Astrophysics, Vol. 51, No. 1, 2008

COSMOLOGICAL BANG AS A CONSEQUENCE OF A SUDDEN CHANGE IN THE QUANTUM STATISTICS OF NUCLEAR MATTER

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An heuristic hypothesis is advanced about dominant Bose statistics during the transition from the radiation era to the matter era in the early universe. It is shown that large scale Bose condensation of matter from baryon-antibaryon pairs is possible, as a result of which a colossal amount of mass may accumulate in a volume of cosmic scale. At a threshold density of matter, the structural bosons decay into the fermions of which they are composed, so that a sudden change in the symmetry of the wave functions of the particles causes a jump from Bose-Einstein to Fermi-Dirac statistics. This involves a large scale phase transition with an enormous pressure jump which may show up as a cosmological bang at the beginning of the matter era.

Keywords: *cosmology: Bose-Einstein condensation: Big bang*

1. Introduction

Given today's knowledge of the physics of the Big bang model as the consequence of a presumed "spontaneous disruption of supersymmetry," in a grand unification theory, it is possible only to make qualitative assumptions regarding the individual stages of the evolution of the universe. In terms of the existing descriptive theory of the Big bang, the physical picture of the evolution of the universe is still not entirely transparent, both in its physical details and in its astrophysical applications [1-3]. Alternative approaches to understanding the picture of the evolution of the universe, even within a particular stage, in the present case during the transition from the radiation era to the matter era, as well as heuristic hypotheses regarding a possible alternative cosmological bang during the period of the matter era, are thus natural as another interpretation of the cosmological phenomena within the set of micro- and macrophenomena found in the large scale analysis, and may still have a right to exist.

In this paper an alternative cosmological model is proposed. A theory of a possible alternative cosmological bang in the matter era as a consequence of a sudden change in the quantum mechanical symmetry (and in the corresponding statistics) of nuclear matter is developed.

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Original article submitted June 25, 2007; accepted for publication November 14, 2007. Translated from Astrofizika, Vol. 51, No. 1, pp. 161-172 (February 2008).

 0571-7256/08/5101-0130

Based on the principle that a thermodynamic description of macroscopic systems is energetically favorable, a hypothesis is proposed according to which a Bose-Einstein ensemble is formed in the early universe from pairs of baryon and antibaryon elementary particles (possibly also leptons and antileptons) by the field of high energy γ photons with the subsequent formation of a Bose-Einstein condensate from these pairs. It is shown a spontaneous change in the quantum mechanical symmetry of the wave functions of the structural Bose particles and a transition from Bose-Einstein statistics to Fermi-Dirac statistics can show up as a thermodynamic phase transition accompanied by an enormous jump in the thermodynamic parameters, in particular the pressure. The possibility of a cosmological bang at the beginning of the matter era is predicted based on this phenomenon.

Mechanisms for the creation of electron-positron pairs by a strong radiation field in various astrophysical situations have been discussed in a series of papers [4]. These can be generalized, in principle, to the case of proton-antiproton pairs by γ photons from a "Dirac vacuum." The situation is different for neutrons and antineutrons: since they do not participate in electromagnetic interactions, the possibility of creating neutron-antineutrons at the very beginning of the matter era must be studied through intermediate physical mechanisms. Some examples of possible reactions of this type [5,6] initiated by primary photons and leading to final product neutrons and antineutrons include the following: (a) $\gamma+\gamma\rightarrow\nu+\tilde{\nu}$ or $\gamma+\gamma\rightarrow\nu+\tilde{\nu}+\gamma$, with the subsequent production of neutrons via the channel $\tilde{\nu}+p\rightarrow n+e^{+}$ (The channel $\nu+n\rightarrow p+e^{-}$ is suppressed both because of the scarcity of primary neutrons and because of a lack of neutrinos.) and, (b) the formation of muon pairs by γ photons in $\gamma+\gamma\rightarrow\mu^{+}+\mu^{-}$, which then can serve as an additional source for generating neutrons via the channel $\mu^{-}+p\rightarrow n+\nu_{\mu}$ for conversion of protons into neutrons.

