WHIRL THEORY OF THE ORIGIN OF GALAXIES AND CLUSTERS OF GALAXIES

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Abstract. This paper reviews the present state of the theory of primaeval whirls which may be responsible for the origin of galaxies and galaxy systems. The main problems on which the author will concentrate are concerned with the pre-recombination evolution of the whirls. Special attention is given to new results, obtained by Kurskov and the author, concerning the dissipation of cosmological turbulence and the constraints which follow on the parameters of primaeval whirls. In contrast to some assertions in the literature, there is not contradiction between the whirl concept and observations. Moreover, the fact that the final spectrum of motions and corresponding inhomogeneities does not depend essentially upon the details of the initial whirl spectrum makes the theory very attractive.

The formation of galaxy systems (groups, clusters etc.) is discussed, and alternatives for the formation of galaxies themselves are briefly outlined. Many aspects of the whirl theory are suitable for further observational and theoretical development.

1. Introduction

Between the two extreme lines of thought – one that the early universe was very smooth and regular and the other that it was entirely chaotic – there is an intermediate approach. One may imagine that the early Universe contained some dynamical structure of the whirl type. More specifically, let us assume that during the radiation dominated phase, combined vortex motions of plasma and radiation existed. In other words the amplitude of the solenoidal (i.e., transverse tensor) waves was greater than that of potential (i.e., longitudinal vector) waves. The possible origin of such a situation will be discussed briefly at the end of this talk.

The hypothesis just formulated was suggested about six years ago by Chernin and myself (Ozernoy and Chernin, 1967, 1968) as a development of the pioneering works of Weizsäcker (1951), Gamow (1952), and Nariai (1956) on pregalactic turbulence and an exteńsion of them to the hot universe. We have drawn attention to the fact that the pregalactic and precluster inhomogeneities may appear during the transition of the cosmological turbulence from the subsonic regime during the radiation dominated phase to the supersonic regime at the epoch of decoupling of matter and radiation when the redshift $z \sim 10^3$. The more detailed theory has been developed subsequently in a number of papers (Ozernoy and Chibisov, 1970, 1971; Ozernoy, 1971) and has become the object of many discussions and new proposals (Oort, 1970; Tomita *et al.*, 1970; Peebles, 1971; Silk and Ames, 1972; Stecker and Puget, 1972; Tomita, 1972; Harrison, 1971, 1973a, b; Jones, 1973; and many others). For the sake of brevity I shall not discuss here the results of these authors. Instead I shall try to give a more general picture of the modern state of the whirl concept in the light of new results obtained recently by our group.

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2. Pre-Recombination Evolution of Vortex Motions

We start with the assumption that in the past during the radiation-dominated stage, large-scale vortex motions existed, and that their initial velocity, v, was subsonic (i.e., $W \equiv v_0/c \lesssim (1/\sqrt{3})$ on all scales. I shall take the scale to be a time-independent quantity R related to the ordinary linear dimensions r by the expression $R = r(1+z)$. An invariant mass $M = (\frac{4}{3})\, \pi \varrho_{\text{now}} R^3$ of material (ϱ_{now} is its present mean density) is contained within the scale R. Further, I shall confine myself only to scales not extending beyond the cosmological horizon, so that the usual Friedmann metric at this stage can be used.

Let me mention some known results concerning the most general properties of cosmological whirls.

The evolution of the whirls is determined by three characteristic times: by the time of viscous dissipation, t_d; by the hydrodynamical, or turn over, time, $t_h = r/v$, and by the time of cosmological expansion, $t_{\text{exp}} = r/\dot{r}$. The interrelation between them is different on various scales, and the evolution of the motions on large, mean and small scales differs drastically.

'Maxi' scales ($R \gg R_h = vtz$, $t_d \gg t_h \gg t_{\text{exp}}$)

Here

$$v = \text{const} \quad \text{if} \quad z > z_{\text{eq}},$$
$$v = \text{const}\, \frac{1+z}{1+z_{\text{eq}}} \quad \text{if} \quad z < z_{\text{eq}}, \tag{1}$$

where z_{eq} is the redshift of equal matter and radiation energy densities. The constancy of v up to $z = z_{\text{eq}}$ obtained first for an ideal fluid by Lifshitz (1946) follows immediately from the requirement of angular momentum conservation. The conservation in time of the velocity on large scales, where the viscosity is negligible indeed, is a very attractive feature of the theory being developed, because it preserves large velocities from the remote past up to the comparatively recent epoch $z_{\text{eq}} = 1.77 \times 10^4\, \Omega h^2 (\Omega = = \varrho_{\text{now}}/\varrho_{\text{crit}}$ where $\varrho_{\text{crit}} = 1.05 \times 10^{-29}\, h^2$ g cm^{-3}; $h = H/75$ km s^{-1} Mpc^{-1}).

'Midi' scales ($R_d \ll R \ll R_h$, $t_h \ll t_{\text{exp}} \ll t_d$)

Here the primaeval whirl spectrum undergoes readjustment due to the energy flow from large scales into smaller ones. The universal Kolmogorov spectrum is established on these inertial scales. The boundary of the established spectrum, R_h, first increases as z^{-1}, reaches its maximum at $z \approx z_{\text{eq}}$, and then diminishes as $z^{1/2}$.

