47. COSMOLOGY (COSMOLOGIE)

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1. PRO AND CONTRA BIG BANG THEORY

The conventional cosmological picture is based on Hubble's redshift and the relic (black body 2·7 K background) radiation.

It uses standard general relativity and laws concerning mechanics, electrodynamics and elementary particle theory established in the laboratory. The hypothetical C-field (Hoyle), the Brans-Dicke scalar field and the cosmological term Λ are not used in the most simple version.

The redshift is explained by the expansion of the Universe. The black body radiation temperature decreases in the course of time, therefore it should have been high in the remote past. A consistent picture of the evolution, beginning at a singularity (infinite density, infinite curvature) starts with a dense and hot plasma with a great abundance of particles and anti-particles. Gradually, the anti-particles anninilate, the remaining neutrons and protons undergo nuclear reactions, electromagnetic radiation is cooled down, electrons are tied with helium particles and protons into atoms, the neutral gas forms dense gas clouds – protogalaxies or protoclusters of galaxies, which evolve into their present-day form.

Most of the following sections deal with an exposition of work done on these lines during the past three years; theoretical work is given more attention than in foregoing reports; this is the cost of making a theoretician President of this commission.

Of course, the most important observational work is included in this report, but many items are left for commissions 28 (Galaxies) and 48 (X-Ray astronomy, relativistic astrophysics). But before going to details, a strong word of caution is necessary.

The picture outlined is *not* proven unambiguously. Many outstanding astronomers point to difficulties and express their doubts.

The first task of an impartial review is to reflect the discussion on the vary basic problems of cosmology.

G. Burbidge published an article 'Was there really a Big Bang', (*Nature*, **233**, 36, 1971), where many objections are summarized:

(1) The redshift is perhaps not reflecting expansion. There are pairs of groups or objects (QSOs galaxies) apparently tied physically (by gas bridges sometimes) with very different redshift. See Burbidge, G. (*Ann. Rev. Astron. Astrophys.* **8**, 369, 1970), Burbidge, E., Sargent, (Vatican Symposium, 1971), Arp, (*Ap. Lett.*, **9**, 1971).

The counter arguments are: In the last time some cases were proven to be angularly close objects at different distances, without any physical connection (Lynds, Millikan, *Ap. J.*, **176**, L5, 1972; Bahcall, J., McKee, Bahcall, N., *Ap. J.*, in press). The Hubble law for galaxies is fulfilled with great accuracy (Sandage, 'Nuclei of galaxies', Vatican Symposium, 1971). The redshift anomalies of QSOs, particularly the absence of a clear correlation between the redshift and the apparent magnitude (Schmidt, Sandage, Vatican Symposium, 1971) are not a threat for cosmology. If the expansion is proved by galaxies, one can e.g. even assume a short distance scale of QSOs with a gravitational redshift without damaging the current cosmological picture.

(2) Attempts were made to explain the redshift by photons losing energy due to some physical process (Hoyle, Narlikar, *Nature*, **233**, 41, 1971; Solomon, Strittmatter, *Ap. J.* **170**, 233, 1971).

Pecker, Roberts, Vigier (*Nature*, **237**, 227, 1972) use the interaction of photons emitted by discrete background objects with the diffuse blackbody radiation. The objection to this kind of explanation is that while losing energy the photons are also changing their directions. The undisturbed photons, travelling straightforward (and contributing to the image of a distant galaxy) are those which never lost energy, and are not reddened by that effect.*

(3) Doubts, expressed (G. Burbidge, l.c.) about the 'relic' origin of the radio-background radiation were supported by experiments which claimed a strong departure from a Planckian spectral distribution; more recent experimental data do not support this result. This topic is discussed further in Section 4. The long wave part ($h\nu < kT$, $\lambda > 0{\cdot}3$ cm) is fully explored and the agreement with the Planckian formula (more precisely – with its Rayleigh-Jeans limiting case) is excellent, departures being smaller than 5 %.

Several theoretical papers attempt to explain the radio-background by some process in the past, not as remote as the singularity. Rees (*Proc. Enrico Fermi Summer School*, **47**, 315, 1971; *Phys. Rev. Lett.*, **28**, 1669, 1972) proposed primeaval turbulence as a source of energy which is converted into equilibrium radiation at redshift values of the order of $Z \approx 10^3$ to 10^4. This leads one to reject the hot Universe picture at $Z \gg 10^3$ to 10^4. There are, however, difficulties to erase all signs of earlier violent processes from the background spectrum (See Section 4).