Since interaction channels (aside from photon-photon) which might facilitate elementary acts leading to the redistribution of energy over the frequency of the photons, i.e., cause thermalization of the initial radiation field with subsequent "Planckization," do not exist during the radiation era, the early universe is without matter (i.e., with just the primordial radiation field) and, in all likelihood, lies in the lowest possible entropy state with the possibility of only small fluctuations, which could not populate all the possible energy microstates. Of course, a reliable determination of the temperature of the universe during the transition from the radiation era to the matter era, when the physical picture of this event is not entirely clear, would be difficult. Nevertheless, temperatures proposed for the early universe, on the order of $T\sim10^{10}$ K [1-3], and for the beginning of the nucleosynthesis period, on the order of $T\sim2\cdot10^{9}$ K, are, in principle, quite adequate to justify the basic ideas of this present paper. In fact, a monotonic rate of temperature decrease for the universe during the transition from the radiation era to the matter era, ending up at a temperature for the baryon matter of $T\sim2\cdot10^{9}$ K is consistent with the physical models of Refs. 7 and 8.

2. "Particle-antiparticle" pair production by γ photons

In terms of the standard mechanisms we assume that initially in the radiation era high energy photons exist and produce all types of pairs by the two-photon mechanism, in particular, baryon-antibaryon pairs. A discussion of whether these pairs form Bose-Einstein condensates, along with competing effects of superfluidity and superconductivity (the BCS theory), in the baryon matter as applied to the hypothetical nuclear matter can be found in Refs. 9 and 10 (and references therein). These papers form a basis for examining the possible intersection of similar "coherent states" in the BCS and

Bose-Einstein condensate theories. They also are used to justify and serve as qualitative illustrations of the physical conditions for the model proposed here in terms of experimental and observational data as viewed through the various theories.

For this model it is first necessary to estimate the order of magnitude of the concentration of the structural bosons. The scale length for quantum electrodynamical effects (in this case, the size of the pairs) is on the order of magnitude of the Compton wavelength of a proton,

$$\lambda_p = \frac{\hbar}{m_p c} \approx 2.1 \cdot 10^{-14}\,\text{cm}.$$

This scale corresponds to the spatial localization of the coherent states of the photons which participate in the processes of pair creation and annihilation; hence, the assumption of an initial structure of nuclear matter made up of structural Bose particles can be regarded as reasonable, to sufficient accuracy, up to concentrations such that no difficulties related to the structure of the pairs of baryons and antibaryons arise when they undergo scattering. Based on the condition of equilibrium between the original gamma photons, baryons, and baryon-antibaryon pairs, as well as the physical requirement that scattering between pairs cannot destroy them up to a certain threshold concentration, we shall estimate this limiting concentration. Here it is appropriate also to use facts that have been well established by experiments on the scattering of structural particles on one another. It is known that the physical approximation of "point" (or elementary) structural particles scattering on one another will not lose its descriptive rigor if the scattering amplitude is several times their sizes. Given this, for the average distance between structural bosons with an average pair size of $\lambda_p \approx 2.1 \cdot 10^{-14}$ cm can reasonably be taken to be $d_{p\tilde{p}} \approx 5 \cdot 10^{-14}$ cm. The permissible concentration of a Bose gas of structural baryon pairs is then

$$n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}\,\text{cm}^{-3}.$$

We now briefly examine the possible creation of electron-positron pairs. The production threshold corresponds to a photon frequency of $\gamma^{e}_{min} \approx 1.3 \cdot 10^{20}$ s^{-1}, so that we find the spatial localization of electron-positron pairs to be

$$\lambda_e = \frac{\hbar}{m_e c} \approx 3.86 \cdot 10^{-11}\,\text{cm}.$$

The Fermi structure of the electron-positron pairs can be neglected when they scatter on one another, as above, if their average separation is less than $d_{e^+e^-} \approx 9.2 \cdot 10^{-11}$ cm. This places an allowable upper bound on the concentration of electron-positron pairs of

$$n_{e^-e^+} \approx 3.1 \cdot 10^{29}\,\text{cm}^{-3}.$$

Hence, the concentration of baryon-antibaryon pairs in the early universe exceeds that of electron-positron pairs by more than a factor of 109. This result is physically acceptable if we take the baryon asymmetry of the universe and the electrical neutrality of the nuclear plasma into account. According to the data, the ratio of the baryon concentration to the concentration of relict photons is $\beta = n_B / n_\gamma \approx 10^{-9}$ (β is considered to be a cosmological constant). It is noteworthy that the relative difference in the amount of baryons and antibaryons (the baryon asymmetry of the universe) is determined by the same β parameter; i.e., $(n_B - n_{\tilde{B}})/n_B \approx n_B / n_\gamma \approx 10^{-9}$. This means that at the very beginning of the matter era, quasineutrality of the nuclear matter was mainly ensured by the antibaryons. Only in a later stage did electrons come into play to ensure neutrality of an *n*, *p*, *e*-plasma.

