HELIUM PRODUCTION IN THE DIFFERENT COSMOLOGICAL MODELS*

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The aim of the present report is to emphasize the role of the helium problem as the key one for different aspects of cosmological speculations. This is not surprising, because the processes which produce the helium and other elements in primordial matter take place during the first stages of the cosmological expansion of the Universe.

The theory gives three critical values of the He^4 abundance in pre-stellar matter, depending on assumptions about the behaviour of the Universe near the singularity. The three critical values are:

(1) practically no He^4 at all;
(2) about 25% of He^4 by mass;
(3) practically entirely He^4.

Although intermediate values of He^4 are in principle possible, the cosmological models permitting such values are highly improbable. It is obvious that the helium abundance is less than 100%, and that even rough estimates of whether the stellar matter consists almost entirely of hydrogen, or if it has a significant part of He^4, are of tremendous importance. The much-more-difficult determination of traces of primeval He^3, D, Li^6, would be of great help in making definite cosmological conclusions.

We shall consider here what are the implications of a knowledge of the helium abundance.

Firstly we recall the well-known facts:

Helium and other element production in the classic hot cosmological model has two stages. During the first one** ($t<1$ sec, $T_9>10$) the thermodynamic equilibrium between neutrons and protons is due to weak interaction:

$$e^+ + n \rightleftarrows p + \tilde{\nu}; \quad \nu + n \rightleftarrows p + e^- . \tag{1}$$

The characteristic time of reactions is

$$\tau_{wi} = 10^5/T_9^5 \tag{2}$$

for high temperatures. The equilibrium fractional n and p content is

$$(n/p)_{eq} = \exp(-\Delta mc^2/kT) = \exp(-15/T_9), \tag{3}$$

where Δm is the mass difference $(m_n - m_p)$.

* The references of the first works and some of modern reviews are given at the end of the report. We do not give references in the text as a rule.
** $T_9 \equiv 10^{-9}\,T(K)$.

De Jager (ed.), Highlights of Astronomy, 318–327.

https://doi.org/10.1017/S1539299600000241 Published online by Cambridge University Press

The temperature change with time during the expansion of a hot model is determined by

$$\tau_{\exp} \approx 10^2/T_9^2. \tag{4}$$

First, at very high temperature $T_9 > 10$, $\tau_{wi} \ll \tau_{\exp}$ and there is equilibrium, which is gradually shifted to small $n/(n+p)$. When τ_{wi} becomes equal to $\tau_{\exp}$ the thermodynamical equilibrium between n and p is no longer maintained. The reactions (1) do not have time to take place. The freezing of the n/p value takes place at $T_9 = 10$, corresponding to $\tau_{wi} = \tau_{\exp}$. One finds from this $(n/p)_{\text{frozen}} \approx e^{-1.5} \approx 0.2$.

During the subsequent stages at lower temperatures ($T_9 \approx 1$) the formation of light elements becomes possible.

The majority of the neutrons are captured by protons to give He^4 (very small amounts of D, He^3, Li^7 are also produced). If every neutron is captured, the He^4 abundance (by mass) will be

$$Y_{\max} = \left(\frac{2n}{n+p}\right)_{\text{frozen}} \approx 0.33\,. \tag{5}$$

Table I gives the results of detailed calculations for values of Y for present-day values of the matter density in the range $3 \times 10^{-28} \leqslant \varrho \leqslant 3 \times 10^{-31}$ g/cm^3, for a relic

TABLE I

Element production in canonical big-bang universes

ϱ (g cm^{-3})	N_γ/N_{bar}	Y	He^3	Li	D
3×10^{-31}	2×10^9	0.25	3×10^{-5}	10^{-9}	10^{-4}
3×10^{-28}	2×10^6	0.31	10^{-6}	10^{-6}	10^{-12}

radiation temperature of 2.7 K. (The ratio N_γ/N_{bar}, the relic photon number density relative to present baryon number density, characterizes the specific entropy of matter in the Universe). The first calculations were performed by Hayashi (1950) and Fermi and Turkevich (unpublished). The numbers in Table I are taken from the calculations of Wagoner *et al.* (1967). Figure 1 shows these results as a dashed curve. Thus the canonical theory of the hot Universe gives $Y \approx 0.25$, practically independently of the specific entropy (or, equivalently, upon N_γ/N_{bar}).