(4) The Big Bang theory predicts a definite chemical composition of primeaval pre-stellar matter. Most characteristic is the prediction of 25 %–30 % ^{4}He and 75 %–70 % H, in the simplest version. Up to now there is no decisive proof for that composition: some exceptions are found (de Vaucouleurs, Reeves, *Astron. Ap.*, **18**, 215, 1972). Even when helium would be found in the right proportion, doubts about its primeval origin remain. We are not sure, what amount of helium was transmuted and thrown into interstellar space from the first generations of stars (or from gigantic pre-stars?).

(5) A concurrent theory explaining the observed redshifts is the Steady State theory of Hoyle. Before the period reviewed, it was claimed that counts of radio sources show indications of evolution and therefore would contradict the Steady State theory (See Longair, *M.N.R.A.S.*, **133**, 421, 1966). During the last three years some doubts were expressed about the counts of the sources (Kellermann, *Astron. J.*, **77**, 531, 1972), and so Burbidge argued for a revival of the Steady State theory.

The characteristic feature of the Steady State is the eternal low density of matter. Therefore one cannot imagine a reasonable process to maintain the equilibrium spectrum of the background radio-radiation. As long as this objection is not answered, the Steady State theory is not a threat to the conventional Friedmannian hot Universe picture.

It would be important also to study in detail the properties of a C-field and its interaction with matter. Particularly if a C-field gives birth to protons and electrons (or other particles) the inverse process of decay into a C-field is inevitable.

Tribute must be paid to the open-mindedness and intellectual freedom of the opponents to the conventional theory. It is more than the courage of a soldier on a forgotten post. Perhaps their critique may turn out not to damage the conventional theory – but that is not yet clear! Anyway their work is important in paying attention to the real difficulties and to problems not yet cleared.

2. THE ANTIMATTER PROBLEM IN COSMOLOGY

The question of the matter-antimatter symmetry in the Universe is a deep and yet unsolved problem. Activity in this field of theory has continued in the years reviewed. No annihilation radiation was found, although searches for 0·5 MeV photons (from $e^+ + e^- = 2\gamma$) and 50–100 MeV photons (from $p + \bar{p} = \pi^0 + \text{other}$, $\pi^0 = 2\gamma$) were conducted. Therefore, the simplest point of view is that everywhere in other galaxies, clusters of galaxies, QSOs, intergalactic gas, etc. we have to do with

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* The wellknown reddening of starlight is not a 'redshift' but a change of the apparent intensity ratio between different parts of the continuous spectrum; the lines are not shifted.

ordinary matter. Today, the overall composition of the Universe is 10^8 photons per baryon (neutron or proton, free or bound in nuclei) and less than one electron. Other particles are present in quite negligible quantities.

But for the remote past, $Z > 10^9$, the laws of thermodynamics predict many electron-positron pairs and for $Z > 10^{12}$ abundant baryon-antibaryon pairs in addition to photons and to a small excess of baryons. Therefore a Universe that is quite asymmetric now, would correspond to a quasisymmetric past, $10^8\gamma:(10^8+1)\ B:10^8\overline{B}$. Such a composition seems to be most unnatural (see for example Zeldovich, *Comments Astron. Ap.*, 1972). Fujimoto, Kawabata and Sofue (*Suppl. Prog. Theor. Phys.*, **49**, 181, 1971) argue, that metagalactic space up to a distance of $Z=2$ is not symmetric with respect to matter and antimatter.

O. Klein (*Science*, **171**, 339, 1971) and Alfvén (*Physics Today*, **24**, Feb., 1971) support a charge symmetrical model of the Universe proposed earlier. In the last few years the magnetic separation of matter and antimatter in a rarefied plasma was considered. No selfconsistent treatment of the expansion, the radio-background and the separation is given.

