MODERN COSMOLOGY

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1. COSMOLOGY AS A SCIENCE

It is a great honour to pronounce this lecture before the General Assembly of United astronomers of all the world.

In fact, the astronomers are really more united, than the representatives of many other sciences. Perhaps this unity is connected with the noble spirit of inquiry into the immense distant worlds, characteristic for astronomers. And of all the problems and all the systems investigated the biggest one is surely the Universe as a whole i.e. the topic of cosmology.

This branch of astronomy is the greatest challenge, one is always confronted with the danger of being captured by prejudices.

In the last decades the situation changed. At least cosmology has transformed into a respectable science, which it was not say 50 or 60 years ago.

There remain deep unsolved questions beginning with the very existence and/or birth of the Universe.

But there are also in modern Cosmology definite successes, there are achievements in the understanding of the Universe. The successes are due to the work of many people, they are due to an international collective effort.

In a talk in the Odeon, an ancient theatre of Patrai, Greece and also in this high-light paper it seems me unappropriate to give precise citations and to divide priorities. Therefore no names will be called except a handful of great men gone of us - Einstein, Hubble, Friedmann, Jeans, Planck.

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2. THE SOURCES OF THE SUCCESS

Before going to the actual results, three sources of knowledge and success must be mentioned, important as they are for the birth of modern cosmology.

The first obvious one is the development of observations, in the optical ground-based astronomy, in radioastronomy with its extreme sensitivity and high-energy radiation detection and measurement on space vehicles. We will see that it`s not only the increased sensitivity and precision, which counts, but also the actual wealth of observations which is important and brings new knowledge, leads to new generalisations.

The second source of cosmology is the physical theory. We use the classical theories of electromagnetism and the gravitation theory. The contemporary gravitation theory is, as well known, Einsteins general relativity. We use the quantum theory, especially the theory of atoms but also the quantum theory of radiation. Nuclear theory is ised and the theory of elementary particles and quantum field theory. To be honest, one must point that the needs of modern cosmology and fundamental physical theory are growing faster than the experimental knowledge. This leads us to use theories not yet proved.

Last but not least the success of cosmology is due to the morale courage of the scientists.

The very investigation of the Universe as a whole needs courage. Are the laws found in the laboratory, applicable to the infinite Universe? Is the Universe closed, finite in volume, but without frontiers?

The celestial sphere seems us to be an example of eternal rest, the rotation of Earth gives rise to periodical changes of day and night and of the seasons. All this leads our ideas toward a stationary picture. Even the genius of Einstein was first fascinated by the idea of a stationary Universe.

The more courage was needed to explore mathematically the idea of an expanding Universe: this is just what was done first by Friedmann in USSR and confirmed observationally by Hubble. Einstein adhered to the idea of the expanding Universe,but Friedmann died in 1925 unaware of the immense breakthrough done by his two short papers.

One really needs courage to imagine the Universe compressed in a nutshell and to remain faithful to the physical laws leading to such a seemingly absurd picture.

In the last few years theoretical cosmology evolves in two directions. One is the detailed investigation of the Universe around us, with the use of new mathematical ideas: catastrophe theory, fractals, percolation and with statistical approach.

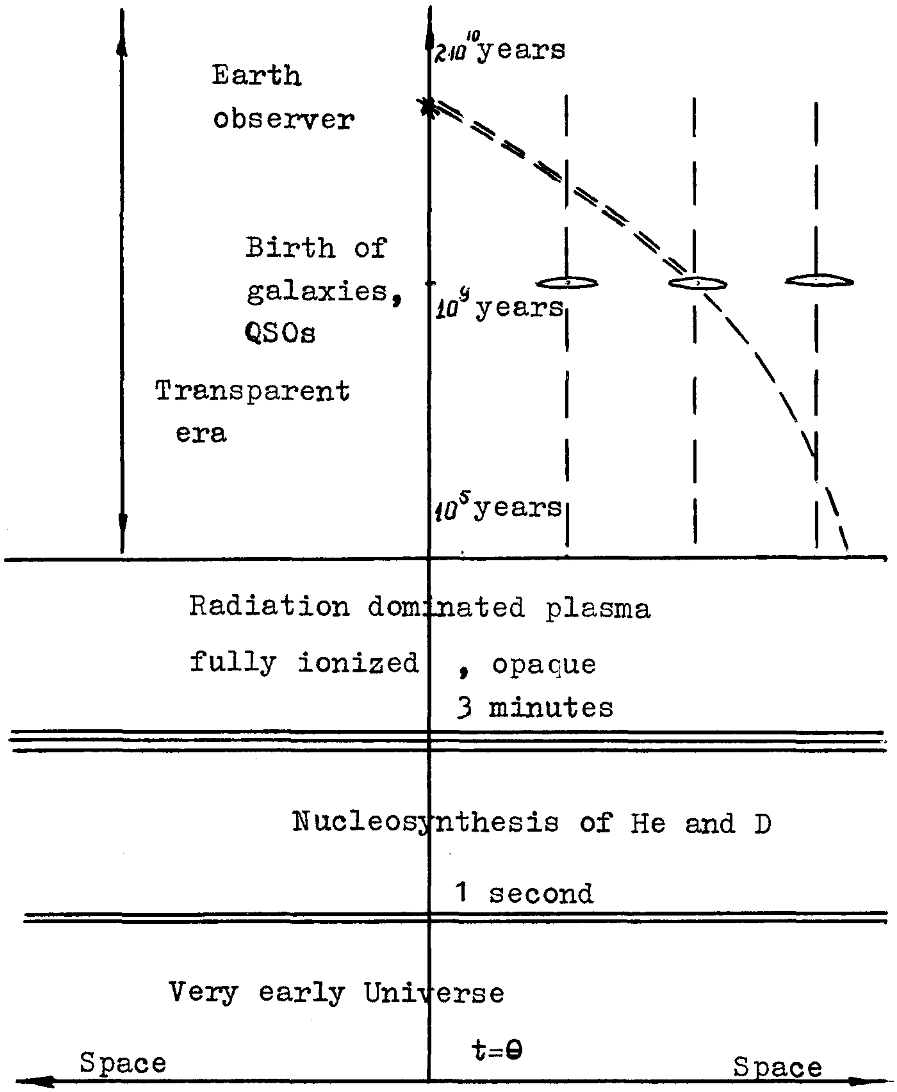

Figure 1

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The other direction goes more and more in the past, to the conditions never investigated in the laboratory. One uses physical yet unproven - and one needs courage to do it. But now cosmology receives a new role: it gives the unique possibility of verification for hypothesis concerning the extremely high energies, i.e. concerning the extreme situations. For many centuries cosmology will remain the proving ground for deepest physical ideas!

