THE WHIRL THEORY OF THE ORIGIN OF STRUCTURE IN THE UNIVERSE

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1. INTRODUCTION

There are at least two reasons for examining different theories of galaxy formation:

(i) We do not know the initial conditions in the early Universe;

(ii) We do not know which forces were most important for the origin and evolution of initial perturbations.

The first reason forces us to deal with perturbations of different types, i.e. adiabatic, turbulent and entropy perturbations. The second makes it necessary to examine the influence of non-gravitational forces - for instance, local vortices. The whirl theory of the formation of structure in the Universe is an example of a consistent theory which introduces - by means of initial conditions - non-potential vortex perturbations.

One point should be emphasized even in these introductory remarks. One of the first questions which often arises in whirl cosmogony is: why should one consider the rotation of galaxies to be primordial if it may be obtained as a result of the evolution of entropy or adiabatic perturbations? These arguments are however far from being completely convincing, at least in a quantitative respect. In fact, the nature of the perturbations has not yet been established. At the same time, the assumption that the rotation of galaxies is of primordial origin does not imply the introduction of any additional parameters. Moreover, the initial whirl velocity is the only essential parameter of the whirl theory. In this theory, as distinct from both adiabatic and entropy perturbation theories, there is no free choice of the velocity spectrum since it will develop into the standard Kolmogorov form in the course of the evolution of cosmological turbulence. Hence what, at first glance, seems to be a weakness of the theory is, in fact, one of its attractive features.

The whirl theory, in its present state, explains, of course, much

M. S. Longair and J. Einasto (eds.), The Large Scale Structure of the Universe, 427–438. All Rights Reserved.

more than the rotation of galaxies alone. This theory enabled us to find the spectrum of cosmological turbulence and the picture of its decay, to explain the origin and magnitude of rotational velocities, as well as the main dynamical parameters of both galaxies and systems of galaxies, gave estimates for the redshifts at which the birth of galaxies and systems of galaxies occurred - and all this by means of substantially only one single parameter which characterizes the amplitude of primaeval whirls. Most of these results have been obtained during the last few years jointly with A. A. Kurskov (see Kurskov and Ozernoy 1974a,b,c, 1975), and I would like to review them briefly (for a more detailed presentation, see Ozernoy 1976). Previous reviews (Ozernoy 1974, Jones 1976) deal with the theory in an earlier and less well developed stage.

2. THE EVOLUTION OF WHIRLS PRIOR TO RECOMBINATION

According to the main assumption of the theory, large-scale whirl motions with subsonic velocity v_o existed on all scales during the radiation-dominated era. This means that the dimensionless amplitude of the whirls was $W = v_o/c \lesssim 1/\sqrt{3}$. In the following we shall use a time-independent distance scale R which is related to physical size r by $R = r(1+z)$ (z is the redshift). We restrict ourselves to those stages of evolution when the maximum size of a whirl does not exceed the size of the horizon. Then we have a simple picture for the dynamical evolution which is determined by three processes: cosmological expansion, hydrodynamical (inertial) readjustment of motions and, finally, viscous dissipation. Characteristic times are different for different scales, and so they evole in a different manner. It is convenient to introduce a characteristic scale $R_h = vtz$ for which the hydrodynamical time $\tau_h = r/v$ is equal to that of cosmological expansion, $\tau_{exp} = r/\dot{r}$.

On <u>large</u> scales ($R >> R_h$) cosmological expansion is dominant, and the velocity of whirl motions, despite the expansion, preserves its initial value because of conservation of angular momentum, up to a redshift, $z_{eq} = 1.8 \times 10^4\ \Omega h^2$*,corresponding to the epoch of equality of matter and radiation densities, after which $v \sim (1+z)$.

On <u>intermediate</u> scales ($R_d << R << R_h$, where R_d is the scale of viscous dissipation) the primaeval whirl spectrum undergoes readjustment due to energy flow from large scales into smaller ones. A universal (Kolmogorov) spectrum is established on these scales as in normal laboratory turbulence. The mass corresponding to the upper limit of the Kolmogorov spectrum, attains its maximum at a redshift $z = z_{eq}$ and equals $5 \times 10^{15} W^3\ \Omega^{-2} M_\odot$. For reasonable values of $W \sim 0.2-0.5$ and $\Omega \sim 0.5$ this mass corresponds to rich clusters and even superclusters. A detailed investigation, both analytical and numerical, of the pre-recombination evolution of whirl motions showed (Kurskov and Ozernoy 1974a) that the

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*Here $\Omega = \rho/\rho_{crit}$, $\rho_{crit} = 1.05 \times 10^{-29}$ g cm^{-3}, $h = H_o/(75$ km s^{-1}Mpc$^{-1})$.

resulting turbulent spectrum becomes of universal form and its amplitude does not depend in any important way on the details of the initial motions.