Omnes (*Phys. Rev. Let.*, **23**, 38, 1969, *Astron. Ap.*, **15**, 275, 1971, *Phys. Report*, **3C**, 1, 1972) proposed a new idea in the framework of a charge-symmetrical hot Friedmannian Universe. He makes plausible (although does not prove definitively) that a separation of matter and antimatter occurs, due to nuclear forces in a temperature interval of the order of 10^{12} to 10^{13} degrees ($kT \approx 0{\cdot}1\ Mc^2$ to Mc^2, where M is the proton mass). The author claims to obtain separation on the scale of galaxies. It seems that the scale is overestimated, but the difficulties due to delayed annihilation are underestimated. Strong objections makes Steigman-Orang (preprints 280, 1972).

Another model consists an initial cold baryon (charge-asymmetric) fluid with some perturbation of the metric. The perturbations die out, giving heat and so the conventional hot model arises early enough to give plenty of baryon-antibaryon pairs. The subsequent evolution, including nuclear reactions, etc. goes as usual (Zeldovich, *M.N.R.A.S.*, 160, 1972).

3. NUCLEOGENESIS IN COSMOLOGY (COSMOGENESIS)

A revival of interest in cosmogenesis is observed. Reeves (preprint, 1972) and Wagoner (preprint, Cornell Univ., 1972) are analyzing the deuterium, helium-3 and lithium-7 abundance due to cosmogenesis.

Unlike helium-4, the abundance of the mentioned rare nuclei depends strongly upon the matter density. The dependence is inverse, at high density values deuterium is destroyed.

The deuterium abundance (including the terrestrial value) has no other rational explanation. Its value leads to the conclusion that $\varrho \approx 0{\cdot}2\varrho_c \approx 0{\cdot}2(3H^2/8\pi G) \approx 10^{-30}\ \mathrm{g\ cm^{-3}}$, corresponding to an acceleration parameter $q^0 \approx 0{\cdot}1$, at $H_0 = 55\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$.

The case of helium-3 in less clear, because ^{3}He is transmuted in stars, by the *p-p*-cycle and also from interactions with deuterium at lower temperatures in the envelope.

The case of lithium-7 is complicated by the concurrent production in cosmic rays; a sophisticated reasoning involving the ^{7}Li/^{6}Li ratio leads to a qualitative agreement with cosmogenetic theo;y.

Of course all these subtle results are valid assuming that the main issue (25 %–30 % primeval ^{4}He) is settled (compare Section 1) (see also Kippenhahn, *Trans. IAU*, **14**, 296, 1972). For review of the problem see Reeves, Wagoner.

4. RADIO-BACKGROUND

Important measurements of the radio-background were made in the long wave region; Howell, Shakeshaft (*Nature*, **216**, 753, 1967), Pelushenko, Stankevich (*Astron. J. (USSR)*, **46**, 228, 1969).

Indirect measurements of the background by the optical investigation of excited interstellar molecules were conducted by Bortolot, Clauser, Thaddeus (*Phys. Rev. Lett.*, **22**, 307, 1969). The CN* molecule has given a definite background density at $\lambda = 0{\cdot}273$ cm, coinciding with the 2·7 K black body spectrum. Other molecules (CH, CH*) have given upper limits only, which does not contradict the black-body hypothesis. First direct bolometric measurements of the main part of the background energy have given densities much higher (by 10–50 times) than the black-body at 2·7 K (see Shivanandan, Houck, Harwitt, *Phys. Rev. Lett.*, **21**, 1460, 1968; Houck, Harwitt, *Ap. J.*, **157**, L45, 1969; Muehlner, Weiss, *Phys. Rev. Lett.*, **24**, 742, 1970).

In a later paper of the Los Alamos group (Blair, Beerg, Edeskuty, Hiebert, Shipley, Williamson, *Phys. Lett.*, **27**, 1154, 1971; *Nature Physical Science*, **234**, 26, 1971) these findings were not confirmed and the results do not contradict the black-body hypothesis, although the precision is low, $T = 3{\cdot}1$ $(+0{\cdot}5;\ -2{\cdot}0)$ K. The indirect molecular methods (see above) are against abnormally high densities.