We note that a study of the equilibrium with respect to pair production and annihilation in a "photon-baryon pair" system [11] yielded results of the same order of magnitude for the dynamically equilibrium parameters (in particular, for the pair concentration) as obtained above by a physically much more intuitive, phenomenological approach.

3. Hypothesis about the primordial hierarchy of Bose statistics in the early universe

An adequate theoretical model of the state of the radiation in the radiation era would obviously be as close as possible to coherent photon states. This proposition makes sense, since in these states, the γ quantum fluctuations are so strongly suppressed that the "approximation of a coherent, squeezed representation" [12-14] is acceptable, in principle. These papers contained rigorous discussions of the physical representation of photons in both "purely coherent" and "squeezed coherent" representations, the interaction of photons with a boson system, and the establishment of a general equilibrium. For the present model, another fundamentally important result is that in coherent-squeezed representations, photons are created and annihilated strictly in pairs, in particular, during creation and annihilation of particles. Since photons are intrinsically neutral, during creation processes intrinsically neutral elementary particles or structural bosons with zero total charge should appear and vanish in each elementary volume of phase space.

We emphasize once again the fundamental physical idea of this hypothetical model: the primordial hierarchy of Bose statistics in the early universe and the fact that this assumption implies a macrosystem that is energetically favorable and has quasientropy.

Now, based on the above estimate $n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}$ cm^{-3} for the limiting concentration of structural bosons, we calculate the temperature of the Bose-Einstein condensate. Since the baryon gas already exceeds the threshold for relativistic behavior at this density, we calculate the temperature of the Bose-Einstein condensate using a relativistic, more intuitive formula (compare with Ref. 11)

$$\frac{N}{V} = \frac{gT^3}{2\pi^2 (\hbar c)^3} \int_0^\infty \frac{z^2 dz}{e^z - 1} = \frac{gT^3}{2\pi^2 (\hbar c)^3} \Gamma(3)\zeta(3). \tag{1}$$

Here c is the speed of light, $\hbar$ is Planck's constant, $g = 2s + 1$ is the spin degeneracy parameter, $\Gamma(x)$ is the gamma function, $\zeta(3) = 1.202$ is the Riemann Zeta function, and $k_B \equiv 1$ is the Boltzmann constant. The temperature of the Bose-Einstein condensate is given by Eq. (1) with the density equal to $N/V = n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}$:

$$T_0 = \left(\frac{2\pi^2}{2.4\,g}\right)^{1/3} \hbar c \left(\frac{N}{V}\right)^{1/3} = \begin{Bmatrix} 4.63 \\ 3.21 \end{Bmatrix} \times 10^{12}\ \mathrm{K}, \tag{2}$$

where the upper row corresponds to the singlet $\{\uparrow\downarrow\}$ spin state of the baryon pairs (g = 1) and the lower, to the triplet state (g = 3). Since a comparatively higher temperature of the Bose-Einstein condensate indicates a greater probability of its realization, the singlet state is more energetically favorable than the triplet state.

For completeness, let us evaluate the possible destruction of the Bose-Einstein condensate owing to a drop in its temperature. If, besides the ground state $\varepsilon_0 = 0$, a bound state of baryon pairs with energy ε_1 can be formed, then the temperature of the Bose-Einstein condensate in that model will be

$$T_0^{\varepsilon_1} = T_0^{(\varepsilon=0)} \left\{ 1 - \frac{1}{3\zeta(4)} \cdot \exp\left[- \frac{\varepsilon_1}{k_B T_0^{(\varepsilon=0)}} \right] + \ldots \right\}. \tag{3}$$

The order of magnitude of the assumed excited state energy ε_1 can be estimated by analogy with photoproduction at nuclei, for which "giant resonances" with energies on the order of $\varepsilon_\gamma \sim 20 \div 25$ MeV have been found experimentally for light elements and $\varepsilon_\gamma \sim 13 \div 18$ MeV for intermediate elements. Taking even the smallest of these resonances for the energy ε_1, it is easy to confirm that the Bose-Einstein condensate temperatures T_0 and $T_0^{\varepsilon_1}$, obtained from Eqs. (2) and (3), do not differ at all.