The canonical theory assumes (1) the Friedman expansion model; (2) charge-symmetry of leptons ($\nu = \bar{\nu}$); (3) slight but uniform baryonic charge asymmetry; (4) no unknown particles. We next consider the relaxation of these restrictions, because the chemical composition of primordial matter is extremely sensitive to the existence of large amounts of as-yet-unknown weakly and superweakly interacting particles and also to possible anisotropy in the early stages of expansion of the Universe.

First of all, let us suppose that there exist large numbers of unknown weakly interacting particles in the Universe. Excess heavy hypothetical particles or antiparticles

https://doi.org/10.1017/S1539299600000241 Published online by Cambridge University Press

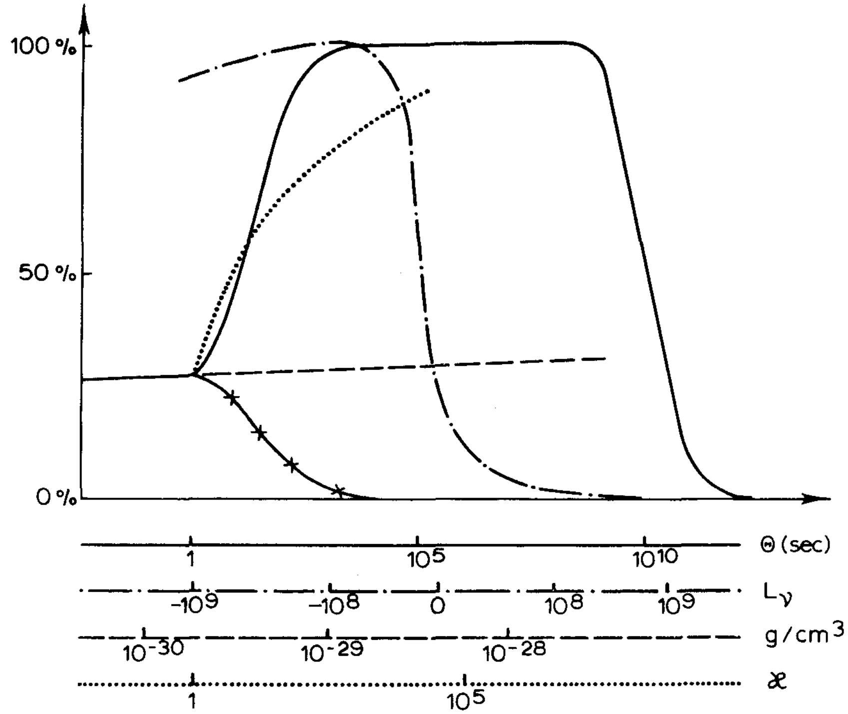

Fig. 1. The calculated helium abundance when various parameters are varied over their reasonable range. *Dashed line:* simple canonical hot universe, with varying density. *Solid line:* simplest anisotropic models: no mass flow. *Solid line with crosses:* anisotropic model with mass flow. See text. *Dotted line:* models with excesses of 'unknown' massless particles. *Dot-dashed line:* models with electron neutrino ($L_\nu > 0$) or antineutrino ($L_\nu < 0$) excess.

would remain at the present epoch and would result in a density great enough to be excluded by the presently observed value of the Hubble constant. On the other hand, particles with zero rest mass, such as neutrinos or gravitons, cannot be excluded by such density arguments. Fortunately the chemical composition gives us valuable information. Large numbers of particles with zero rest mass (e.g., gravitons) which do not directly take part in the reactions involved in He^4 production will influence the He^4 abundance indirectly through their influence upon the dynamics of the expansion of the Universe during the stage of nuclear processes in which He^4 is formed. We denote by μ the ratio of total matter density, including unknown particles, to the total energy density of known particles ($\gamma, e^+, e^-, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$) in thermodynamic equilibrium*;

$$\mu \equiv (\varrho_{\text{total}}/\varrho_{\text{known}}); \quad \mu \geqslant 1 .$$

* $\varrho_{\text{total}} - \varrho_{\text{known}}$ also includes not only the density of unknown massless particles but also the density of muonic neutrinos and antineutrinos if there is large excess of one or the other compared with the equilibrium concentration.

Then we have, instead of (4),

$$\tau_{\exp} = \frac{10^2}{T_9^2 \mu^{1/2}}. \tag{6}$$

We find T_{frozen} from (2) and (6):

$$T_9 = 10\,\mu^{1/6}; \qquad (n/p)_{\text{frozen}} = \exp(-1.5\,\mu^{-1/6}). \tag{7}$$

The dotted curve in Figure 1 shows the variation of the helium content with μ. One concludes that $\mu \gg 3$ is impossible because it will give $(n/p)_{\text{frozen}} > 0.3$. Almost every neutron will be incorporated into He^4 nuclei, so that the He^4 content will become much more than 40%–50%, which is in contradiction with observations. Thus, $\mu \leqslant 3$.