The conclusion is that spectral measurements must be continued, but there is today at least no immediate threat to the hot Universe model. Measurements of the large angular scale and small-scale anisotropy of the microwave background were made by Partridge. A recent measurement at $\lambda = 3{\cdot}5$ mm on an angular scale at 80″ sets an upper limit of 0·006 K on the intensity fluctuations in the background radiation (Boynton and Partridge, to be published). Paryisky (*Astron. J. (USSR)* 1973, Stankevich, ibid).

5. HUBBLE CONSTANT AND DECELERATION PARAMETER

Much previous work on the Hubble constant derived from the luminosity and redshift of galaxies is summarized by Sandage (Vatican symposium, 1971), Peach (*Ap. J.*, **159**, 753, 1970) (see also Hutchius, Ph.D. dissertation, University of California at Berkeley). The best estimate was 75 km s^{-1} Mpc^{-1}. By the analysis of the angular dimensions of H II regions Sandage (Vatican Symposium) gives a lower figure 50 km s^{-1} Mpc^{-1}, corresponding to a time span $1/H_0 = 18 \times 10^9$ years. The deceleration parameter determination is still very uncertain. Sandage gives 0·65–1·03. The determination of q_0 is hampered by evolutionary effects, see details Sandage (*Ap. J.*, **178**, 1, 1972). The evolution effects are absent in the Steady State theory, which predicts a unique value of $q_0 = -1$. Obviously the actual data are unfavourable to this theory.

6. MATTER DENSITY

A new determination of matter density in galaxies was carried out by Sandage (Vatican Symposium). The result differs little from Oort's (1958). All kinds of dark invisible matter in galaxies is included because such matter, by its gravitation, influences the stellar motions and those of gas clouds. The discrepancy between the masses of galaxies and the virial masses of clusters of galaxies (Karachentzev, *Astr. J. (USSR)*, **47**, 509, 1970, Karachentzev, Zonn, Scherbanovsky, *Ap. Lett.*, **11**, 151, 1972, Field, Saslaw, *Ap. J.*, **170**, 199, 1971) is still unsolved. There are indications that a careful analysis would make two figures converge, making the contradiction less stringent.

The density of ionized gas was searched for by its ultraviolet and X-radiation (Longair, Sunyaev, *Sowiet Phys. Uspekhi*, **105**, 41, 1971; Field, *Ap. J.* **165**, 29, 1971; Cowsik, Kobetich, *Ap. J.*, November 1972; Cowsik, Mauschovias, to be published; Field, *Ann. Rev. Astr. Astroph.*, **10**, 1972). The determinations are limited by the opacity of the galaxies. Indirect estimates of ionized radiation for wavelengths exceeding that of the Ly-continuum, involving the tenuous neutral hydrogen halo, were made by Sunyaev (*Ap. Lett.*, **3**, 33, 1969; Comp. Felten, Bergeron, *Ap. Lett.*, **4**, 155, 1969).

The results is $\bar{\varrho}_{\text{gas}} < 0{\cdot}3\ \varrho_c$. Silk, Gruddee and Reeves (*Bull. A.A.S.*, **4**, 258, 1972) showed that an extremely hot and tenuous intergalactic medium at $T \approx 10^{10}$ K may provide a plausible interpretation of recent γ-ray observation. Silk and Tarter have derived stringent limits on the permissible amount of intergalactic matter in clusters and groups of galaxies by using the catalogues of Abell and de Vaucouleurs to obtain a clumpiness function, which was used to calculate the diffuse background radiation emitted by the intergalactic gas (in preparation).

For the same theoretical problems for a homogeneous Universe see Sapar (*Astron. J. (USSR)*, **47**, 503, 1970) and Publications of Tartu's Astrophysical Observatory named after V. Struve, 1970–1971. An open world model seems to be more plausible, than a flat $(\varrho = \varrho_c)$ or a closed $(\varrho > \varrho_c)$ model. Some indirect indications confirm this hypothesis. Still the evidence is not final.

7. THE SINGULARITY AND PHYSICAL PROCESSES NEAR THE SINGULARITY

From the very beginning the question of the cosmological singularity was placed before the theoreticians: Was there a singularity at the beginning of the expansion? It has long been suggested that departures from the Friedmannian model at the origin of the expansion do not allow the singularity to be avoided. A series of investigations by Penrose, Geroch and Hawking were devoted to this problem. In 1970 the generalizing work by Hawking and Penrose was published. They could prove that a singularity in the past is unavoidable (*Proc. Roy. Soc.*, **A314**, 529, 1970). The homogeneous anisotropic cosmological models underwent a careful analysis to describe the early stages of cosmological expansion.