'Mini' scales ($R \ll R_d$, $t_d \ll t_h$)

The motions on these scales dissipate due to viscosity. The value of R_d increases with time.

In order to obtain galaxies and clusters of galaxies from the turbulence produced by primaeval whirls, it is necessary to know the main characteristics of the turbulence at the epoch of recombination ($z \sim 10^3$), when the matter and radiation decouple. Beginning at this epoch, the inhomogeneities produced by the turbulence can grow without any hindrance from the relic radiation.

The pre-recombination evolution of whirls has been studied in detail, both in analytic and numerical form, by Kurskov and Ozernoy (1974a, b, c). The result of the evolution depends strongly of the parameter $\alpha = k_0 v_0 \tau_{max}$ which is determined by the initial value of the main energy containing scale R_0 (the wave number $k_0 = \pi/R_0$); by the initial amplitude of the vortex velocity, v_0, on that scale; and by the value

$$\tau_{max} = \begin{cases} 2.0\ t_{rec} z_{rec} & \text{if} \quad \Omega h^2 \ll 0.08 \\ 5.0\ t_{eq} z_{eq} & \text{if} \quad \Omega h^2 \gg 0.08 \end{cases} \tag{2}$$

which gives the time-scale of subsonic evolution. From the physical point of view, the parameter α determines the hydrodynamical spreading of whirls. The number of revolutions of a whirl of the scale R_0 up to the instant t_{rec} is equal to $N \sim \alpha$ if $\alpha \ll 1$, and $N \sim \ln \alpha$ if $\alpha \gg 1$.

For different values of α the following variants of the evolution of cosmological turbulence are possible:

(I) If $\alpha \ll 3$, the initial velocity spectrum transforms into the Kolmogorov spectrum up to the inertial scale $R_i \ll R_0$. On scales $R_i < R \leqslant R_0$ the spectrum retains its relic form. The viscous dissipation of energy is insignificant.

(II) If $\alpha \sim 3$, then the inertial scale R_i grows by the instant t_{rec} up to R_0. Consequently, on all the scales, from the internal, R_d, up to the external one, R_0, the Kolmogorov spectrum is established. The dissipated turbulent energy is of the order of the initial whirl energy.

(III) If $\alpha \gg 3$, the scale R_i has time to grow up to R_0, after which the spreading of the whirls occurs. The energy of the turbulence generated is small compared with the initial whirl energy since the latter dissipates almost entirely into heat.

Let us define the spectral energy density $E(k)$ by the relation

$$\tfrac{1}{2}\overline{v^2} = \int_0^\infty E(k)\, \mathrm{d}k. \tag{3}$$

If the initial whirl spectrum was of power-law form

$$E_0(k) \propto k^m, \tag{4}$$

it would transform according to a self-similar solution. The maximum scale increases with time due to the spreading as

$$R_{max} = R_0 \left[1 + \frac{(\tau - \tau_0)\, k_0 v_0}{\sqrt{2 p_m^2 q_m}} \right]^{2/(m+3)}, \tag{5}$$

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where both p_m and q_m are constants of the order of unity weakly depending on m; and

$$\tau = \left(\frac{\pi}{8\mathscr{G}\varrho_{r,\,\mathrm{eq}}}\right)^{1/2} z_{\mathrm{eq}}\,\frac{6}{\pi}\left(\mathrm{arc\ tg}\sqrt{3+4\,\frac{z_{\mathrm{eq}}}{z}} - \pi/3\right). \tag{6}$$

The turbulent energy content decreases with time as

$$\tfrac{1}{2}v^2 = \tfrac{1}{2}v_0^2 \times \left(1+\frac{z_{\mathrm{eq}}}{z}\right)^{-2} \times \left[1+\frac{(\tau-\tau_0)\,k_0 v_0}{\sqrt{2p_m^2 q_m}}\right]^{-(2m+2)/(m+3)} \tag{7}$$

The first term in Equations (7) is the initial energy content, the second term corresponds to the adiabatic decrease of the energy due to the expansion, and the third term describes the energy losses which turn into heat in the course of the hydrodynamical readjustment of the initial spectrum.

On scales $R < R_{\max}$ the initial power spectrum transforms into the Kolmogorov form

$$E(k, t_{\mathrm{rec}}) = A\left(1+\frac{z_{\mathrm{eq}}}{z_{\mathrm{rec}}}\right)^{-2} k^{-5/3}, \tag{8}$$

where $A \sim v_0^{4/3}\tau_{\max}^{-2/3}$. The numerical factor in A reaches its maximum when

$$\alpha = \alpha_{\mathrm{opt}} \equiv \frac{m+3}{2m+2}\sqrt{2p_m^2 q_m}. \tag{9}$$

The value of $A_{\max}$ remains within the limits 0.33–0.411 when m changes from zero to infinity. The value of A in Equation (8) changes little even if α differs significantly from α_{opt}.