3. HOT BIG BANG AND PERIODIZATION OF THE EVOLUTION

The HBB (Hot Big Bang theory) is now established beyound any reasonable doubts. In this respect I would compare it with the statement that the Earth and other planets are rotating around the Sun. In both cases some of the contemporaries of the corresponding scientific revolutions (Copernicus statement of the central position of the Sun and XX century statement of HBB) were strongly against, claiming that the new ideas are absurd that they contradict to the common sence ets. But these isolated voices did not prevent the success of new theories...

Postponing the detailed discussion to later chapters, we shall use HBB to give the general picture of the Universe evolution and the division of evolution in qualitatively different periods.

It is shown on the figure 1. The vertical axis is the time, with arbitrarily distorted scale of course, because in a uniform scale it would be impossible to show periods of the order of fractions of second and those taking billions of years on one picture. The horizontal scale is for distance, or linear scale.

Going from the bottom to the top begin with the era of "very early Universe", corresponding to the time less than one microsecond. The energy of individual particles are larger than those obtained on most advanced accelerators. The mass density is much larger than the density of atomic nucleus. The very early Universe is a period where the physical laws used are a long-range extrapolation of the well-established theories, proved by the experiment.

Nevertheless the complete cosmological theory is impossible without understanding the very-very-early Universe: obviously it is needed as the initial condition for the subsequent stages. What is done now is the reconstruction of these initial conditions from observations made in the present time. So here two direction of investigation emerge. The more modest one reconstructs the initial conditions of the periods following very-very-early Universe using the observational datas. The more audacious direction wishes to explane the observed data from first principles applied just to the first state. Let's proceed further

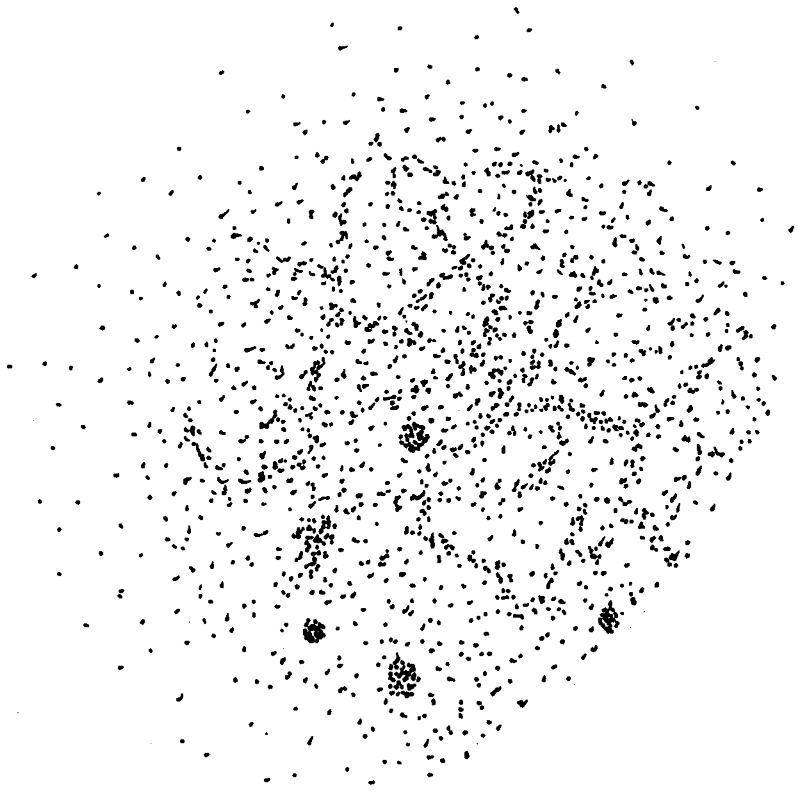

Figure 2

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in following the evolution. The next large part of the evolution is called "radiation dominated period" (See once more Fig.1). Beginning at microseconds, this era stretches up to some 100000 years.

Given the assumption of spatial uniformity and of expansion rate compatible with the present day situation we can calculate all processes occuring in the radiation dominated era.

The most important processes at the beginning of this era, in the first three minutes, are annihilation of antiparticles and nucleosynthesis. The observational confirmation of nucleosinthesis predictions is the greatest success, really a cornerstone of HBB. Thereafter slow cooling of the radiation due to expansion occurs. The third era begins when electrons are tied to protons, giving hydrogen aroms. As seen on the Fig.1 we call this era "transparent Universe". Schematically it is shown on the figure by the direct part of photons, i.e. light rays and radiowaves, coming to the observers sitting on the top of the vertical axis. In the previous era the part of the photon was visualised by the broken line, consisting of short pathes between successive scatterings. The Universe was opaque. Sometime inside the transparent era, the structure of the Universe emerged, including the birth of galaxies. It is a prerequisite for life and civilization.

Actually, in the narrative, we reverse the temporal order of events. We return to the order in which the scientific investigation proceeded, from above-from our vicinity and immediate past to eras more distant in time which are shifted to the end of our article.

4. THE TRANSPARENT UNIVERSE AVERAGED

The direct view of the sky, be it with naked eye or with telescope, is dominated by the neighbouring stars confined in the milky way, i.e. in our Galaxy.

Erase them you obtain a rather dull picture without sharp contrasts and/or preferred directions (Fig.2).

This means that the Universe is uniform on the average, taken on the large scale. There are no indications of a preferred position of our Galaxy, there are no definite, established indications of any preferred axies.

The counts of distant radiogalaxies, X ray sources and quasars are supporting the spherical symmetry of the distribution of all these objects around the observer. With much better precision the spheric symmetry is established for CBR (Cosmic Background Radiation). Obviously if one discards the egocentric idea of the special position of the earth, the spherical symmetry (isotropy) means actually uniformity on the corresponding agent, be it quasars or galaxies or

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CBR.

The expansion of the Universe is proved by the redshift of distant objects. The linear dependence of recession velocity on distance (Hubble law) is proved. This law is consistent with the persistence of density uniformity, it is contained in the Friedmann theory of expanding Universe. The quantitative situation is somewhat complicated. The first determination of Hubble constant was given by the author of the law with three figures but it was in error by a factor 5 or 10.

The expansion rate is tied with the age of the Universe: the first simple guess is to take the distance of some object and to divide it by recession velocity. The law $U=Hr$ leads to $t=r/U=1/H$. The Hubbles first figure has given $t=2\cdot10^9$ years which was in flagrant contradiction to the geological age of the Earth ($4,6\cdot10^9$ years), not to say about globular clusters age ($10\div17\ 10^8$) or cosmochronology giving $8\div13\cdot10^9$ years. The new estimations of Hubble constant remove the contradiction, but still the delate between $H=50$ km/sec Mpc and $H=100$ km/sec Mpc is going with excitement.