A very important study of the most general singular solution was given by Belinsky, Khalatnikov, E. Lifshitz (*Soviėt Phys. Uspekhi*, **102**, 463, 1970, *Adv. Phys.*, **19**, 525, 1970, *JETF*, **60**, 1969, 1971). A cosmological model in which the optical horizon is absent and a smoothing out of inhomogeneities is possible in principle was proposed by Misner (*Phys. Rev.*, **186**, 1319, *Phys. Rev.*, **186**, 1328, 1970) on the base of this latter solution (mixmaster Universe). The model was examined by E. Lifshitz, I. Lifshitz, Khalatnikov (*JETF*, **56**, 322, 1970), Doroshkevic, Novikov (*Astron. J. (USSR)*, **47**, 948, 1970), Belinsky, Khalatnikov, E. Lifshitz (*JETF*, **60**, 1969, 1971), Matzner, Shepley, Warren (*Ann. Phys.* **4**, 57, 401, 1970), Gricshuk, Doroshkevich, Lukash (*JETP*, **61**, 3, 1, 1971). Doroshkevich, Lukash, Novikov (*JETF*, **60**, 1201, 1971) showed that light has not time enough to cycle the Universe even one time and the smoothing out of inhomogeneities is, in principle, impossible.

Homogeneous models were also examined by Gricshuk (*R.A.S.C. USSR*), **190**, 1066, 1970, *Bull, Acad. Polon. Sci. Math., Ast. Phys*, **19**, 129, 1971 Grishuk, Demyansky (*Comm. Math. Phys.*, **25**, 233, 1972), MacCallum (*Comm. Math. Phys.*, **20**, 57, 1971). The process of 'isotropisation' was considered by Doroshkevich Lukash, Novikov (JETP, 1973). A complete discussion of the Einstein equations for anisotropic models with hydrodynamic stress energy tensor was given. The mathematics formalism for dealing with properties of models was built by Zelmanov. Belinsky, Lifshitz, Khalatnikov, who showed that the oscillatory type of expansion near a singularity takes place in the general case without assuming homogeneities (*JETP*, **62**, 1606, 1972).

The physical processes near the singularity are of specific interest. Matzner and Misner (*Ap. J.*, 1972) continued their examination of the influence of the viscosity of neutrinos during an anisotropic expansion, on the kinematics of the model and its physical processes. The idea that particles could originate from the gravitational field was forwarded by Parker (*Phys. Rev.* **D3**, 346, 1971; *Phys. Rev. Lett.*, **28**, 705, 1972). The process of the birth of the particles is especially important in the case of an anisotropic beginning of the cosmic expansion. See Zeldovich (*JETP, Lett.*, **12**, 443, 1970); Zeldovich, Starobinsky (*JETP*, **61**, 2161, 1971); Pitayevsky and Zeldovich (*Comm. Math. Phys.* **23**, 185, 1971). Probably the birth of particles may lead to homogeneous and isotropic expansion starting from the Planckian period of time, $t_p \approx 10^{-43}$s.

The change of the gravitational equations near the singularity was examined in Ginzburg's, Kirgnitz's and Lubushin's work (*JETP*, **60**, 451, 1971). The importance of changes of the equation of state under extremely temperatures is still a matter of discussion (See Hagedorn's idea of the appearance of baryon resonances; and Omnes's interaction of baryons and antibaryons). Meszaras (Nature, **235**, 50, 1972) showed that the tendency of forming fluctuation's, connected with Hagedorn's equation of state was not sufficient for creating galaxies. The discussion of the physical processes near the singularity is given in review by Novikov and Zeldovich (*Ann. Rev. Astr. Ap.* 1973) where also a detailed bibliography is given.

8. THEORIES OF FORMATION OF GALAXIES

The theory of the structure of the Universe, including the separation of matter into distinct gravitationally bound sub-units (galaxies, clusters of galaxies, etc.) is the natural next question after having established a plausible picture of the Universe as a whole.