It should be stressed that this limit on the total density of zero-mass particles is much stronger than that which follows from considering their possible influence upon the dynamics of expansion and the present value of the Hubble constant. The last limit, the condition that expansion time of the Universe be more than the age of the Earth, gives only $\mu < 10^5$.*

The He^4 problem in a hot Universe is especially sensitive to the possible electron neutrino or antineutrino excess (that is, large specific leptonic charge $L_\nu = (N_\nu - N_{\bar{\nu}})/N_{\text{bar}}$).

If $L_\nu \neq 0$, the electron neutrinos have a strong influence upon the rate of reactions (1) and greatly change the n/p ratio at a given temperature: roughly $(n/p)_{\text{eq}} = (\bar{\nu}/\nu)^{1/2} \exp(-\Delta mc^2/kT)$, for $0.01 < \bar{\nu}/\nu < 100$. A secondary effect is that the moment of freezing is also changed, due to the influence of the particles upon the rate of expansion. It is obvious that a greater neutrino number will result in a much smaller (n/p) ratio and therefore a decrease of the He^4 content to zero. On the other hand, an increase of the number of antineutrinos will result in the growth of (n/p) and in an increase in the He^4 abundance up to 100%. The dot-dash curve in Figure 1 shows how the helium abundance depends on L_ν. It seems that a strong antineutrino excess is not compatible with the observation that primordial matter is mostly hydrogen, and a strong neutrino excess is compatible with only negligible He^4 abundance.

The He^4 production is also sensitive to assumptions about the anisotropy of the cosmological model during the early stage of the expansion of the Universe. The rate of change of the matter density with time in anisotropic homogeneous models is quite different from that in isotropic models. This leads to a different rate of the nuclear reactions in the expanding matter, and, as a consequence, to a different chemical composition for the primordial matter.

The most simple Heckmann-Schücking anisotropic models with flat comoving space (with critical matter density, $\varrho_0 = 2 \times 10^{-29}$ g/cm^3 at the present epoch) are

* Note that an enormous energy density of zero mass particles, $\mu \gg 1$, can lead to such a rate of expansion that the nuclear reactions of He^4 formation do not have time enough to take place and the He^4 content will be small. But in this case these particles would also have such a influence upon the present rate of expansion of the Universe as to be in contradition with the estimates of the Earth's age and with the Hubble constant.

characterized by one parameter: the moment of time θ which separates the stage of strongly anisotropic deformation from the stage at which the solution rapidly approaches the isotropic one.

Making canonical assumptions about particles, and without taking into account nonequilibrium processes with weakly interacting particles as was done in the first of Thorne's calculations, at the stage $t<\theta$ we have for τ_{exp}, in place of (4),

$$\tau_{\mathrm{exp}} = \frac{10^3}{T_9^3 \theta^{1/2}}, \tag{8}$$

and consequently

$$(T_9)_{\mathrm{frozen}} = 10\,\theta^{1/4}, \qquad (n/p)_{\mathrm{frozen}} = \exp\left(-1.5\,\theta^{-1/4}\right).$$

After this time, the neutrons are captured by protons and therefore the He^4 production in anisotropic models with $\theta \gg 1$ sec is 100%. If, however, the anisotropy parameter is very large, $\theta > 10^{11}$ sec, the expansion during the stage of neutron capture is so rapid that the capture does not have time to take place and the helium production is almost zero. The solid line in Figure 1 shows the abundance of He^4 as θ is varied. But in an anisotropic model the neutrinos acquire greater energy and an anisotropic momentum distribution after the decoupling of the neutrinos from the other particles. Reactions with these neutrinos lead to an increase of the entropy of matter. Formula (8) is valid only up to the moment τ_{frozen}. After this time the decoupling of neutrinos takes place. The entropy increases and the moment of isotropization, θ^*, does not coincide with θ. For example, for anisotropic deformation along the three axes $l_1 \sim t^{-1/3}$, $l_2 \sim t^{2/3}$, $l_3 \sim t^{2/3}$ we have $\theta^*(\text{seconds}) = [\theta(\text{seconds})]^{7/16}$. According to approximate calculations which do not consider the hypothetical weakly interacting particles (e.g., gravitons) and which make the simplest assumptions about neutrino properties, the anisotropy does not qualitatively change the solid curve in Figure 1. Consideration of the particles and neutrinos would not change the conclusions very significantly.