The difficulty is connected with the determination of distance which goes through many intermediate steps. A russian song says about love's explanation: this is a thing too important to be done through intermediaries...

Perhaps the same principle is applicable to distance determination. There is a proposal to use the hot ionized gas clouds in distant clusters of galaxies in order to obtain direct distance determination.

It's spectra gives the temperature of electrons. The X-ray brightness depends at given temperature on the product of $n_e^2 R$, with n electron density, R the cloud radius. But the electrons are also changing the CBR spectrum, causing local temperatire drop in the longwave part of the CBR. The effect is proportional to $n_e R$.

Simultaneous accurate measurement of one cloud in X-ray and CBR can be used to determine both the n and R.

With R known we have a "standart stick". The clouds angular dimensions are actually of the order of several minutes, easily measured - and they give us directly the distance if R is found independently. The method is applicable at distances of several thousands of megaparsecs corresponding to redshift of the order 0,5-1 and even higher which is important to get rid of local perturbations.

Archimedes discovering the wheel exclaimed: give me a point of support and I will overturn the Earth. So were the astronomers asking for a standart candle or a standart stick (stick and canle instead of the classical stick and carrot).

Thinking over the method described above, we can formulate that to the last end it is the classical radius of the electron which plays the role of the stick and the energy

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flux of CBR through the electron crossecrion which is the candle.

The next important quantity caracterizing the Universe is the average density. One can ask about the density of electrons (free and bound) heavy particles-baryons (protons and neutrons, free and bound in nuclei together), about the density of photons or neutrinos - all given by the average number per unit volume. One can ask also about mass density-gramms per centimenter cube due to every single component.

The averaging consists in taking the number of particles or the amount of mass in a volume much larger than that of single galaxies and clusters of galaxies and dividing the number or mass by the total volume, including the space between clusters. The number of particles of different kind and their ratios are important for the elementary particles processes including nucleogenesis. But the simple mass density, gramms per cubic centimeter, is even more important for the Universe as a whole. In General Relativity the curvature of the space depends on density. At densities less than a critical, the Universe is "open" which means infinite and it will expand forever in the future. If the density is greater than the critical, then the Universe is closed. This means that at every moment of time as a 3-dimensional entity it is finite, although without borders - just like the 2-dimensional surface of the sphere. In this case the future of our Universe is bound to be the general collapse following the expansion phase we are living now. The danger is not immediate, more than 20 billions years of expansion are granted, but it is important as a matter of principle.

The dependence of the future expansion or contraction upon the density is easy to explane in terms of Newtonian mechanics. Let us consider a spherical part of the Universe. Let its radius be R, its volume $V=4\pi/3R^3$, the mass inside the volume $M=\rho V=\frac{4\pi}{3}R^3\rho$. The gravitational potential due to this mass on its surface is $\varphi=GM/R=\frac{4\pi}{3}G\rho R^2$
The Hubble velocity on the surface is HR the kinetic energy of a unit mass $K=v^2/2=H^2R^2/2$. The mechanical behaviour-unlimited expansion or a turn to compression in future - depends on the ratio of kinetic and potential energy (the outside matter does not interfere). This ratio $\frac{4\pi}{3}G\rho R^2 : H^2R^2/2$ does not depend on R which cancels, it can be written as ρ/ρ_c where $\rho_c=3H^2/(8\pi G)$ =5 10^{-30} for H=50 km/sec Mpc. We are beginning with the density of CBR as one component filling the Universe. The photon movement is practically noninfluenced by the irregular gravitational fields of galaxies and clusters. The photons fill the Universe uniformly. Direct measurement of the CBR (3K) gives a flux of $1{,}3\cdot10^{12}$ photons per cm^2 per second per steradian. It is easy to convert this flux into number density, 500 photons per cm^3, of all energies and flying in all directions. With the average energy of a CBR photon 10^{-3}ev=1,6 10^{-15}

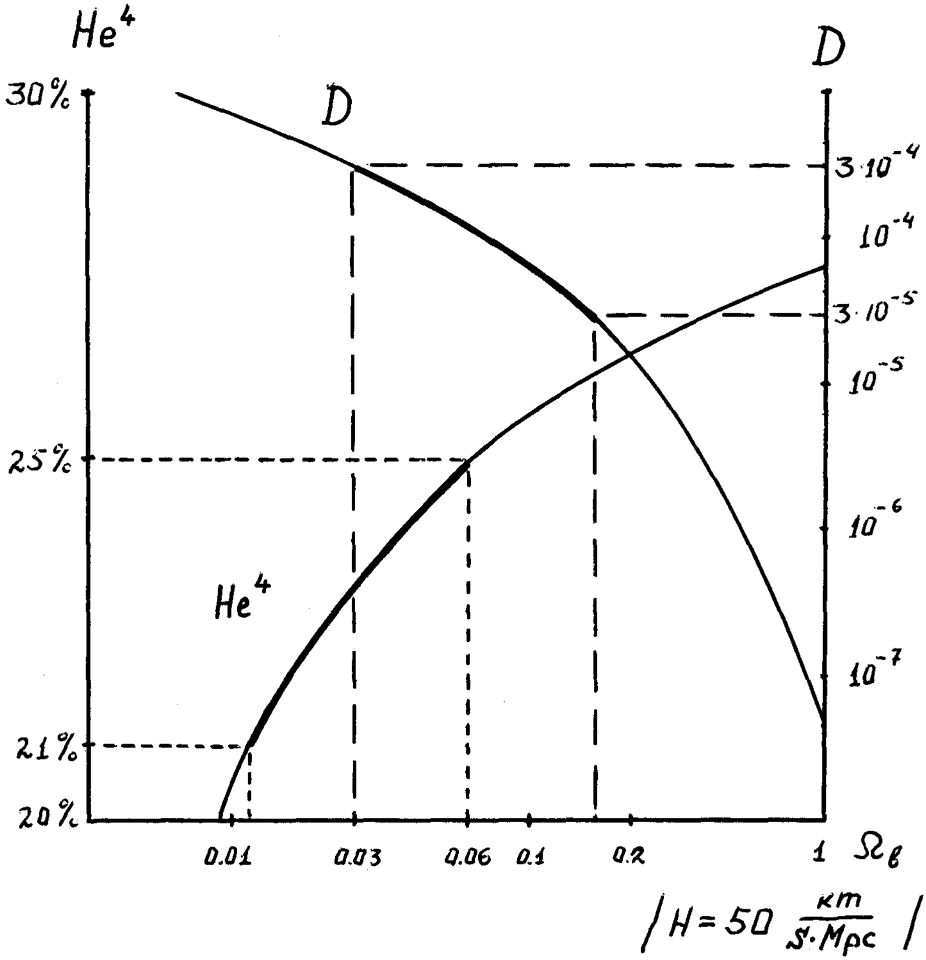
He4
30%
25%
21%
20%
D
D
3·10^-4
10^-4
3·10^-5
10^-5
10^-6
10^-7
He4
0.01
0.03
0.06
0.1
0.2
1
Ωb
/H = 50 km/(s·Mpc) /

Figure 3

ergs, its mass (actual mass, the rest mass being zero) is by $E=mc^2$, $m=1,6\cdot10^{-15}/9\cdot10^{20}=2\cdot10^{-36}$g.