Consequently, whatever the initial whirl spectrum, the resulting turbulent spectrum at the instant t_{rec} has the universal Kolmogorov form, and its amplitude essentially does not depend in detail on the initial spectrum.

We have proved this important conclusion by numerical computations. The initial spectrum has been taken as a hump with power-law asymptotes rather than as a pure power-law spectrum which had been used in the analytical study. The inertial term which describes the energy flow from larger scales to smaller ones had been taken in its Heisenberg form. This investigation is somewhat similar to that carried out by Chandrasekhar (1950), who considered the evolution of turbulence in a non-expanding medium. The results of our computations are illustrated in Figures 1–3. The common feature of the evolution of various initial spectra is that after a few hydrodynamical times the region $k > k_0$ turns out to have a Kolmogorov spectrum and then evolves according to a self-similar solution.

The conclusion is that in the inertial region the velocity spectrum at the epoch of decoupling is rather insensitive to the form of the initial spectrum.

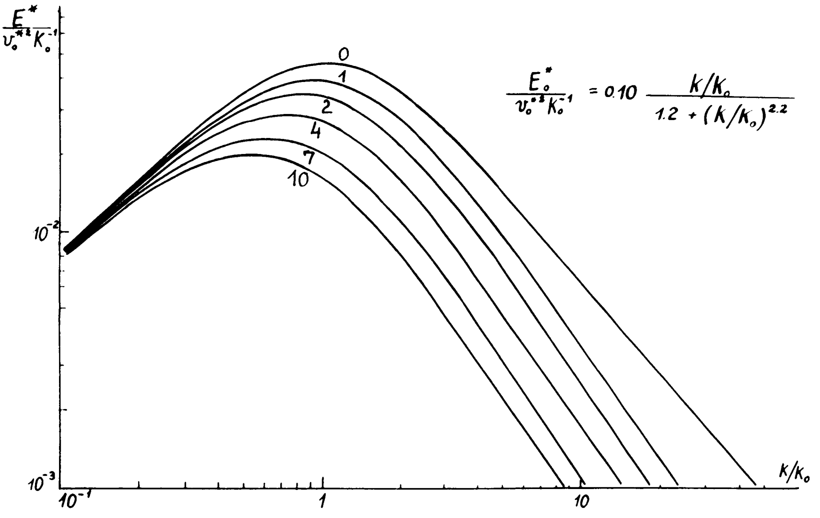

Fig. 1. The readjustment with time of the whirl spectrum whose initial shape is described by the formula shown at the top of the figure. New variables are used which reduce an evolution in the expanding universe to that in a non-expanding medium. Asymptotically $v^* = v$ at $z \gg z_{eq}$ and $v^* = (z_{eq}/z)\, v$ at $z \ll z_{eq}$; $E^* = E$ at $z \gg z_{eq}$ and $E^* = (z_{eq}/z)^2\, E$ at $z \ll z_{eq}$. The figures near the curves give time in units of the initial hydrodynamical time.

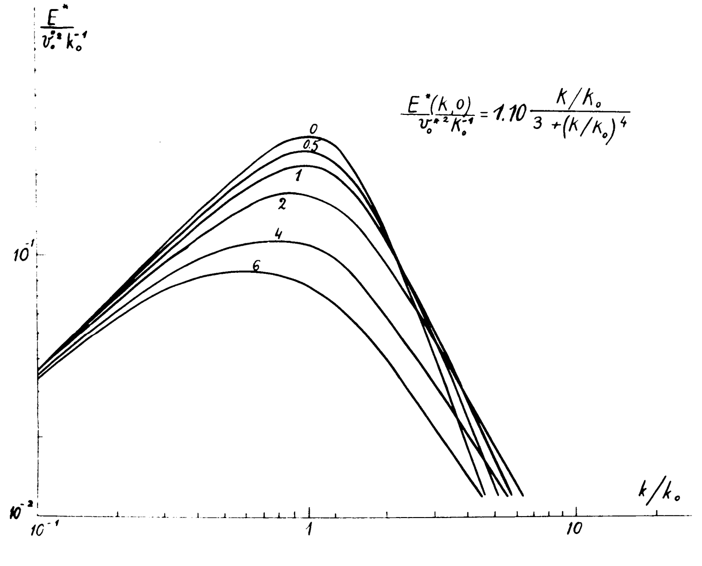

Fig. 2. The same as in Figure 1. The initial velocity spectrum is steeper on small scales.

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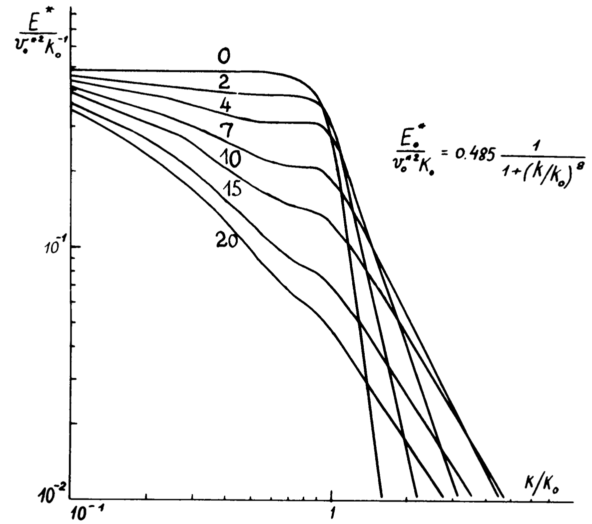

Fig. 3. The same as in Figure 1. The initial velocity spectrum is still steeper on small scales and is flat on large scales. The time needed to transform into Kolmogorov spectrum at $k > k_0$ is largest for this case as compared with Figures 1 and 2.