4. Thermodynamic and hydrodynamic equilibrium

Assuming that the physical basis of this model is sufficiently justified, we can now proceed to examine the major cosmological consequences of this theory. In order to establish the primary picture of events in the initial phase of the matter era, it is sufficient generally to obtain some qualitative ideas about the distribution of primary matter and its scales. Of course, we do this first for a spherically symmetric model, in the newtonian approximation, using the equations of thermodynamic and hydrostatic equilibrium in the form discussed in Refs. 2 and 15. These equations have to be supplemented by the equations of state for matter in the Bose condensate state and for radiation in a common thermodynamic equilibrium.

The pressure of a system of equilibrium photons is given by [11]

$$p_{ph} = \frac{4\sigma}{3c} T^4 \tag{4}$$

(σ is the Stefan-Boltzmann constant), which we shall compare with the pressure of the baryon-antibaryon Bose pairs. For simplicity and clarity, in calculating the total energy of the matter, we transform to the ultrarelativistic limit in the dispersion law for the particles:

$$E = \frac{gVT^4}{2\pi^2(\hbar c)^3} \int_0^\infty \frac{z^3 dz}{e^z - 1} = \frac{gVT^4}{2\pi^2(\hbar c)^3} \Gamma(4)\zeta(4). \tag{5}$$

Then, from the general definition of the pressure (F is the free energy),

$$p_{BEC} = -\left(\frac{\partial F}{\partial V}\right)_T = \frac{1}{3}\left(\frac{\partial E}{\partial V}\right)_T \tag{6}$$

for a Bose-Einstein condensate of baryon pairs, we obtain the following expression:

$$p_{BEC} = \frac{gT^4}{6\pi^2(\hbar c)^3} \Gamma(4)\zeta(4) = \frac{g\pi^2 T^4}{90(\hbar c)^3}. \tag{7}$$

A comparison of Eqs. (4) and (7) shows that the pressure of the photon system is negligibly small compared to the pressure of the matter; hence, we include only the pressure of the matter in the hydrodynamic equilibrium equations. A spherically symmetric distribution of matter made of structural bosons in the early universe can be described qualitatively under the assumption of convective equilibrium [2]. (The entropy per nucleon is constant over the entire configuration; this approximation is valid in superheavy stars, as well.) The equations of hydrostatic equilibrium without the corrections for general relativity [2,15] can be written in the form

$$\begin{cases} \dfrac{dm}{dr} = \dfrac{4\pi}{c^2} r^2 \rho_\varepsilon(r), \\ \dfrac{dp}{dr} = -\dfrac{G}{c^2}\dfrac{1}{r^2} m(r)\rho_\varepsilon(r). \end{cases} \tag{8}$$

Here G is the gravitational constant, $\rho_\varepsilon(r)$ is the energy density of the matter in the Bose-Einstein condensate state, and the function $m(r)$ represents the mass contained within a central sphere of radius r.

As noted above, the equation of state of a Bose-Einstein condensate in the form (7) describes a unique property: the pressure of the matter is independent of concentration-- this is a macroscopic consequence of the condensation of the bulk of the Bose particles in energy space. The theoretical treatment of Bose-Einstein condensates presupposes a constant temperature in the local sense, which is not entirely correct with gravitational compression on cosmic scales. Evidently, there is more justification in assuming that the pressure of the matter in the Bose-Einstein condensate state can react to a spatial dependence in a self consistent way-- owing to the gradient in the temperature $T(r)$ which arises because of compression. Then, the closed system of equations describing this model is generalized, and a position dependence of $p(r)$ of the form $dp/dr = (dp/dT)[dT(r)/dr]$ must be taken into account in the second of Eqs. (8).

The next refinement requires further theoretical justification: if there is no significant change in the pressure of the Bose-Einstein condensate during gravitational compression of an ideal Bose gas (the local nonidealness of the Bose-Einstein condensate is "absorbed" step-by-step), then it is necessary to reexamine the approximation of an ideal Bose gas because of the reduction in the average distance between the structural bosons, beginning with a certain value of the baryon pair concentration. This critical concentration is obviously of the same order of magnitude as the concentration $n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}$ cm^{-3} determined above, although a well substantiated approach would require a deeper analysis of the results of a numerical integration of the system of Eqs. (8) with various empirical equations of state for the Bose-Einstein condensate. This will be the subject of a later article, but here we restrict ourselves to the ideal gas approximation under the assumption that it is adequate to describe the nuclear matter in the Bose-Einstein condensate state, with the generalized dependence of $p(r)$ on $T(r)$, by a formula analogous to Eq. (7)