The mass density of the photon gas is equal to 500 x 2 $10^{-36}=10^{-33}$gramms per cm^3. This gives a very small nondimensional Ω_r =0.002 (index r in Ω_r for radiation).

Now we return to ordinary matter . Obviously it is more important. The first estimates of baryon density were done by the method of classical astronomy, by star count. They have given low numbers, of the order of $10^{-31}g/cm^3$ to $3\cdot10^{-31}g/cm^3$, corresponding to 0.05-0.2 atoms per m^3 (meter not centimeter). This means that photons are much more numereous, but being so light they give the priority in mass density to baryons.

One always fears that there are dark stars not accounted for: low mass stars or stars died long ago transformed now in neutron stars or black holes. Perhaps the interstellar or intergalacric gas adds much? The detailed theory of nucleosynthesis gives the dependence of primordial helium-4 and promordial deuterium upon the density of baryons in the primordial plasma. It is shown on the picture. Taking the admissible $21\%<He<25\%$ and $2\cdot10^{-5}<D<3\cdot10^{-4}$. We obtain the baryon density range (Fig.3). The star count data are approximately confirmed by a quite independent method! This leads to nondimensional density of baryons Ω_b=0.02-0.10 which is much less than unity.

The first guess is that the Universe is open and bound to expand forever. But such a conjecture is premature. Many astronomical observations indicate the presence of some "hidden" mass. The mass of large clusters of galaxies seems to be much greater than the sum of masses of individual galaxies in the cluster. Other indications are discussed in the next part, concerning the genesis of large scale structure. This means that the question remains is the Universe open or closed! There is no easy way to answer this critical question.

What is quite certain now - the hidden mass must not consist of baryons. Good candidates for filling the Universe are neutrinos. Processes in the first second leave the Universe with neutrinos almost as numerous as photons: 75 neutrinos of each type and 75 antineutrinos per cm^3, with three types it makes 75 x 2 x 3 = 450 ν and $\bar{\nu}$ compared with 500 photons per cm^3.

Without rest-mass, the neutrinos would give a contribution to total density equal to the radiation contribution $\Omega_\nu \approx$ 0.002. This would not solve the hidden mass problem, nor would it change the total density.

But even a small rest mass of one type of neutrino - 25000 times less than the restmass of an electron - would change the picture drastically. It would be enough to close the Universe. A very strange Universe of course: with photons most numerous, neutrino giving go 5-98% of mass and normal matter being dethroned in number of particles and also as a mere 2% or 10% of total mass density. These ratios

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characteric for the Universe are very different from what is usual or Earth, in common practice.

But the modern physics is no more reluctant to give a small mass to neutrinos. There are confirming Moscow experiments, and there are also suggestions that some other yet undiscovered particles may play an important role. The confusion connected with hidden mass will remain for 5 or 10 years - honefully not longer. Perhaps it is important to stress onse more that the caracteristic results of Hot Big Bang theory concerning nucleogenesis, radiation-dominated plasma, electron and proton recombination - all this stuff is the rigid backbone of cosmology, it remains independent on the hidden mass troubles and neutrino rest mass problem.

5. THE STRUCTURE OF THE UNIVERSE AND ITS PROVENANCE

The Universe now consists of galaxies, unevenly distributed in space (compare the Fig.2 placed much earlier).

On the other hand, all measurements of cosmic background radiation (CBR) do not detect any spatial fluctuations. The theory of the early Universe, including nucleosynthesis and formation of CBR spectrum are also arguments for a highly uniform Universe. The general idea is that gravitational instability works.

There are some small perturbations of the density in the early radiation-dominated plasma but they are multiplied by the action of gravitational instability so as to give the observed structure now around us.

Specific to the Hot Big Bang, the action of the instability is prevented by the radiation pressure as long as we have to do with ionized plasma. At so called decoupling, the electrons are bound to protons in neutral atoms and they practically do not interact with radiation. The neutral gas is fully subject to gravitational instability. It`s to the period of transparent Universe the growth of perturbations is ascribed.

The pressure of the neutral gas is negligible. Of course this statement is not absolute: one can neglect the pressure because the wavelength of perturbations is large enough. Such is the heritage left by the radiation dominated era.

But with pressure neglected, the motion of the gas is very specific. Nothing prevents particles to come close and to form regions of high density.

In three-dimensional space one can compress the gas in every one of the three independent perpendicular directions.

It turns out that simultaneous strong compression on two or three axies is a very rate, nontypical event. As a rule there is one most dangerous direction. Compression along this direction leads to formation of thin sheets of dense material originally called pancakes. The next portions of gas colliding with the pancake are heated by the shock wave and stick. The pancakes grow in their plane also. As a matter of fact they are curved but it does not matter.

In the later stage the pancakes are into secting themselves. A complicated cell structure is formed with sheets of compressed gas surrounding voids with rarefied gas. An example of calculated density in two dimensions is shown on Fig.4.

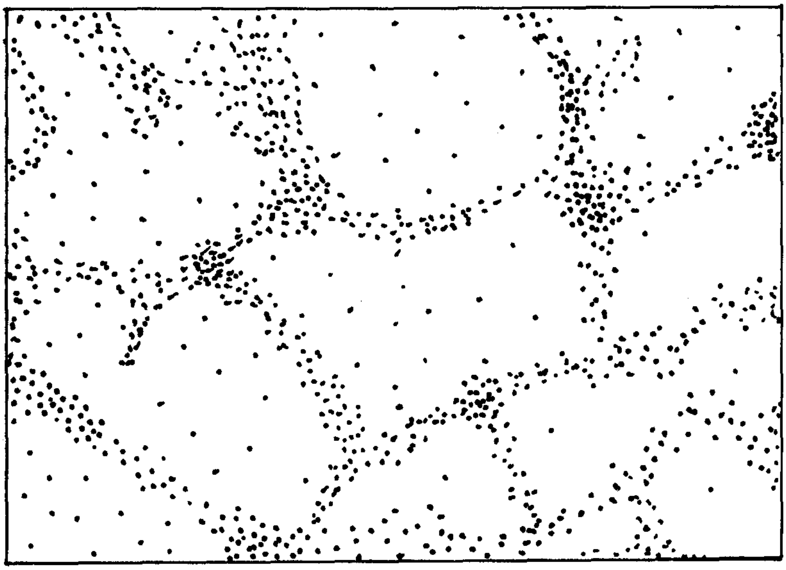

Figure 4

This picture is confirmed by numeratical simulation and also by deep mathematical analysis of the type of catastrophe theory and synergetics. Links are found between the gravitational instability and the geometrical optics of light retlected or refracted by random waves on water surface. One can observe directly in a sunny day pictures similar to those of the pancake theory on the bottom of a swimpool.

