other modern considerations.

The analysis of the relative chaos of other N-body configurations shows, that, say, the systems with massive centre are more unstable than the homogeneous ones; systems with rotational moment are more regular than those without moment, etc [11]. The role of the hidden mass in this question was also made clear [13]. Without going into technical details, we only mention that in view of impossibility of application of the earlier known criteria (via calculation of Lyapunov characteristic numbers, Krylov-Kolmogorov-Sinai (KS) entropy, etc) in ref. [11] a new method was used based on the estimation of Ricci curvature in the direction of velocity in configurational space

$$r_u(s) = \frac{R_{ij}(s)u^i u^j}{\|u\|^2}\,; \quad i, j = 1, \dots 3N.$$

Thus, the observed Universe "consists" of exclusively typical systems (including highly unstable ones), there are no integrable systems.

4. On the Properties of Cosmological Solutions

The expansion of the observed Universe is explained in the framework of General Relativity, where, as it was proved by

Penrose and Hawking, the singularities are inevitable. This fact ever more differentiates between the cosmological problem and those considered in previous section, so far as the questions of initial (boundary) conditions of classical phase (i.e. determined by equations of General Relativity) remains open until the construction of quantum gravity.

In accordance with the conventional viewpoint that General Relativity can be the low energy approximation of a more general theory (maybe superstrings), Hawking assumed that semiclassical approximation of quantum mechanical path integral with Einstein action can unambiguously give the boundary conditions of the present classical phase - the ground state of the Universe [14-17].

The probability for a quantum state of the Universe with topology S, metric h and matter field configurations ϕ is represented by the path integral [15,16]:

$$P[S,h,\phi] = \int_C DgD\varphi\, e^{-I[M,g,\varphi]},$$

where C is a class of all oriented compact Euclidean 4-manifolds (with 4-metric g and matter fields φ), for which there exists an insertion ι, satisfying the following conditions:

1. $\partial M = \emptyset$,
2. $\iota S \subset M$,
3. $\exists M_+, M_-;\ M = M_+ \# M_-;\ \partial M_+ = -\partial M_- = \iota S$,
4. $\iota^* g = h$,

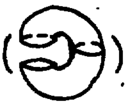
5. $\varphi_{1S} = \phi$.

Here $\#$ indicates operation of the connected sum of the manifolds; i^* is the differential of mapping i ; I is the gravitational action.

The probability $P[S, h, \phi]$ is the square of the Universe wave function $\psi[S, h, \phi]$ which satisfies the Wheeler-DeWitt equation in the superspace.

The approach based on this "no boundary" condition was applied mostly to minisuperspace models of homogeneous, isotropic Universe and led to results enabling to explain several main properties of the observed Universe [12,13]. For instance, the existence of inflationary solutions is shown (it is not clear, however, how general they are due to the mentioned difficulties of definition of measure in the space of cosmological solutions [3]. And hence, the homogeniety, isotropy, flatness, etc. of the Universe can be explained.

One can also imagine the possibility of mixed quantum states of the Universe described by the Hawking-Page density matrix [17,22] , which can be represented as*

$\rho(S,h,\phi;S',h',\phi') = \rho_0($  $) + \rho_1($  $) + \rho_2($  $).$

The ultimate test of correctness of any boundary condition (which cannot be derived from some other principle), as Haw-

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[*] In ref. [23] a model of topology quantum change of the Universe is considered, which allows to differentiate between the pure quantum states and the mixed ones.

king emphasized, is "whether it enables one to make predictions that agree with observations" [16] . In this relation it is worth while noticing that according to the widely adopted viewpoint just special boundary (initial) conditions are required to explain the mentioned global properties of the observed Universe (see, e.g., ref.[21]).

The "no boundary" condition means to impose boundary conditions on the wave function of the Universe on Cauchy surface in the Wheeler-DeWitt suparspace. The dynamical equations determining the change of ψ (i.e. evolution of the Universe - its expansion, inflation, etc) is the Wheeler-DeWitt equation. Hence, the investigation of geometrical properties of the superspace can expose the properties (including typical ones) of cosmological solutions. The problem of geometrical properties of the superspace was originally raised by Wheeler already in the 60-ies [24] and, in general, appears to be an extremely complicated one.