One direction of thought is based on the idea of gravitational instability, tied to the names of

Newton, Jeans, Lifshitz, Bonnor. Put in a nutshell, small perturbations in the initial state of the Universe (near the singularity) increase during their evolution to build the observed structures. The hot Universe model makes important contribution:

(1) during the radiation-dominated epoch density contrasts on scales smaller than 10^{18} $M_\odot$ are transformed into acoustical waves, due to radiation pressure;

(2) on a more modest scale (less than 10^{13} $M_\odot$) these waves are damped due to radiative viscosity and heat conduction;

(3) fluctuations of the entropy and composition (baryon; photon ratio) are a new type of perturbation, characteristic for the hot model. A summary of the situation around 1967 is given in Zeldovich, Novikov, *Relativity and Astrophysics* (Nauka, Moscow 1967); Peebles (*Ap. J.*, **155**, 393, 1969); Doroshkevich, Zeldovich, Novikov (*Astron. J.* (*USSR*), **44**, 295, 1967), Peebles (*Physical Cosmology*, 1971). During the last three years much more theoretical work was done on these lines.

Peebles (*Astrophys. Space Sci.*, **11**, 443, 197, 1971) and Chibisov (*Astron. J.*, *USSR*, **49**, 1, 1972), made exact calculations of the transfer function from initial perturbations to the matter-dominated period. Important work done by the Japanese group is reviewed in 'Evolution of the Universe and Formation of Galaxies' (*Suppl. Prog. Theor. Phys.*, **49**, 1971). Sato, Matsuda and Takeda have discussed the evolution of the expanding hot Universe. Their main efforts were devoted to the theory of galaxy formation in connection with the physical state of matter and radiation in the early stages of the hot Universe. Their discussions include dissipation of the inhomogeneous motions in the cosmic medium due to collisions between electrons and photons, and the effects of the resultant heating on the thermal history of the hot Universe.

Nariai and Tomita have summarized the problem of gravitational instability and galaxy formation. The non-linear behaviour of various perturbations has been treated. Konde, Sofue and Unno have discussed the general characteristics of a thermal instability for a medium in a non-equilibrium state with regard to the change of the ionization and the optical depth effects of the fluctuations. Long before the time of decoupling, the dimension of an irregularity may exceed the horizon count (anti-Newtonian stage), the general relativistic non-linearity plays an essential role. Tomita (*Prog. Theor. Phys.*, **48**, 1972) has elaborated on the evolution of an irregularity during an anti-Newtonian stage.

Sunyaev, Zeldovich (*Astron. Astrophys.*, **20**, 189, 1972) considered the fine structure of the transfer function ('Sacharov oscillations', *JETP*, **49**, 345, (1965), compare Peebles *l.c.*) and the possibility of their detection. Most calculations are done for a flat Universe. However, Guyot and Zeldovich (*Astron. Ap.*, **9**, 227, 1970) studied the case of $\bar{\varrho} \ll \varrho_c$. Sunyaev (*Astron. Ap.*, **12**, 19, 1971) came to the conclusion $\bar{\varrho} \approx 0{\cdot}2\varrho_c$.

An approximate theory for the growth of large perturbations was given by Zeldovich (*Astron. Astrophys.* **5**, 84, 1970; *Astrophysica*, **6**, 319, 1970). The main result is that first flat gas condensations are formed. A detailed picture, including a discussion of the heat balance and radiation of these protogalaxies, was given by Sunyaev and Zeldovich (*Astron. Astrophys.*, **20**, 189, 1972).

Rotation and magnetic field are important properties of galaxies. Peebles (*Ap. J.*, **155**, 393, 1969) explains the rotation by gravitational tidal interaction of protogalaxies. Doroshkevich (Reprint I.A.M. **2**, 1972) pointed out that due to shockwaves in protoclusters the vortex motion of the gas is induced, unlike in the case of an ideal fluid. A magnetic field is induced due to the interaction of electrons and protons with radiation. A mechanism for the radiation-dominated epoch was proposed by Harrison (*Ap. Lett.*, **3**, 133, 1968, *Nature*, **224**, 1089, 1969), for the matter-dominated epoch by Mishoustin and Ruzmaikin (*JETP (USSR)*, **61**, 441, 1971).

