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TURBULENCE IN AN ISOTROPIC UNIVERSE

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A number of observational and theoretical arguments offer definite evidence in favor of the hypothesis [1, 2] that a developed turbulence exists in the intergalactic medium during the epoch of galaxy formation at an average density $\rho = \rho_G \simeq 10^{-23} - 10^{-25}$ g/cm^3 and at a universe age $t = t_G \simeq 10^{15} - 10^{16}$ sec. Direct extrapolation of the notions of metagalactic turbulence to the past ($t < t_G$) leads to the conclusion of an anisotropic, non-Friedmann character of the earlier phase of cosmological expansion [3, 4], which is equivalent to a "primordial" existence of strong turbulent vortical motions that determine the metric properties of space-time. However, an analysis of the hydrodynamics of a "hot" universe under conditions when the radiation density ρ_r exceeds the density of matter ρ gives grounds for a fundamentally different solution of the problem of the earlier expansion phase. We shall show that the state of developed metagalactic turbulence need not necessarily be "primordial"; it could arise during the period of recombination of the cosmic plasma, owing to small (in a sense indicated below) motions of a potential or an acoustic type. These motions, unlike vortical motions, are compatible with the isotropy of the metric in all the phases of expansion.

The evolution of potential motions superimposed on the regular cosmological expansion consists of the following three stages: 1) gravitational instability, in which the motion velocity $v \sim t^{3/2}$ increases while the perturbations of the metric remain constant in time, and the characteristic scale of motion ℓ exceeds the critical Jeans length $\ell_1 \simeq u(G\rho)^{-1/2}$ (here u is the speed of sound, $u = u_0 = c/\sqrt{3}$ when $\rho_r > \rho$); 2) conversion of the motions into acoustic waves of constant amplitude, corresponding to time-decreasing perturbations of the metric and to a wavelength ℓ smaller than ℓ_1; 3) hydrodynamic instability.

The transition from stage 1) to stage 2) is determined by the fact that the ratio $\ell/\ell_1 \sim t^{-1/2}$ decreases during the course of the expansion. According to the general theory [5], these motions produce either a small perturbation in an isotropic universe (i.e., the relative deviation of the metric from the Friedmann metric is always smaller than unity), if in phase 2) the amplitude of the velocity is not too close to the velocity of sound u_0:

$$v < (1/10)u_0 \approx 2 \cdot 10^9 \text{ cm/sec.} \qquad (1)$$

Phase 3) is due to physical phenomena in a "hot" universe, not accounted for by the theory [5] and its cosmogonic applications [6 - 8]. The hydrodynamic instability arises during the time of a sharp decrease of the velocity of sound in the matter, because its interaction with the relict radiation [3] during the recombination stops ($t = t_r \simeq 3 \times 10^{13}$ sec) if the motion velocity is larger than the new speed of sound u_1, and the characteristic time of the hydrodynamic processes $t_g \simeq e/v$ does not exceed the age of the world:

$$v > u_1, \quad e/v \lesssim t_r. \tag{2}$$

Here $u_1 \simeq (kT_r/m^{1/2} \simeq 5 \times 10^5$ cm/sec, $T_r \simeq 3 \times 10^3$ °K is the recombination temperature, and m is the mass of the hydrogen atom.

When conditions (2) are satisfied, the sound waves become unstable and the motions go over into a new regime, in which they produce in the shock waves an appreciable density inhomogeneity, as well as vortical motions corresponding to the picture of the developed "compressible" turbulence.

Conditions (1) and (2) are compatible if

$$\ell < \ell_0 = (1/10)u_0 t_r \ . \tag{3}$$

The upper limit ℓ_0 of hydrodynamically unstable scales (3) corresponds to a mass

$$M_0 = 4\pi/3\,\rho(t_r)\,l_0^2 \approx 3\cdot 10^{14} M_\odot \ ,$$

which is close to the mass of large galactic clusters. We call attention to the fact that M_0 greatly exceeds the limit of action of the dissipative processes [9, 10].

Relations (1) - (3) show therefore that the "bare" motions considered here are compatible with the isotropy of the world during earlier epochs ($t \to 0$), and at the same time are capable of ensuring the state of a developed compressible turbulence at $t \gtrsim t_r$.

The hydrodynamic instability initiates an active phase of the cosmogonic process in the "hot" universe. But the overwhelming part of the matter condensations produced by this instability are not at all transformed immediately into gravitationally-coupled systems. This is hindered both by the intense stirring due to the hydrodynamic motion [3] and by the dissipation of the kinetic energy of these motions, which is capable of producing, at $t > t_r$, enough strong heating of the matter to raise the degree of ionization again to a value at which the interaction with the radiation is restored, so that the Jeans length spans a mass exceeding M_0. The second of these factors act, however, only until the time of the free path of the quantum - even in the case of complete ionization becomes larger than the age of the world. At that instant, as can be readily seen, the average density and the cosmological age are precisely near the values ρ_G and t_G indicated above. Under such conditions, formation of a stellar population of cosmic systems becomes possible; dense objects (galactic nuclei, quasars), which constitute only a small fraction of the total mass, they can arise in principle also earlier in those regions of the medium where the turbulent fluctuations have produced favorable (differing from average) conditions for gravitational condensation.

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