3. Post-Recombination Evolution of Cosmological Turbulence on Large Scales and the Formation of Clusters of Galaxies

Let us consider the post-recombination fate of turbulence on scales sufficiently large that the mass $M \gg 10^{12}\, M_\odot$ is contained within them (Ozernoy, 1971). Such large masses obviously do not dissipate either before or during the decoupling phase unless Ωh^2 is too small. At the epoch $t \approx t_{\rm rec}$ on these scales which correspond to protoclusters of galaxies inhomogeneities of cosmogonical importance are generated. It should be noted that inhomogeneities with amplitude

$$\delta\varrho/\varrho \sim W^2 \tag{10}$$

were produced before decoupling when the medium was only weakly compressible (Ozernoy and Chernin, 1968). However these inhomogeneities cannot grow, because their scale $R < ctz$, i.e. is less than the Jeans wavelength.

At the epoch of recombination, when the pressure drops sharply, the eddies will go over to the supersonic regime. Irrotational (potential) velocities will be generated with an amplitude greater than that of pre-recombination inhomogeneities unless the parameter $W = v_0/c \gtrsim 0.3$. The amplitude of the inhomogeneities that are generated during the decoupling phase will be determined by the ratio $(t_{\rm exp}/t_h)|_{\rm rec} = (vtz/R)|_{\rm rec}$, and on sufficiently large scales, where this ratio is small, it can readily be evaluated from perturbation theory. The linearized system of Euler's equation (with zero pressure), Poisson's equation and the equation of continuity leads to the conclusion that the asymptotic behaviour of the density contrast has at $t \gtrsim 3t_{\rm rec}$ the following form:

$$\frac{\delta\varrho}{\varrho}=\tfrac{9}{20}(t_{\rm rec}z_{\rm rec})^2\ \nabla(v\nabla)\,v\,\big|_{\rm rec}\left(\frac{t}{t_{\rm rec}}\right)^{2/3}. \tag{11}$$

Thus the inhomogeneities grow owing to the usual gravitational instability, and their distribution in space is determined completely by the spatial structure of the parent turbulence.

The growth of the density contrast will ultimately suppress the differential velocity of cosmological expansion inside a perturbation of a given scale, and isolate the perturbation from the expanding background. The condition

$$\frac{\delta\varrho}{\varrho}\approx 1 \tag{12}$$

can be taken as a rough criterion for isolation. The subsequent transition of a cluster into a steady state, as well as relaxation processes, will hardly change significantly the gross dynamical parameters of the cluster, for example, its effective radius and internal velocity dispersion. Therefore it is reasonable using Equation (12) to calculate dynamical relations such as 'mean density – effective radius', 'velocity dispersion – effective radius' in order to compare them with the observational data.

An example of such a comparison is presented on Figure 4 where the virial mean density of a sample which contained 143 galaxy systems of various richness is plotted versus the effective radius of a system. Surprisingly, the agreement with the theoretical relation

$$\langle\varrho\rangle\approx 10^{-26}(\Omega h^2)^{3/7}\left(\frac{R}{1\ \rm Mpc}\right)^{-12/7}\ {\rm g\ cm^{-3}} \tag{13}$$

is more than satisfactory. The relation 'radial velocity dispersion-radius' (or mass)

$$\langle v_r^2\rangle^{1/2}\approx 10^3(\Omega h^2)^{3/4}\left(\frac{R}{1\ \rm Mpc}\right)^{1/7}\frac{\rm km}{\rm s}\approx 10^3(\Omega h^2)^{1/6}\left(\frac{M}{10^{15}\ M_\odot}\right)^{1/9}\frac{\rm km}{\rm s} \tag{14}$$

agrees qualitatively with observation as well, although the weak dependence in Equation (14) on mass does not permit a test of the value of the exponents.

The theory predicts that galaxy velocities in clusters are a mixture of both the relic rotation and motions produced later owing to the hydrodynamical and gravitational instabilities. The ratio of the chaotic to vortex velocities is expected to be of the order of $v_{\rm chaot}/v_{\rm rot}\sim(10^{12}\ M_\odot/M)^{4/9}$ for gravitationally bound systems.