Obviously the galaxies must be born in the compressed gas. The sheets are unstable against further gravitational clustering. Still some cell-or net structure remains for a rather long time. To what extent does this theoretical picture correspond to the real world? A specific prediction of the theory is that in rarefied regions the gas is ionized and never condences in galaxies. This seems to be in accord with the discovery of large voids i.e. regions free of galaxies.

Just now in the last five years we have a better ans-

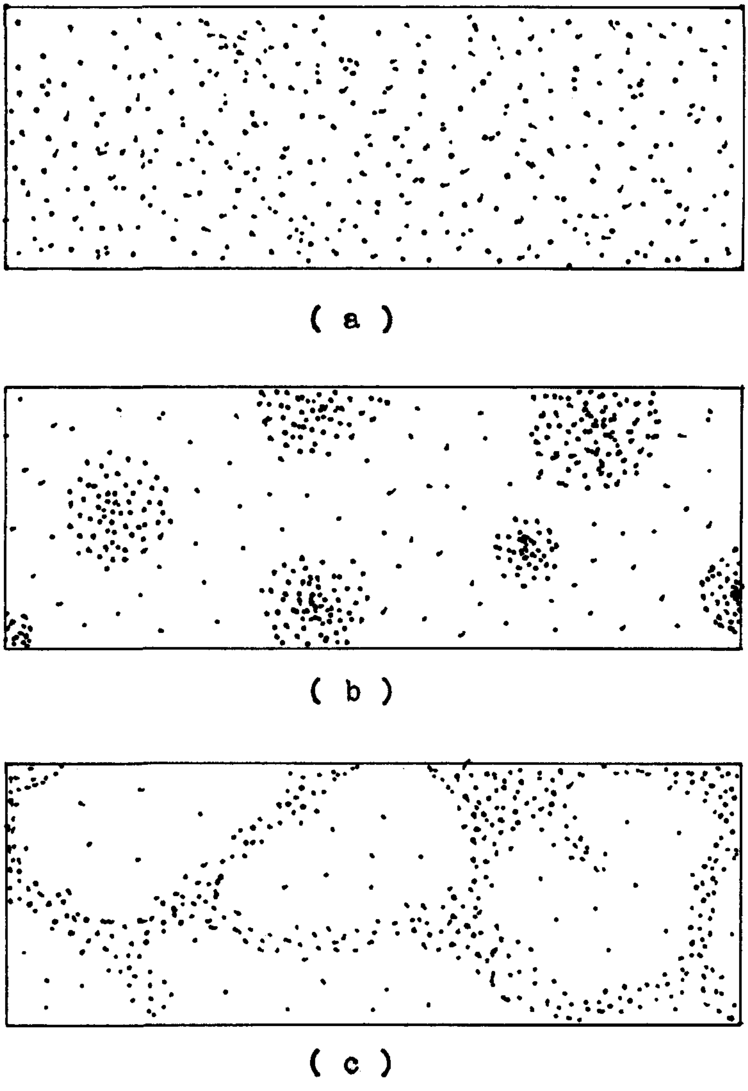

Figure 5

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wer than before. There is no reasonable doubt in the Hubble expansion law and there are approximately 10000 redshift measurements.

Converting redshifts into distances, one can obtain the true three dimensional structure of the Universe, not mere its two - dimensional projection. For a long time it was known that there is a positive correlation between galaxies positions correlation is observed also for. Near by to one object the probability to find nother is larger than the average probability normalized to the same volume. This type of investigation was extremely useful to determine the caracteristic scale of the Universes. Actually it gives 10 Megaparsecs applied to single galaxies and 50 Mps applied to rich clusters of galaxies.

But in connection with the pancake theory a new question arose - that of pattern recognition. It could be illustrated (in two dimensions) by the figures 5. The (5a) represents a statistical random distribution. In the next (5b) the points are brought together in clumps. On the third (5c) the points are arranged on strength. The correlation is zero on (5a) its just the definition of random distribution. It is positive on both (5b) and (5c). The correlation estimates are not suitable to distinguish (5b) and (5c).

But clearly (5b) and (5c) are very different. A criterium was found in the last (1982) year to differentiate between them without appealing to the naked eye, which could be suspected in some beas.

The application of the criterium to the actual dimensional distribution of galaxies in space favours our conclusion about preference of sheets and strings over clumps in the real Universe. It confirms the ideas of gravitational instability and its nonlinear behaviour on the late stages.

Of course it does not exclude the possibility of an important role played by another mechanism - Supernova explosions.

One can imagine the supernova explosion compressing the surrounding gas. This would lead to increased star formation. A massive star is evolving rapidly, in one million year from birth to explosion. New generation of stars explodes etc. Perhaps this would lead to a shockwave driven by the total energy of many stars. There are suggestions explaining the intergalactic empty voids by the interplay of such events.

But even in the case of an important role of explosions, the start must be given by gravitational instability for the formation of first compressed gas clouds and first stars. Now we are coming to a difficult and not yet solved problem.