Estimates for more complex cosmological models with the curved 3-dimensional space for the density less than the critical value show similar changes. The qualitative picture as a whole will be the same.

Thus, the chemical composition of primordial matter gives strong limits for possible parameters of the simplest anisotropic models.

In the general case the matter moves as a whole. This gives at least one more parameter K in expressions similar to (8) and (9). For a simple cosmological model we have

$$\tau_{\mathrm{exp}} = \frac{10^{3K}}{\theta^{(1.5K-1)} T_9^{3K}}; \tag{10}$$

$$T_{\mathrm{frozen}} = 10\,\theta^{(1.5K-1)/(5-3K)};$$

$$(n/p)_{\mathrm{frozen}} = \exp\left[-1.5\theta^{-(1.5K-1)/(5-3K)}\right]. \tag{11}$$

The case $K=1$ corresponds to Expressions (8) and (9). Models with $0 \leqslant K < \infty$ are in principle possible.

Note that for $K>1$ the conditions of He^4 production are more favourable than for $K=1$.

When $K \to \frac{5}{3}$, the temperature of freezing also becomes infinite. When $K > \frac{5}{3}$ there is no equilibrium stage between neutrons and protons at all, and the helium production in primordial matter is determined by the initial conditions for a hot Universe.

Although all values of K are in principle possible, the most probable values are in the range $0 < K \leqslant \frac{1}{3}$. Such values of K correspond to homogeneous cosmological models, in which the uniform matter motion with relativistic velocity is obtained as a result of instability against the formation of such a motion (for details see Novikov (1970)).

For $K = \frac{1}{3}$ we have

$$(n/p)_{\text{frozen}} = \exp\left(-1.5\,\theta^{1/8}\right), \tag{12}$$

and for $K \to 0$

$$(n/p)_{\text{frozen}} = \exp\left(-1.5\,\theta^{1/5}\right). \tag{13}$$

One can see from these formulae that the helium production in primordial matter for the case of anisotropic models with matter motion will be less than 1%* if $\theta > (10^3\text{–}10^4)$ sec. The crossed solid curve in Figure 1 shows the He abundance.

We will not consider here the helium production in Steady-State and Brans-Dicke cosmology. In the latter case, the He^4 abundance can be small; see Dicke (1968).

Summary

Figure 1 shows the helium production in primordial matter as a function of the different parameters discussed above. The range of every parameter covers practically all possible values of the parameter. One can see from this collection of curves that only three values of Y may be considered as 'stable' with respect to variations of the parameters: $Y \approx 1$; 0.25; 0. Whenever values of the parameters predict $Y \approx 1$, these values can be ruled out from the present observations.

Most astronomers seem to be of the opinion that on the basis of He^4 observations in the solar system, in stars, nebulae and from stellar evolution calculations, there is a significant amount of He^4 in primordial material.

If future observations bear out this conclusion, then it will be strong evidence in favour of the hypothetical 'canonical' homogeneous isotropic hot model with no neutrino excess and no large amount of 'unknown' particles. Even if the expansion

* For every anisotropic cosmological model not considered here, the limits of the parameters are connected with observations of the isotropy of the relic background radiation. See the literature in the end of the report.

https://doi.org/10.1017/S1539299600000241 Published online by Cambridge University Press

were anisotropic in the beginning of the evolution of such a model, the anisotropy vanished as long ago as in the first second of the expansion of the Universe.

Appendix. The Possibility of Primordial Helium Observations

It is usually believed that about 90% of galactic matter has been reprocessed in stars. Therefore one needs to study the intergalactic gas in order to obtain reliable data about primordial helium abundance. The intergalactic gas is not detected as yet, and if it is at all its temperature will be high ($T \sim 10^5$–10^6 K). For such a temperature, the ratio He^+/He^{++} is 10–100 times more than the ratio H^0/H^+. Observations of absorption bands in ultraviolet quasar spectra will be hence the most convenient method of measuring the helium concentration in intergalactic space. It is analogous to the idea of Gunn and Peterson, who investigated the neutral hydrogen Ly-absorption line ($\lambda = 1216$ Å) in the spectrum of 3C 9. For quasars with $Z > 0.7$ the absorption band resulting from the red-shifted neutral helium absorption line at $\lambda = 584$ Å will be in a region available for observations (that is, unaffected by galactic H absorption at $\lambda < 912$ Å). For quasars with $Z > 2$, the absorption band connected with absorption line $\lambda 304$ Å of He II will be observable. The bands corresponding to hydrogen Ly-α and He II $\lambda 304$ might also be observed in emission. All such observations must be from outside the atmosphere, but the progress of orbital astronomical observatories suggests possible success in the very near future.