The amplitude of the inhomogeneities generated has a cut-off on the scale $R_{\rm max}$, because at $R>R_{\rm max}$ the velocity spectrum preserves its relic form. It appears from the theory discussed that if $\alpha\sim\alpha_{\rm opt}$ and $\Omega h^2\sim 0.1$–0.5, then the maximum scale of metagalactic structures, R_0, is about 100 Mpc. Approximately the same value is given by observational cosmology for the homogeneity scale size. The choice $\alpha\sim\alpha_{\rm opt}$ means,

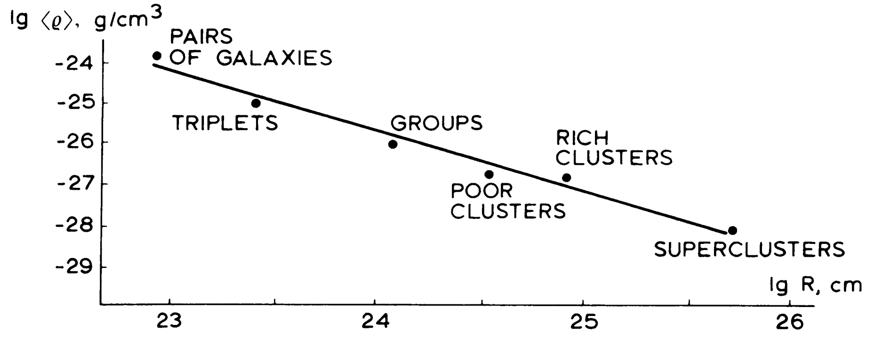

Fig. 4. The virial density of a group or cluster of galaxies as a function of its effective radius. The heavy line is the theoretical relation (13).

roughly speaking, that at the moment $z = z_{eq}$ the value of $r_0 = R_0/(1+z)$ is not significantly different from the horizon size. If this coincidence is not accidental then on scales as large as $R \gtrsim 100$ Mpc the density contrast must tend to zero very sharply. If this is the case, the velocity spectrum on scales $R \gtrsim 100$ Mpc is indeed relic. The detailed investigation of such large scales may give valuable information about the form of the primaeval velocity spectrum.

4. Alternatives for Post-Recombination Evolution of Small-Scale Turbulence. The Formation of Galaxies

Let us turn now to problems concerning the post-recombination evolution of turbulence on small scales which contain the mass $M \lesssim 10^{12}\, M_\odot$. In contrast to the large scales, the picture here is much more complicated. The reason is that the viscous dissipation may damp the motions on small scales. The post-recombination evolution depends strongly on whether the value $R_d/\hat{R}$ is greater or less than unity by the time recombination has finished. Here

$$R_d \approx 2.8 \times 10^{24} (\Omega h^2)^{-3/2}\ \text{cm} \qquad (\Omega h^2 \gg 0.08) \tag{15}$$

is, according to Chibisov (1972), the maximum damped scale of turbulence (R_d contains the mass $M_d \approx 4.7 \times 10^{11} (\Omega h^2)^{-7/2}\, M_\odot$), and

$$\hat{R} \equiv R_h(t_{rec}) = (vtz)_{rec} \approx 6.2 \times 10^{24}\, W (\Omega h^2)^{-7/4}\ \text{cm} \qquad (\Omega h^2 \gg 0.08) \tag{16}$$

is the scale of 'frozen out' motions in the absence of damping ($\hat{R}$ contains the mass $\hat{M} \approx 5.3 \times 10^{12}\, W^3 (\Omega h^2)^{-17/4}\, M_\odot$).

If $R_d/\hat{R} \ll 1$, then on scales $R_d < R < \hat{R}$ the supersonic character of the post-recombination turbulence can display itself completely. During one turn-over time which is less than that of expansion, the restoration of the damped motions as well as the generation of large irrotational velocities and corresponding large inhomogeneities may, in principle, occur. The quantitative scheme of their transformation into galaxies is considered by Ozernoy and Chibisov (1970).

However this scheme is invalid if $R_d/\hat{R} \gtrsim 1$. In this situation the motions remain 'frozen out' on all scales rather than only on the scales of protoclusters ($R > \hat{R}$). Consequently, appreciable restoration of the damped velocities and generation of large inhomogeneities will not occur.

These alternatives for the post-recombination evolution of the cosmological turbulence, I shall call for brevity 'rumbling' and 'silent' evolution, respectively.

The important details of 'rumbling' evolution discussed by Peebles (1971), Ozernoy and Chibisov (1970, 1971) are poorly understood at present. Harrison (1973b) suggested that the magnetic field generated by the whirls before decoupling prevents the isolation and collapse of protogalaxies immediately after recombination.

In any case it is of interest to calculate the fraction of the turbulent matter which will undergo appreciable contraction just after recombination if pressure and gravitation are neglected. This fraction, Δ, is plotted against $R_d/\hat{R}$ in Figure 5 (Kurskov and Ozernoy, 1974c). If $R_d \ll \hat{R}$, then $\Delta \approx 0.5$. On the other hand, if there is even a small excess of R_d over $\hat{R}$, then the fraction of turbulence evolving in the 'rumbling' way decreases exponentially, and we have predominantly 'silent' evolution.