There is a quantitative discrepancy in the simplemin-

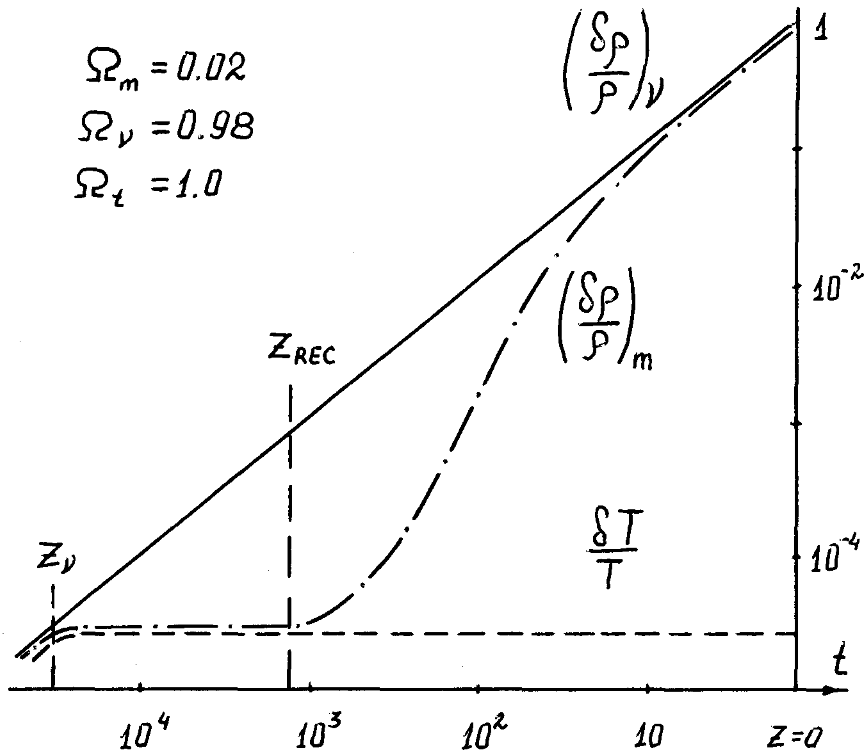

Figure 6

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ded advent of gravitational instability.

It is connected with the low density of matter, being between 0.02 and 0.10. In a Universe with low matter density one needs large initial perturbations, because the growth of perturbations is slow compared with the case of critical density $\Omega = 1$.

This leads to the necessity of large initial fluctuations and therefore of to the prediction of large fluctuations of the cosmic background radiation - in flagrant contradiction to the observations.

To go out from this stalemate one must assume some hidden mass, which is not baryons. This indirect argument for hidden mass seems me at least as strong as those from study of galaxies and clusters of galaxies.

So we are led again to the idea of massive neutrinos, taking 90 % to 98 % of the total mass of the Universe, we are led to the idea of a neutrino Universe .

The evolution of perturbations in a neutrino Universe, proceeds in following steps (Fig.6). The neutrinos with a mass say 25 electronvolts are nonrelativistic after temperature drops lower than 100000 Kelvins. There after begins the growth of perturbations of neutrino density. It is worth pointing that during a large part of time (temperature dropping from 100000K to 3000K) the plasma is still ionized and therefore quite unperturbed or perturbed only very slightly. After decoupling $p + e^- = HI$ the neutral atoms are falling into gravitational potential wells formed by neutrino density distribution. The normal matter density perturbation soon achieves the same level as neutrino perturbations. The radiation perturbations remain small, there is no more contradiction between the existence of structure and the measured yet upper limits for CBR perturbation. (a contradiction should emerge even in a neutrino Universe if the upper limit is pushed down to less than, say $\frac{\delta T}{T} < 3 \cdot 10^{-6}$ but up to now this did not occur, thanks God)

A very happy coincidence is the applicability of all our theories - pancakes formation, cell structure, cell or string disgnosis by percolation criterium, the prediction of voids - in the case of neutrino Universe.

The physical situation is rather different in the cases of matter - dominated Universe compared with the neutrino-dominated one. Novertheless many most general observable properties the same. Especially those conserning the geometrical structure. It is not a simple coincidence. It is depends on the gravitation being the prime mover in both cases.

The phYsicists must find the masses of neutrinos of different kinds and one must find methods to measure the enhanced concentration of neutrinos at least in our Galaxy. The amount of heavy elements in the voids is very important. And there is a lot of numerical work on the theory of gra-

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vitarional clustering, thermal processes, star formation and star explosion - primordial and second generation ets.

Some successes in the understanding of the large scale structure of the Universe must not overshadow the large amount of work to be done.

6. BARYON ASSYMMETRY OF THE UNIVERSE

There is matter in the Universe and practically no antimatter. This is a well established fact despite the intrinsic symmetry of the properties of matter and antimatter. The masses of the electron and positron are equal, and so are pairwise the masses of proton and antiproton, or those of neutron and antineutron. The electric charges of electron and positron are opposite in sign but equal in absolute value, so are those of protons and antiprotons.

Why is the amount of protons so different of the amount of antiprotons in our Universe? The idea that their amount is equal on the average, i.e. that there are large regions full of antimatter does not work.

So we know by observations that protons exist and antiprotons are practically lacking. We know by physical experiment that protons are stable even in cosmological time. Therefore the situation today in our vicinity, with the ratio of protons to photons approximately one to billion can be extrapolated safely to regions far away of us in space and in time. The hot big bang theory works with a plasma with $p:e^-:\gamma:\nu = 1:1:10^9:10^9$ (approximately) for all the period of nucleosynthesis, radiation dominance, formation of structure, galaxies and stars.

The situation changes for cosmological time of the order of microsecond and smaller, which is the very-very-early Universe (VVEU) of our periodization - see Fig.1.

At temperature equal or higher the restmass of the proton, there must be a lot of proton and antiproton pairs in equilibrium with photons and other particles. But the astonishing point is that there still must be a small overabundance of protons over antiprotons in order to obtain a small number of protons remaining after cooling and annihilation. Therefore the high temperature ratio is $p:\bar{p}:\gamma:\ldots = (10^9+1):10^9:10^9:\ldots$

It's even more strange than the composition togay. Now does Nature choose so an ugly ratio 1000000001 to 1000000000 for proton to antiproton ratio in the early era of temperature hisher than 10^{13} Kelvin degree?

The modern language of elementary particle physics is quarks. Every proton or neutron is build of three quarks , the antiproton of three antiquarks . This does not change the question: we have the same problem of 3000000003: 3000000000 ratio of quarks to antiquarks.

The modern answer is based on two statements: 1) the proton needs not to be absolutely stable. This principle is not a sacred cow. If proton decay was never observed before the eighties, this means that the decay probability is less than $3 \cdot 10^{-38}$ inverse seconds, 10^{-30} inverse years corresponding to lifetime gteater than 10^{30} years.

Perhaps the experiment will proven the proton decay in positron and energy just during the time when this article is written and printed.

What means such an unusually - large lifetime? The natural explanation is that the decay goes through an intermediate particle X and its mass is large. Namely

$$p = qqq = q + X = q + \bar{q} + e^{+} = \gamma + \gamma + e^{+}$$

(We do not elaborate all decay variants). This implies that the particle X has two channels of decay

$$X \begin{array}{l} \nearrow q + q \\ \searrow \bar{q} + e^{+} \end{array}$$

It is assume that X is heavy, the process of proton decay written above is sort of barrier process. The intermediate state with X is prohibited in classical physics. In quantum theory it is allowed, but the probability decreases if the mass of X increases. It turns out that the experimental limits on proton stability are consistent with the X - mass larger than 10^{14}Gev.