These magnetic fields are very weak. Amplification due to differential rotation, convection and turbulence was considered by Fitremont and Frisch (*C.R.Acad. Sc. Paris*, **268**, 705, 1969) and later by Vainshtein and A. Ruzmaikin (preprint I.A.M. U.S.S.R. **2**, 1972).

About the early stages of galactic evolution see Pecker (*Astron. Ap.*, **18**, 253, 1972). Dicke and Peebles (*Ap. J.*, **194**, 836, 1968), Peebles (*Ap. J.*, **155**, 393, 1969) propose entropy perturbations to be the precursors of globular clusters, with a characteristic mass $\approx 10^5$ $M_\odot$. A mechanism of the fragmentation of the precursors of globular clusters into stars was considered by T. Ruzmaikina

(*Astron. J. (USSR)*, **49**, 1298, 1972). Sveral papers deal with the evolution of gravitationally bound gas clouds of different mass – do they develop into a star cluster or into a superstar, does the superstar explode – see Matsuda, Sato (*Progr. Theor. Phys.*, **41**, 1021, 1969). The theory of small initial perturbations outlined above is not unique, a somewhat different point of view is possible, as exposed in the next section.

9. VORTEX THEORY OF GALAXY FORMATION

There is a widespread belief, that the initial state of the Universe was very irregular, turbulent. Specifically initial vortex motion is a ready explanation of the rotation of galaxies. An early version of the theory was given by Weizsacker and developed by Gamov. In the context of a hot Universe, the turbulent fluid is radiation-dominated. Ozernoy and Chernin formulated the theory, introducing concepts such as 'photon eddies', 'photon turbulence' (*Astron. J.(USSR)*, **45**, 113, 1968). Ozernoy and Chibisov (*Astron. J. (USSR)*, **47**, 769, 1970) developed this theory of turbulence evolution and made approximate calculations of the masses, densities and the rotational moments of clusters of galaxies and individual galaxies. They obtain a good agreement with the observed values (*Ap. Lett.*, **7**, 201, 1971).

Other research groups participated in work on the vortex theory. Nariai (*Prog. Theor. Phys.*, **44**, 110, 1970) has derived the basic equations for dealing with various non-linear effects of a cosmic fluid such as the interaction between eddy and shearing motions, by introducing a new shearing tensor q_{ij}, Nariai (*Prog. Theor. Phys.*, **45**, 61, 1971) has refined his formulation in dealing with the various non-linear effects of a cosmic fluid which are important in the process of galaxy formation. The fundamental equations for perfect fluids have been extended to those for real fluids with viscosity and thermal conductivity included in the theory of an expanding universe in the general theory of relativity (Sakai, Fluid Dynamics in an Expanding Universe, Thesis, Univ. of Tokyo, 1971). The damping rates for the vortical motions and for acoustic waves are calculated, and the formation of galaxies is discussed by making use of the results of these calculation. These basic equations are also applied to an expanding universe with no local inhomogeneities and it has been shown that the second kind of viscosity makes entropy increase, and tends to accelerate the expansion (Sakai, *Prog. Theor. Phys.*, **46**, 1292, 1971).

Silk and Ames have investigated the role of primordial turbulence in galaxy formation, and have derived analytic expressions for the density fluctuations produced by fully developed incompressible turbulence in the early universe, prior to recombination (*Ap. J.* in the press). Silk and Lea have studied the probable range predicted for the random velocities of galaxies according to theories which involve a turbulent origin (in preparation). Some difficulties of this approach are pointed out. Peebles (*Astrophys. Space Sci.*, **11**, 443, 1971) showed that the early formation of galaxies at $Z \approx 100$ leads in this theory to density values that are too high.

Sunyaev, Zeldovich (*Astrophys. Space Sci*, **7**, 20, 1970), Zeldovich, Illarionov, Sunyaev (*JETP*, **62**, 1217, 1972) give upper limits of the vortex motion in order to avoid distortion of the background spectrum.

The vortex is incompatible with a Friedemannian type of singularity; Ozernoi and Chernin already admitted this point, a detailed discussion is given by Zeldovich and Novikov (*Astrophysica* **6**, 379, 1970). This should destroy the results of the conventional (Friedman) Big Bang theory concerning nucleogenesis. Further investigation is needed.

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