The value $R_d/\hat{R} \approx 1$ when

$$W = W_{\text{crit}} \approx 0.45(\Omega h^2)^{1/4} \qquad (0.08 \ll \Omega \ll 1). \tag{17}$$

The ratio $R_d/\hat{R} > 1$ when $W < W_{\text{crit}}$, and vice versa. Unfortunately, the observational constraints on the value of W do not allow one to determine reliably whether W is greater or smaller than W_{crit}. Therefore, we cannot conclude which of the 'rumbling' or 'silent' alternatives is preferable. To solve this problem, we need detailed theories of both alternatives.

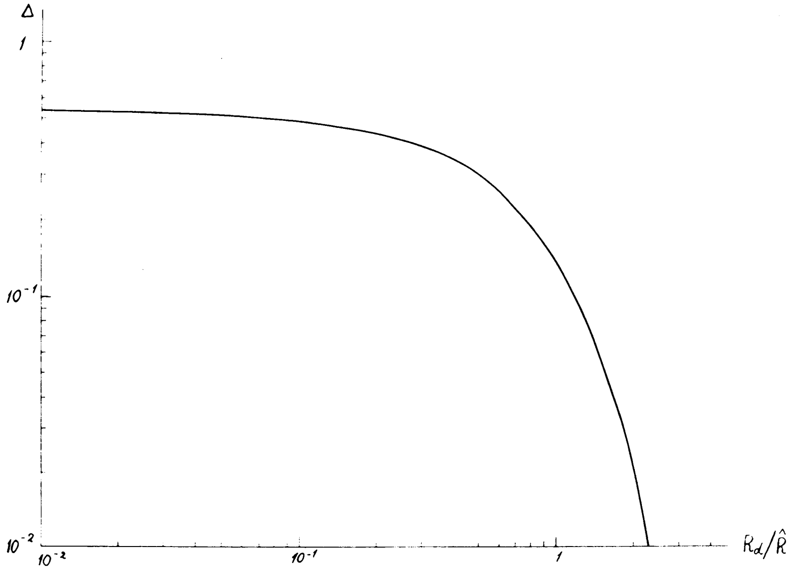

Fig. 5. The fraction of the turbulent matter which undergoes appreciable contraction just after decoupling if pressure and gravitation are neglected. vs $R_d/\hat{R}$.

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The lack of physical theory for supersonic turbulence makes difficult further investigation of 'rumbling' evolution. On the other hand the theory of 'silent' evolution may be developed, in principle, in great detail. This study is now in progress (Kurskov and Ozernoy, 1974c, d), and only preliminary results may be given at present.

'Silent' evolution has, generally speaking, two variants.

(I) If the amplitude of inhomogeneities on the scale of the damped motions is small compared with that on large scales, then galaxies will form at the stage of isolation of protoclusters owing to fragmentation of the latter. Asymmetric contraction of protoclusters will lead to the generation of supersonic turbulence and shock waves, which produce large inhomogeneities that evolve subsequently into galaxies. The resulting galactic angular momentum is high enough to explain the observed galaxy rotation. This variant is very similar to the appearance of supersonic turbulence in the theory of adiabatic perturbations considered in the last Section of the paper by Ozernoy and Chibisov (1970). It is also quite analogous to the 'pancake' model of Zel'dovich (1970). The important difference is that the clusters themselves may possess rotation related to the primaeval whirls, while the 'pancakes' do not.

(II) The second variant of 'silent' evolution is as follows. Let us assume that the amplitude of inhomogeneities on the scales of the damped motions is sufficiently high to produce galaxies *before* the isolation of clusters of galaxies. Estimates show that all kinds of inhomogeneities generated by the turbulence before and during the decoupling are insufficient to make the birth of galaxies independent of the formation of clusters. In principle only inhomogeneities related to primaeval entropy perturbations, which are not damped before and during the epoch of decoupling, may prove to be of sufficient amplitude.

The angular momentum of these inhomogeneities is $(R_d/\hat{R})^{2/3}$ times smaller than in 'rumbling' evolution. For R_d only slightly larger than $\hat{R}$, this factor is insignificant; on the other hand the small excess of R_d over $\hat{R}$ is quite sufficient to realize this variant of 'silent' evolution.

In this way it is possible to explain a number of observational data. However much more work is needed in order to reach definite conclusions about the validity of either variant of 'silent' evolution.

5. Discussion

5.1. Observational Constraints on the Velocity of Primaeval Whirls

It is of importance to know what limits – both theoretical and observational-constrain the dimensionless amplitude $W = v_0/c$ of the initial whirl velocity. A *lower* limit to W may be obtained from the condition that the energy-containing scale must not dissipate after the end of recombination. The most informative *upper* limit on W is given by the fact that distortions of the Rayleigh-Jeans part of the present microwave background spectrum are small in spite of the dissipation of cosmological turbulence. This dissipation and the corresponding distorsions of the spectrum are calculated in detail by Kurskov and Ozernoy (1974b).

The upper and lower limits of W are presented in Figure 6 as a function of Ωh^2 for various values of the whirl spreading parameter α. The constraints are more severe for large α and small Ωh^2 because turbulent dissipation is greater and earlier, the larger α and the smaller Ωh^2. If α is of the order of α_{opt} (see Equation (9)), as apparently follows from the theory of the formation of clusters of galaxies, the region of permitted values for W is rather wide.