$$p_{BEC}(r) = \frac{g\,\pi^2\,T^4(r)}{90(\hbar c)^3}. \tag{9}$$

Let us dwell in somewhat more detail on the method for solving Eqs. (7) and (8). Depending on the gravitational compression, the hydrostatic forces, with no reaction from the matter in the Bose-Einstein condensate state, will accumulate mass up to a critical concentration at which the hydrostatic pressure is balanced by the thermodynamic pressure of the Bose-Einstein condensate, $p_{BEC}(r)$, at the same concentration. Then the scattering amplitude of the structural bosons becomes comparable in order of magnitude to the intrinsic size of the Bose pairs, the structural bosons decay into their constituent fermions, and an instantaneous transition from Bose-Einstein statistics to Fermi-Dirac statistics follows in parallel with the global change in the quantum mechanical symmetry of the wave functions. In the final stage, because the Pauli exclusion principle comes into play, the pressure undergoes a colossal jump.

It might seem that this pressure jump could be evaluated only after integrating the system of Eqs. (8); however, we can obtain satisfactory estimates based on theoretical considerations. Let us trace the physical picture of gravitational compression of matter in a Bose-Einstein condensate state and the transition from Bose-Einstein statistics to Fermi-Dirac statistics under two possible physical assumptions:

Process (A): during gravitational compression the buildup of matter to the critical density $n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}\,\mathrm{cm}^{-3}$ proceeds isothermally at $T \approx 10^{10}\,\mathrm{K}$, and

Process (B): gravitational compression to the critical density $n_{p\tilde{p}} \approx 1.9 \cdot 10^{39}\,\mathrm{cm}^{-3}$ proceeds with a monotonic variation in the temperature of the matter from its initial value $T \approx 10^{10}\,\mathrm{K}$ to a final temperature $T_0 = 4.63 \cdot 10^{12}\,\mathrm{K}$ at which the Bose-Einstein condensate state is destroyed.

In process (A), according to Eq. (7), the pressure of the Bose gas reaches

$$p_{BEC}^{T=const} = 1.26 \cdot 10^{24}\,\mathrm{Pa}. \tag{A.1}$$

In this "large-scale metastable state," the universe of baryon-antibaryon pairs is extremely unstable: the Bose-Einstein condensate of baryon-antibaryon pairs is immediately destroyed (in the final stage we get a two-component relativistic Fermi gas of free baryons and antibaryons) and, because the Pauli principle comes into play, the transition from Bose-Einstein statistics to Fermi-Dirac statistics causes a discontinuous rise in the pressure to

$$p_{F-D} = 3.36 \cdot 10^{35}\,\mathrm{Pa}. \tag{A.2}$$

Equations (A.1) and (A.2) determine the relative change in the pressure owing to the shift in quantum mechanical symmetry:

$$\frac{p_{F-D}}{p_{BEC}^{T=const}} = 2.27 \cdot 10^{11}. \tag{A.3}$$

In process (B), the analogous calculations yield

$$\frac{p_{F-D}}{p_{BEC}^{T=const}} = 2.27 \cdot 10^{11}. \tag{B.1}$$

and

$$\frac{p_{F-D}}{p_{BEC}^{T\neq const}} \doteq 5.8. \tag{B.2}$$

Equations (A.3) and (B.2) imply that the relative pressure jump is incomparably greater for isothermal compression of the matter. Equation (A.3) points to a colossal pressure rise with the sudden change in symmetry by process (A), that is, to the possibility, in principle, of a cosmological bang in the initial stage of the matter era. Note that the pressure jump is sensitive to the initial temperature of the universe. Thus, there is some astrophysical interest in further studies of the evolution of the universe in the early stage of the matter era with equilibrium initial temperatures on the order of $T \leq 10^9 \div 5 \cdot 10^8\,\mathrm{K}$. (See Refs. 6 and 7.)

In process (B), of course, problems arise in connection with the physical effects of energy release during