It is hopeless to produce such a particle on accelerator. It is equal to the largest energies sought out in cosmic rays - but the energy used in a collision of a cosmic particle with normal matter is much smaller. Therefore there is no hope to observe the X directly neither in laboratory nor in cosmic ray experiment. The passive experiment waiting monthes for proton decays in thousand-tons apparatus is the only possibility of indirectly studying the X. But remarcable is that modern theories are predicting X with needed properties, we know more than lower limit of X mass.

2) The second statement needed for cosmology is the lack of exact symmetry between particles and antiparticles. The masses are equal. But some branching ratios are not! And this was proved experimentally for some other than X particles two decades ago.

Now we must add these two bits of information and apply it to the VVEU (very-very-early Universe).

It was a paradise for physicists - so hot and plenty of very different very heavy particles. The processes very slow at room temperature (like proton decay) would go rapidly, in 10^{-38} sec at a temperature which prevailed at a cosmological time equal to 10^{-38}sec.

We cannot produce pairs of X and $\bar{X}$ - but the VVEU was full of them. During the cooling they decayed by ways

$$X \begin{array}{l} \nearrow q+q \\ \searrow \bar{q}+e^{+} \end{array} \qquad \bar{X} \begin{array}{l} \nearrow \bar{q}+\bar{q} \\ \searrow q+e^{-} \end{array}$$

The masses and total decay probabilities of X and $\bar{X}$ must be the same - but the branching ratios between the upper (pure quark) and lower (quark-lepton) decay direction can be different. Assume this ratio greater for X than for $\bar{X}$.

In this case when the cooling and decay ends, we are left with an excess of quarks over antiquarks. After X decay, the temperature is cold enough so that quarks and later protons are practically stable, except for mutual annihilation of particles and antiparticles. The excess of quarks turns out in the excess of baryons, and somewhat later in the pure baryons, with antibaryons annihilated. These are the baryons from which we and the Sun and all other stars are build.

In principle we expect that the ratio of baryons over photons will be calculated using the results obtained in laboratorium and physical theory.

Remember, that now this ratio is obtained from observations.

We are omitting many subtleties of the underlying physical theory. But one result of astronomical importance should be mentioned. In the simplest straightforward theory the ratio of baryons to photons must be the same everywhere - just because the physical constants are everywhere the same.

We used it already without mentioning explicitly in treating the perturbations. We admitted that proton density fluctuations are equal to photon density perturbations as long as they move together before decoupling.

The modern ideas favour - but dont prove finally - this picture.

7. INFLATIONARY PERIOD OF THE VERY-VERY-EARLY UNIVERSE

Let us postpone with the explanation of the intriguing term "Inflation", cursed in every day life but blessed in cosmology.

It is assumed that the equation of state - the relation between pressure and density was very pecular

$$p = -\varepsilon = -\rho c^2$$

with p pressure, ε energy density, ρ mass density, c light velocity. The energy density is assumed to be high and positive, although not connected with high proton density. The pressure is assumed to be negative. This

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is not so unusual as it seems at first glance: pressure is negative is some direction in a stretched solid. The liguids can also support negative pressure when surface tension and adhesion to the walls prevents the formation of bubbles.

But the combination $p=-\mathcal{E}$ is really unusual, never yet found experiment but prophecied by modern theoretical physics for some specific situations. A shall describe the importance and usefulness of this assumption for cosmology, leaving out the explanation how did the physicists (quite independently of cosmology) come to such unusual equation of state. The most important property is that such "situation" is selfconsistent, perpetuating in an expanding Universe with constant p, $\mathcal{E}$, ρ.

The density of matter is decreasing during expansion - and that is normal, because the volume increases.

But the density of "Situation" is constant: with negative pressure expansion leads to work being done by external forces and this work is exactly enough to compensate the increased during expansion. In mathematical (simple enough) terms the local first law of thermodynamics - energy conservation law-is written dE=-pdV with E=$\mathcal{E}$V. Obviously with p=-$\mathcal{E}$ we obtain $d(\mathcal{E}V)=\mathcal{E}dV$ consistent with $d\mathcal{E}=0$, $\mathcal{E}$ =const. If you ask, who is doing the work ultimately, I shall interpret the question in terms of global energy conservation of all the Universe. Take a closed Universe: its total energy is zero and it remains zero, independent of its radius and volume, as long as Einstein general relativity equations are fulfilled tying density, radius and expansion velocity[x)]

As a matter of fact the closed Universe with the radius changing as

$$R=\frac{1}{H_0}\,ch\,H_0t$$

is actually the solution with $H_0=\sqrt{8\pi G\mathcal{E}/3c^2}$, $\mathcal{E}$ and H_0 being constant. In this version the minimal radius of the Universe is of the order of 10^{-28} to 10^{-32}cm. What would say the people who called "the Universe in a nutshell" - several centimeter - to be a crazy outrage of common sence?

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x) The mystery of zero total energy has simple meaning: the sum of positive energies of the stuff (matter radiation or "situarion") filling all elementary volumes is exactly compensated by the negative energy of gravitational interaction between them.

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The law of expansion is peculiar: as we are going further from the minimal radius it tends to be exponential (Fig.7). So are process with constant inflation rate, and so was born the name. The expansion curve of normal Friedmann Universe is shown on Fig.8 for comparison ($R \sim \sqrt{t}$ or $R \sim \sqrt[3]{t^2}$).

The "situation" is something internally unstable. It is obvious mechanically - matter under strain can be broken. It is obvious thermodynamically: we assume high energy density to exist in spite of the Universe being cold, without temperature and radiation with zero or small entropy. The principle of maximum entropy shows that the transformation of "situation" into radiation giving high entropy is preferred, is irreversible.

Sure, we are not living in the "situation" - filled Universe. It is invoked as a first step, it has to transform into "half normal" radiation dominated Universe to be transformed ultimatery in matter (or neutrino) "normal" Universe we are living now. Therefore the main questions are 1) how long is dragged the inflationary era and 2) what is the exact mechanism transforming the "situation" in radiation.

These questions are yet worked out hardly by highbrow theoreticians. Known for sure now is that a rather long inflationary phase would be useful to explane the properties of the Universe as we observe them.

By long is meant $H_c t \gtrsim 70$ which would give $t \sim 10^{-36}$ seconds, not much usual standarts.