A more obvious presentation of the same constraints is given in Figure 7, where W is plotted against α for the two most popular values of Ωh^2 (1 and 0.05). The critical line between the alternatives of 'rumbling' and 'silent' evolution is also plotted. As is seen, no definite choice between these modes of evolutions can be made at present, but 'silent' situation seems to be more probable.

The other constraints on the parameter W, related to small-scale anisotropy of the present microwave background (Chibisov and Ozernoy, 1969) or to the abundance of cosmological helium (Silk and Shapiro, 1971; Tomita, 1972) are much less conclusive.

5.2. Some problems concerning further work

Apart from the further development of the whirl cosmogony (the choice between the two alternatives is an example of topics to be discussed) there is an important problem concerning the origin of the whirls themselves. When the dimension of a whirl exceeds the horizon size, the cosmological expansion is considerably anisotropic (Ozernoy and Chernin, 1968) and the influence of whirls on the metric is important. This situation was christened by Tomita (1972) as 'space-time – curvature turbulence'. The

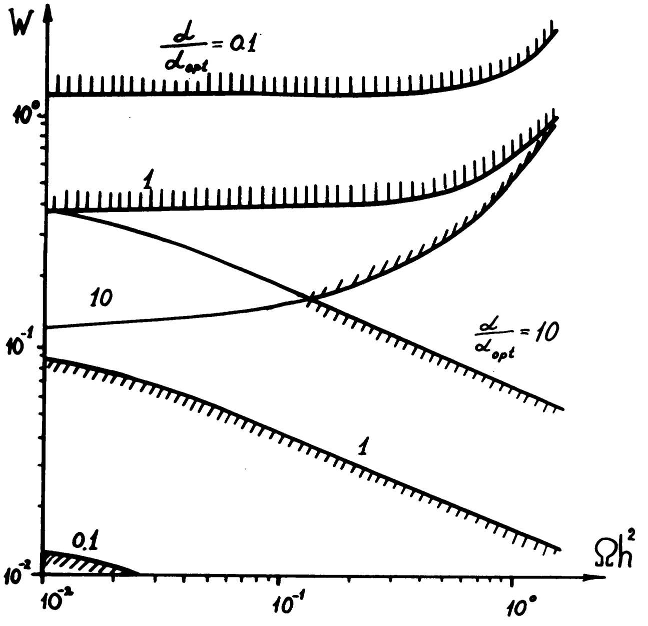

Fig. 6. The upper and lower limits of $W = v_0/c$ as a function of Ωh^2 for three values (0.1; 1 and 10) of the whirl's spreading parameter α.

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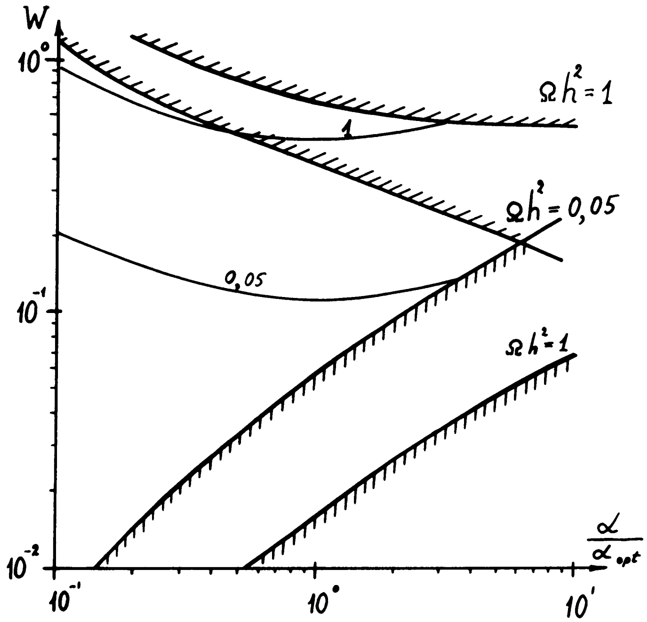

Fig. 7. The same constraints on W plotted vs α/α_{opt} for two limiting values of Ωh^2 (1 and 5×10^{-2}). The lines labelled 1 and 0.05 are dividing lines, W_{crit}, between 'rumbling' and 'silent' variants of evolution.

detailed analysis of this stage, including the possibility of the origin of whirls from shear (Silk, 1972), may give the expected connection between cosmology and the present characteristics of galaxies and clusters of galaxies.

Most important, in this respect, are searches for rotation on scales as large as clusters of galaxies and, especially, superclusters. There is some observational evidence summarized in Ozernoy (1973) that such rotation does exist. If this rotation actually exists, it cannot be produced by any local effects and must be primaeval.

6. Conclusions

At the very origin of our Universe it apparently hesitated between two extreme alternatives: to be very smooth and regular or to be entirely chaotic. It is rather unnatural to imagine that the Universe was entirely successful in evolving according to a very special cosmological model such as the Friedmann case with an accuracy as high as 10^{-4}! On the other hand, it is hardly conceivable that Nature was so irresponsible and careless as to make the Universe absolutely chaotic.