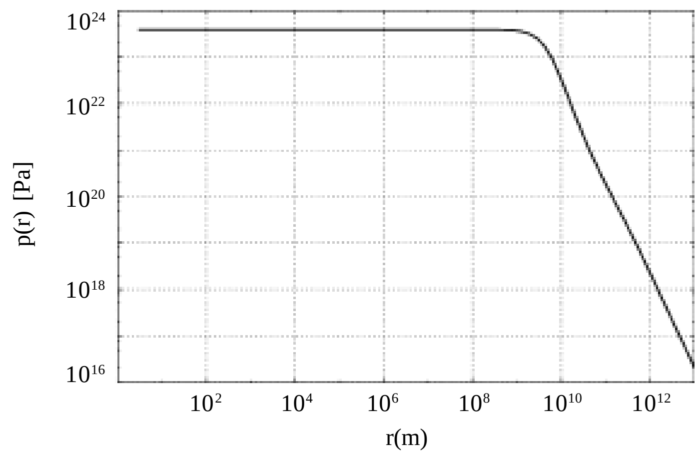

Fig. 1. The pressure $p(r)$ as a function of distance from the center of a spherically symmetric configuration. /key: ordinate: $p(r)$ [Pa]

gravitational compression, which require a rigorous study of the entropy equations and of dissipation effects and of all sorts of processes leading to instabilities and perturbations or conversion of the waves generated by them. These questions are beyond the scope of this paper and warrant a separate article. Thus, here we restrict ourselves to numerical integration of the system of Eqs. (8) in the isothermal approximation with an ideal gas equation of state for the Bose-Einstein condensate as a first approximation.

Figure 1 shows the variation in the pressure p(r) from the center of spherically symmetric matter in a Bose-Einstein condensate state. Finding the value r_{max} from the center of the configuration where the integration of the system of Eqs. (8) should be "stopped" and, thereby, determining the effective radius of the configuration, $R_{conf}^{eff} = r_{max}$, is equivalent to the validity of the Bose-Einstein condensate model in the "gas approximation." Physically, this requirement is equivalent to the condition $T >> T_{cr}$, where T_{cr} is the crystallization temperature of the matter. To estimate it we use data on the crystallization of the crust of neutron stars and take $T_{cr} \leq 10^8\,\mathrm{K}$ [16], so that we find the crystallization pressure

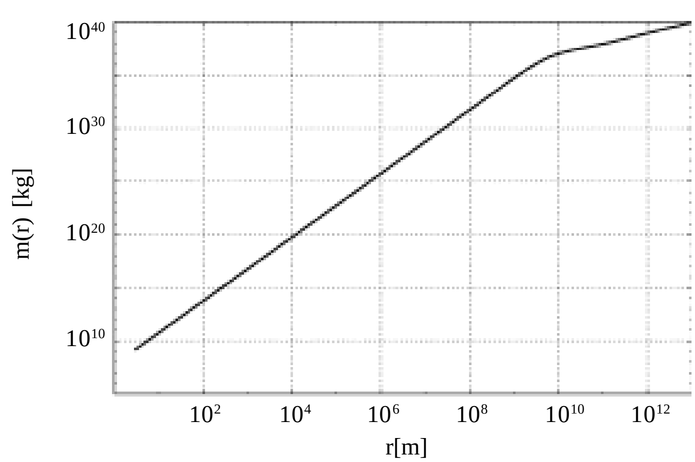

Fig. 2. The central mass $m(r)$ as a function of distance from the center of a spherically symmetric configuration.

$p_{cr} \leq 1.3 \cdot 10^{16}$. Thus, in principle we can assume that for $p > p_{cr}$ it is valid to treat the Bose-Einstein condensate in the "gas approximation."

Figure 2 shows the variation in the central mass $m(r)$. In accordance with the condition $p \geq p_{cr}$, the integration of Eqs. (8) is "cut off" at $r_{max} \sim 10^{13}$ m. This automatically determines the effective radius of the configuration, $R_{conf}^{eff} \approx 10^{13}$ m, and, based on Fig. 2, yields a self consistent estimate for the total mass of the configuration, $M_{conf}^{eff} \approx 10^{40}$ kg.

Naturally, the possible formation of such large scale configurations can occur in more than one local space, as well as over time scales. The proposed physical hypothesis and the corresponding model, as well as its astrophysical applications may have cosmological consequences in both small- and large-scale structures. After the cosmological bang, both comparatively "small-scale islands" of superdense matter that subsequently evolved into various kinds of stable celestial configurations, and all sorts of clusters or even associations of large-scale formations, might have been formed in the universe.

In conclusion, we note that the above values for the mass and radius parameters of spherically symmetric configurations "react" comparatively weakly to variations in the parameters of the equation of state for an ideal Bose-Einstein condensate.

A more complete study of this theoretical model in terms of the general theory of relativity and using some more realistic semiempirical equations of state for the Bose-Einstein condensate will be published in a future article.

I thank Academician D. M. Sedrakian of the National Academy of Sciences of the Armenian Republic for his interest in this work. This work was supported by ISTC project No. A-1308

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