For the gas in the clusters of galaxies, it is possible to observe neutral He in intergalactic gas owing to absorption from metastable level $2\,^3S$, having the gigantic lifetime $\tau \approx 10^6$ sec (one can neglect the collisions of the second kind in intergalactic gas). Corresponding lines are $\lambda = 10830$ Å and $\lambda = 3889$ Å. The optical depth in a line depends upon temperature and may be as large as 0.1 for $\lambda 10830$. For $\lambda 3889$, the optical depth does not exceed one percent. One can try to find the same lines in an emission of clusters.

Important information about the chemical composition of primordial matter may be obtained from the radio frequency deuterium line ($\lambda = 90$ cm) and from observations of once-ionized He^3 ($\lambda = 3.5$ cm), as well as from observations of radio recombination lines of D and He^3.

Even the existing limits on the He^3 content in nebulae ($He^3/H < 4 \times 10^{-5}$), are useful for an analysis of different cosmological models (anisotropic, with a large lepton number). In anisotropic models, neutrinos acquire energy which is easily enough to produce breakup of He^4 nuclei. At this process He^3 and D are born. Even the breakup of 10^{-3} of the He^4 contradicts the upper limit to the abundance of He^3 as given by observations.

One also needs to keep in mind that observation of helium content in stars does not give reliable information about the chemical composition of primordial matter. Nebular abundances are also subject to changes due to the processing of gas into stars with subsequent gas outflow from stars into nebulae.

The existence of stars of like 3 Cent A, in which there is a small helium fraction, and in which there is more He^3 than He^4, is perhaps an indication of possible non-thermal processes in a stellar atmosphere. It suggests that a strong decrease of helium concentration relative to primordial matter has occurred. The other possibility is a gravitational diffusion separation of He and H.

Nucleosynthesis by stars within a galaxy can of course change the chemical composition of the gas inside a galaxy considerably. The decisive answer on the problem of the chemical composition of primordial matter will be the analysis of gas composition in the space between clusters of galaxies.

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DISCUSSION

E. Schatzman: Let us assume with Harrison (1968) that the present universe is made of an equal amount of matter and antimatter. Annihilation is supposed to take place for a long span of time, the final phase ending a little before the recombination time. During that low temperature phase, hydrogen annihilates according to the reactions

$p+\bar{p}\rightarrow$ annihilation products,

whereas alpha particles are broken up into pieces,

$\alpha+\bar{p}\rightarrow$ annihilation products $+(2n+p)$

so that hydrogen is finally destroyed at a different rate than helium. At the end of the annihilation process the helium abundance is determined by the ratio of the average σv terms, $\langle\sigma v\rangle_{p\bar{p}}$, $\langle\sigma v\rangle_{p\bar{\alpha}}$, and $\langle\sigma v\rangle_{\alpha\bar{\alpha}}$. With our present knowledge, we obtain $Y=0.3$, but this is very sensitive to the cross sections.

Presently, the reactions ($\bar{p}$, Be), ($\bar{p}$, C), and ($\bar{p}$, Al) are known, but not ($\bar{p}$, α). Possibly, the Serpukhov accelerator will soon lead to the study of $\bar{\alpha}p$ reactions in bubble chambers. Anyhow, the estimate of the $\langle\sigma v\rangle$ ratios is presently sort of an extrapolation. A slightly larger cross-section for α destruction would lead to a zero helium content for the universe. This is one of the possible tests of the matter, antimatter model of the universe.

R. J. Tayler: A student of mine, Dr. R. F. Carswell, has recently studied a wide variety of anisotropic cosmological models and has found that many of these can be shown to be irrelevant because of either

(1) too much anisotropy in the microwave background, or

(2) beams of intense directed neutrinos that would already have been detected.

Is there anyone here who is now happy about the problem of galaxy formation in the homogeneous big bang? (General silence).