But the $\mathrm{ch}H_0 t \simeq e^{H_c t}$ would grow 10^{30} times up to a nutshell scale. The point is that the expansion velocity is proportional to the derivative of $\mathrm{ch}H_0 t$, which is $\mathrm{sh}H_0 t$. The potential and kinetic energy of a cut out part of volume behave like $\mathrm{ch}^2 H_0 t$ and $\mathrm{sh}^2 H_0 t$, their difference being constant. But this difference is now extremely small compared with potential and kinetic energy themselves. The two energies are wonderfully tuned - and this makes it possible to the Universe to expand further, up to the present day see once more the chapter on density and critical density above. The points that will occupy very far places in the sky now, are at a small distance when the inflationary expansion begins. Therefore we can imagine how the uniformity of the world was granted. The mass created during the inflationary regime and the process of transformation into normal radiation - dominated Friedmann Universe must give also the initial perturbations needed to create the observed structure. Still nobody has done a comprehensive theory of all these problems partly because the underlying fundamental physics is not finally settled yet.

The cosmological appeal of an inflationary, exponentially growing era is so strong, that it seems now to be a quest made by astronomy to theoreticians.

8. COMPLETE THEORIES, QUANTUM BIRTH, COSMOLOGICAL CONSTANT

We discussed the cosmological solution beginning as a closed world filled by cold stuff with large positive energy density and corresponding negative pressure $p_o = -\mathcal{E}_o$.

We were beginning with minimal radius $R = 1/H_o$, at momentary rest at $t=0$, $R = R_o \mathrm{ch} H_o t$ (Fig.7). The never sleeping inquiring guess asks what was before. One could extrapolate the solution to negative t up to $t = -\infty$ (dotted line on the left of Fig.7). But it is unphysical, because the stuff with negative pressure is unstable.

One has thought about a hot era before with normal equation of state $p = \mathcal{E}/3 \neq$ const and Friedmannian behaviour $R \sim \sqrt{t - t_\ell}$ (Fig.8). But this means that anywhere at t_ℓ the expansion velocity is so large, that classical general relativity is no more applicable.

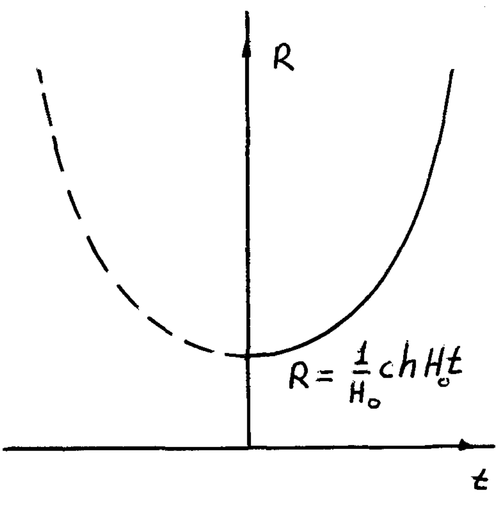

Figure 7

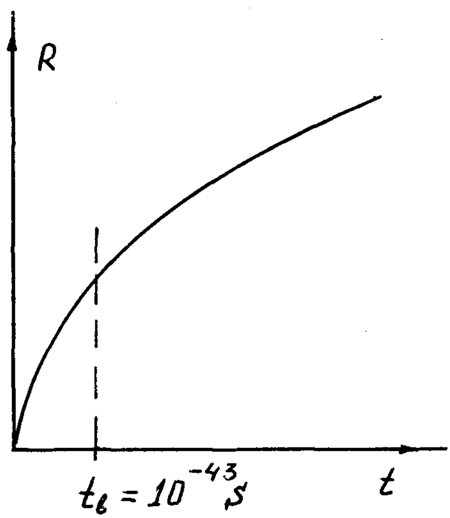

Figure 8

One calls this situation "Singularity". There were many attempts to avoid singularity. The dotted curve on Fig. 7, is an example. But another approach is to say, that perhaps the quantum general relativity will include the possibility of the quantum birth of the Universe, of its creation from nothing.

With all the uncertainty of predictions based on a non yet existing theory, two positive arguments could be used. The total energy of the closed world is zero. There is no

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strictly conserved baryonic charge. The newborn Universe can be closed and charge-symmetric, with baryon excess developed later.

So there are no conservation laws which would prevent the quantum birth of a closed Universe from nothing.

The other idea often mentioned is the antropic principle. Perhaps there are many Universes, but we are living in such one which is fit to life creation and evolution. This needs several billion years and makes the choice narrow of Hubble constant and matter density. But we are rapidly going here from science to handwaving.

One particular problem concernong not the VVE, but our neighborhood should be mentioned: the cosmological constant or, in other context, the lowest energy density level ε_{min} in flat space. In classical physics it seemed quite natural to take it zero. Not so in quantum physics. We know

$$|\varepsilon_{min}| < 10^{-10}\ erg/cm^3$$

but we know this only from cosmological observations themselve. Incidentally $\varepsilon_{min} = 0$ is not excluded. But we have no fundamental item demonstrates the weaknees of fundamental physics. Its greatness was exhibited on many occasion earlier. There are many other surprising things which can occur in principle, with the all-allowing ideas of modern physics. It is the formation of primordial blackhols in the processes of phase transition. Especially the latest one, connected with theories of weak interaction and electromagnetism, should be of the mass equal to the Earth mass. The modern theory does not exclude new yet unknown quasistable heavy particles. At least there is the question of magnetic monopoles - free charges of magnetic field. One needs new efforts in physics to obtain firm ground for cosmology. A peculiar point is that cosmical nucleosynthesis is practically unaffected by all these new ideas! It remains a backbone of HBB. Much is to be done, but some parts of cosmological knowledge is firm.

9. CONCLUSION

Let us return from wild speculations of chapter 8 to the whole subject of cosmology.

We see that cosmology really acquired the status of a respectable science. It has already found undeniable results, forming a hard backbone. Such is the status of the hot Big Bang theory.

It has definite, well formulated problems, waiting for systematical research work. Least but not last it has deep questions about the very origin of the Universe. This mesns that there are no danger of unemployment in cosmology.

The three sources of already achieved success in cosmology were mentioned at the beginning: observations, physical theory and moral courage.

To develop cosmology further we shall need the same: more refined observations, progress of physical theory and more courage.

The man and his cosmic ship - the Earth rotating around one of the many stars in one of many galaxies - it`s a very tiny fraction of all the Universe. Nevertheless we are studying and understanding more and more all the immense Universe, its past and its future.

The sincere faith in the possibility of studying the Universe, of discovering truth, the faith in Science - that`s what unites all of us, astronomers, scientists.

It`s just like the sincere faith in goodness, fairness, in human dignity, in the value of human life unites all the men of good will.