In [25] the superspace W was studied on hyperbolicity property in case of n-metric g_{ij}

$$G^{ijkl} = \frac{1}{2} g^{1/2} \left[g^{ik} g^{jl} + g^{il} g^{jk} - 2 g^{ij} g^{kl} \right]; \; i,j,k,l = 1,\dots,n,$$

$$G_{ijkl} = \frac{1}{2} g^{-1/2} \left[g_{ik} g_{jl} + g_{il} g_{jk} - \frac{2}{n-1} g_{ij} g_{kl} \right].$$

For this metric of the superspace the following relations are fulfilled (cf. [26])

$$\bar{R}_{AB} = -\frac{n}{4} \bar{G}_{AB} \; ; \; A,B = 1,\dots,\frac{n(n+1)}{2} - 1.$$

$$\bar{R}_{AB\underline{C}\underline{D};E} = 0 .$$

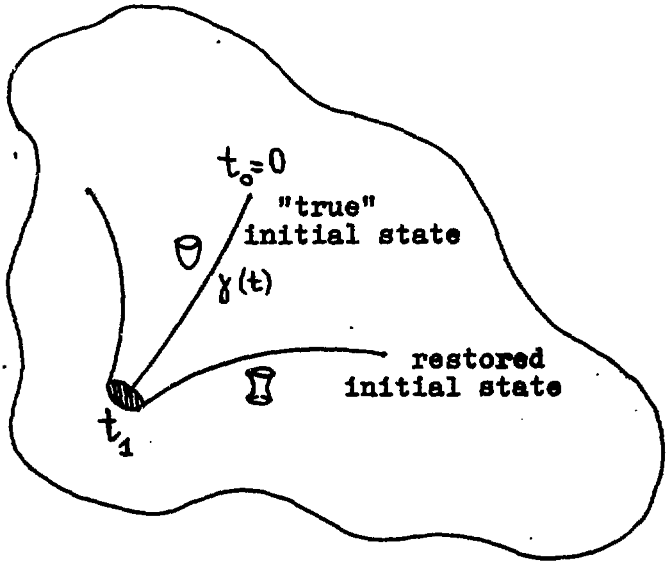$t_o=0$
"true"
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Figure 2

Considering the behaviour of close geodesics in that region of the superspace for the Jacobi equation

$$\nabla_u \nabla_u z + \tilde{R}(u, z)u = 0$$

(z is the vector of divergence) the following solution was found [25]

$$z^a_i(t) = X^a_i \exp\left[\pm(-\lambda_i)^{1/2} t\right],$$

where X_i is the eigenvector of $K^a_b = \tilde{R}^a_{cbd} u^c u^d$ with eigenvalue λ_i :

$$\sum \lambda_i = \frac{n}{4} \neq 0,$$

which means the Lyapunov exponential instability and hence, hyperbolicity of the geodesic flow determined by the kinetic part of Wheeler-DeWitt equation. In a two-dimensional case one has a Lobachevsky space and the flow satisfies all conditions of Anosov systems except for the compactness.

Hypothetical inhabitants of the Universe described by these solutions would have no practical possibility to restore the initial conditions of their Universe, as the smallest inevitable inaccuracy of measuring would exponentially grow backwards in time. A loss of information about initial conditions took place: through every inaccuracy "circle" there an infinite number of trajectories pass and hence, an infinite number of initial conditions at $t_0 = 0$ lead to one and the same final (observed at "present" t_1) state (Fig.2) .

As shown in ref.[27] , for the special case of de Sitter metric and free scalar fields, the Wheeler-DeWitt equation has one and the same solution for almost arbitrary initial conditions.

The question of typicalness of dynamical systems in the whole superspace appears to be a very complicated one and requires a special consideration.

In order to emphasize that the instability (chaotic properties), discussed here as a typical property of cosmological solutions, differs in principle from those of models with chaotic inflation, etc. [28], we note that:

1. The chaos under consideration is a property of dynamical equations and not of initial conditions, and can occur in systems with absolutely regular initial conditions of Cauchy type;
2. The equations themselves are completely deterministic, i.e., they do not include fluctuation effects;
3. Dynamical equations (or systems of equations) can have a very simple form.

Finally, it is necessary to say that certain cosmological models, possessing chaotic properties, have been earlier investigated in detail [29-31] (e.g., there is a claim that the Mixmaster-Bianchi IX model is a K-system [32]).

5. Conclusion

Thus, is our Universe typical?

We know that the answer must be "yes" or "no" .

As we have seen, with respect to the surrounding us world governed by Newton law, the answer to this question is "yes".

For the Universe as a (3+1)-dimensional manifold with matter, there is no such unambiguous answer yet. If it is typical too, then its such global properties as homogeniety, isotropy, flatness and several others are, perhaps, a result of dynamics and not of spherical initial conditions, the restoration of which is practically impossible now. In this sense the situation is analogous to the "hair-falling" effect at formation of a black hole during the collapse. At the same time, there could have survived such properties ("hairs") of the Universe, which are just the result of special initial conditions. In this case an interesting problem of reconsideration of the antropic principle arises.

One can consider the dynamical chaos also as the third, after the quantum mechanical (uncertainty principle) and quantum gravitational (ignorance principle [33] , including the loss of quantum coherence [34]), channel of loss of predictability.

If, nevertheless, the Universe is non-typical, then even a more intriguing question arises: why it is non-typical? According to what principle?

Recall Einstein's words (as cited in ref.[35]): "What really interesting is whether God had choice in creation of the World". It looks like that God choice in defining Newton's Law of Gravity and classical mechanics.

Was there a choice in creation of the World?

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