P. J. E. Peebles: I would like to ask Dr. Novikov if the motions in anisotropic universes are 'turbulent' or systematic?

I. D. Novikov: In the anisotropic homogeneous models near the singularity, there is a contraction of the reference system along one axis (the x-axis say), and an expansion along two other axes. Pecular small velocities of matter as a whole along the x-axis must grow. The velocity of the matter motion becomes relativistic. This is uniform matter motion (radiation and ordinary matter together) as a whole, without turbulence but with a relativistic velocity. The law for decrease of energy density is $\varepsilon\propto t^{-\alpha}$, where $4\leqslant\alpha<\infty$.

J. Silk: It is well known that the primordial helium abundance is isotropic. Friedman cosmologies are not significantly affected by the local density enhancements, expected in a more realistic cosmology, which accounted for the formation of galaxies. However, temperature fluctuations can have a more important effect, at least in principle. This can be seen as follows:

One may regard He^4 as being formed in two stages. First, at $T\approx 10^{10}$ K, the neutrons are frozen in when the time-scale for neutron production first exceeds the expansion time. Subsequently, at about $T\approx 10^9$ K, the density has fallen sufficiently so that the neutrons can decay and form deuterium and helium. The frozen-in neutron abundance N_n is approximately $N_n/N_p=\exp(-Q/kT)$, where N_p is the proton density and Q the mass difference between neutron and proton. Almost all the neutrons end up in He^4 atoms. Hence, relatively small enhancements in temperature can produce significant reductions in the primordial He^4 abundance. For example, a 10% temperature fluctuation reduces He^4 by 30%, and a 20% fluctuation reduces He^4 by more than a factor of 2. The main restraint limiting this effect is that there be no significant reduction in the expansion time owing to the enhancement in the energy density. It is important to note that these fluctuations must be of small-scale ($\sim ct$ at 10^{10} K), corresponding to only $10^{-4}\,M_{\odot}$. Consequently, at subsequent epochs, damping occurs by photon diffusion and/or viscosity, but any primordial composition inhomogeneities are maintained. For these fluctuations to be significant over stellar or galactic dimensions, the temperature fluctuations must all be positive. Primordial vorticity would necessarily produce such fluctuations. It is necessary to assume that these vortical motions are present on scales of $\sim ct$ at 10^{10} K, over regions of galactic scale. The vortical velocity must be of order of the sound velocity in order to produce sizable reductions of the primordial He abundance. Variations in the primordial He abundance within our galaxy could possibly be related to spatial variations in the spectrum of primordial turbulence. Primordial turbulence, if present on large scales with similar strength, can also be used to explain the formation of galaxies and the origin of galactic angular momentum, according to the theory of Ozernoi and Chernin.

William A. Fowler: Are the fluctuations to which Dr. Silk refers a function of the spatial or the time coordinates during the early expansion?

J. Silk: The adiabatic temperature fluctuations needed depend on spatial coordinates in an arbitrary manner, and are simply an initial condition. However, vorticity fluctuations are frozen in the expansion at radiation-dominated epochs, and so the amplitude and spatial distribution can be specified independently of the epoch.

The time dependence of the temperature fluctuations is such that wavelengths less than the particle horizon oscillate as sound waves with constant amplitude. Wavelengths exceeding ct would increase in amplitude inversely with redshift; however, since dissipation occurs only on scales within ct, the primordial turbulence hypothesis would not predict any growing temperature fluctuations.

Novikov: Dr. Silk's idea is interesting, but I am afraid that temperature fluctuations can hardly lead to any significant fluctuations of helium abundance on the scale of even a single star, much less a galaxy.

One easily finds from Formula (5) that the helium abundance is

$$Y = \frac{2}{1 + 5 \exp\left[-1.6\,(\delta T/T)_{\text{frozen}}\right]}\,.$$

Note that the fluctuations in the formula above are *not* at a space slice ($t = \text{const}$), but rather are the fluctuations in the freezing temperature for the (n, p) equilibrium. For volumes larger than the particle horizon, δT_{frozen} is practically zero because of the independence of the evolution of such a volume upon temperatures of neighbouring volumes, and the expansion of the volume is at the hydrodynamic rate. For scales many times smaller than the particle horizon, the fluctuations oscillate and the average must be used.

Thus the temperature fluctuation effect can take place only on the scale of the particle horizon at the time $t \approx 1$ sec, so the mass of horizons in the volume is $M \approx 10^{-4}\,M_{\odot}$. For masses larger than this (say solar or galactic masses), the effect practically vanishes for any reasonable assumption about the perturbation spectrum. It should also be noted that in Ozernoi and Chernin's theory of primordial turbulence, the early stages of expansion of the Universe must necessarily be very different from the Friedman Universe on scales of galaxies or smaller.