The main purpose of this lecture was to investigate what happens if the early universe were anisotropic and were prepared in some intermediate manner – not too carefully and not too negligently. Surprisingly, it turns out that the final spectrum of motions and corresponding inhomogeneities does not depend essentially on the details of the initial spectrum. This attractive result must, I think, encourage the further development of the vortex cosmogony.

The theory leads to the conclusion that the origin of galaxies may be related to an essentially more complicated cosmology than the Friedmann models, because other factors such as primaeval whirls may be needed. In this case the rotation of galaxies and, especially, of clusters of galaxies and superclusters will be of the same importance as the relic radiation. Of course, the whirls themselves as well as the relic radiation must be produced in some way in the more remote past. In any case further development of the whirl concept may give valuable information concerning the very earliest stages of the expansion of the Universe.

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DISCUSSION

Poveda: Does the kinetic energy of the galaxies formed by your vortices satisfy the Virial theorem as members of clusters?

Ozernoy: Yes, but on scales as large as superclusters the initial density contrast produced by turbulence may be insufficient to form gravitationally bound systems during the course of clustering.

Rees: What constraints does the microwave background isotropy place on the parameters of the primordial turbulence?

Ozernoy: The constraints on W from the microwave background isotropy were calculated in *Astrophys.*

Letters **3**, 189 (1969) and are not too informative because they contain the unknown small factor $e^{-\tau}$ where τ is the optical depth due to Thomson scattering. The secondary reheating of the intergalactic medium must be investigated in detail in order to obtain some realistic constraints.

Bardeen: Is damping of rotational motions by electron drag during recombination really negligible on the scale of clusters of galaxies in a low density universe, in view of the importance of electron drag in damping velocity overshoot of density perturbations?

Ozernoy: The damping of rotational velocities is given by Equation (15) and is indeed larger for low Ω. However, in a low density universe the same problem will appear for theory of primaeval inhomogeneities: the masses damped at this epoch may be as large as $10^{15}\ M_{\odot}$. Very small values of Ω give a very narrow window of permitted values of W and seem rather improbable.

Novikov: Does the theory give any predictions about the orientations of the axes of rotation of different galaxies in the same cluster?

Ozernoy: The spatial correlation of metagalactic turbulent velocities provides an explanation of the connection between the morphological type of a cluster of galaxies and that of the galaxies themselves (see *Soviet Astr.* **15**, 923, 1972). Although the detailed picture needs to be elaborated in detail, a rough correlation between the rotational axis of galaxies and of the cluster of galaxies as a whole may be expected unless tidal forces destroy this correlation. It is most desirable that observers cast some light upon the actual orientation of galaxies as well upon the rotation of clusters of galaxies.

Silk: At what redshift do the metric perturbations become singular in the whirl theory?

Ozernoy: The metric perturbations become of the order of unity at the instant $t_F \approx W^4 t_{eq}$ (t_F, the moment of 'Friedmannization', corresponds to the transition from intrinsically anisotropic early stages to a more or less isotropic [Friedmann] expansion). The behaviour of the metric at $t < t_F$ remains unknown since cosmological models in which the influence of whirls on the metric is important do not exist.

Novikov: What is the epoch of galaxy formation in the whirl theory?

Ozernoy: It depends on whether the post recombination evolution is of the 'rumbling' or 'silent' type. Detailed calculations to choose between them are now in progress. Crude estimates are not very useful.

Reinhardt: I would like to make a short remark on the orientation of galaxies in superclusters. Some of them seem to be flattened systems; at least this is true for the Local Supercluster. I think it is a legitimate and interesting question whether the constituent galaxies, being flattened objects themselves, exhibit a preferential orientation with respect to the equatorial plane of the supercluster. Dr Roberts and I looked into this problem using the apparent axis ratios and position angles of spiral and lenticular galaxies in the Local Supercluster. For the axis ratios we used de Vaucouleurs' Reference Catalogue and for the position angles Brown's measurements, which are the largest body of data available for this quantity. We found the following:

(i) The axis ratios increase with increasing supergalactic latitude.

(ii) The position angles tend to avoid the direction to the Supergalactic Poles.

Both results are significant at the 2 to 3σ level of confidence. They imply that the planes of the galaxies tend to be parallel to the Supergalactic Equatorial Plane, or, to put it another way, that the angular momenta point preferentially to the Supergalactic Poles.

The same result seems to hold in a concentration of galaxies in Pisces which is of the size of a supercluster.

I made this comment because I think that these findings are of fundamental importance for the formation of superclusters and the origin of the angular momenta of galaxies. However, much work has still to be done, before this effect can be regarded as being established, especially in the light of the recent results of Peebles and his group which cast doubt on the measurements of position angles by Brown.

Icke: This alignment can be very simply explained if galaxies form in elongated clusters. Then streaming will tend to be parallel to the gravitational potential lines of the cluster (the 'geostrophic effect') and hence alignment will result.

Partridge: A few years ago I looked at the orientation of spiral spin axes in the Hercules cluster and found no statistically significant result.