The inertial readjustment of an initial whirl spectrum into a Kolmogorov spectrum proceeds only down to some minimum scale. On smaller scales the motions dissipate due to radiative viscosity, and the most important damping occurs both immediately and in the process of decoupling. The resulting scale R_d of damped motions corresponds to a mass $M_d \simeq 4.7 \times 10^{11}(\Omega h^2)^{-7/2} M_\odot$.

The relation between R_d and R_h at the instant of recombination is of great importance with respect to the post-recombination evolution of cosmological turbulence. At $z = z_{rec}$ the sound velocity drops, and all the motions become supersonic. The problem is whether at the instant of recombination the scale of hydrodynamical "freezing" of motions $\hat{R}$ is larger or smaller than R_d. In an earlier rather crude sketch of this theory (Ozernoy and Chibisov 1970) it was assumed that $\hat{R} > R_d$. On that basis the adversaries of the whirl theory came to the conclusion that immediately after recombination large density jumps produced by shock waves would appear on scales $R_d < R < \hat{R}$. However, this conclusion has not been confirmed by the detailed calculations made by Kurskov and Ozernoy (1974c) which, though model-dependent, were performed using rather reasonable assumptions about the influence of dissipation on velocity gradients. The calculations showed that not only on scales $R > \hat{R}$ but on <u>all</u> scales up to $\hat{R} \sim R_d$ the motions by the epoch of recombination become supersonic and at the same time "frozen-in". This means that the generation of shock waves by cosmological turbulence is impossible. Hence, the corresponding evolution of cosmological turbulence is "silent" rather than "rumbling".

It should be emphasized that the conclusion concerning the silent character of the evolution follows only from taking into account consistently the damping of turbulence, and <u>not</u> by the choice of a lower value of W which remains the same. The evolution of cosmological turbulence is "silent" up to the maximum value of $W = 1/\sqrt{3}$.

3. THE SPECTRUM OF DENSITY INHOMOGENEITIES PRODUCED BY COSMOLOGICAL STUDIES

Knowledge of the evolution of cosmological turbulence allows one to calculate the spectrum of small density inhomogeneities produced by turbulence at the epoch of decoupling of matter and radiation after which the inhomogeneities start to grow due to gravitational instability. The resulting spectrum of these density perturbations is shown in Figure 1. The spectrum is a sum of undamped inhomogeneities generated before recombination and those produced by undamped motions after recombination (marked A). Concerning the latter, they are generated on large scales where the hydrodynamical time is much larger than the expansion time. As a result, these inhomogeneities are rather small and are given

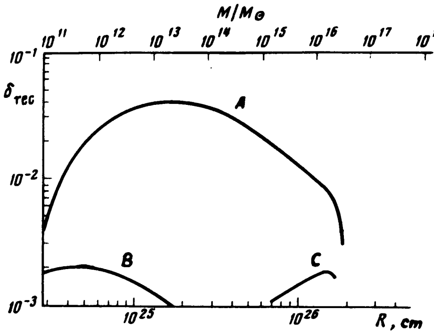


Figure 1

by a perturbation theory. Taking account of velocity damping, it follows that their amplitude attains its maximum value $\delta_{max} \simeq 0.3\ W^{4/3} (\Omega h^2)^{-1/3}$ on the scale $R \simeq R_d$ and diminishes sharply at $R < R_d$. On scales $R > R_d$ "frozen-in" motions generate inertially inhomogeneities with the amplitude $\delta \sim R^{-4/3} \sim M^{-4/9}$. Their amplitudes exceed those of local density inhomogeneities produced by turbulence before recombination (they are marked C in Figure 1). It is interesting that on scales $R < R_d$ post-recombination inhomogeneities (marked as B) are much smaller than those produced before recombination in the course of velocity damping. In the two-component cosmological substratum (matter + radiation), velocity damping due to radiative viscosity and thermal conductivity is accompanied by the generation of composition inhomogeneities, i.e. specific entropy perturbations. After decoupling, the radiation density becomes homogeneous and perturbations remain only in the matter. The amplitude of these entropy inhomogeneities attains a maximum value $\delta \simeq 10^{-2}\ W^{4/3}(\Omega h^2)^{-1/6}$ on a scale which contains the mass $M \simeq 3 \times 10^{10}(\Omega h^2)^{-11/4}\ M_\odot$.

4. FORMATION OF GALAXIES AND SYSTEMS OF GALAXIES

Having derived the spectrum of density perturbations produced by cosmological turbulence, it is easy to calculate their growth during the linear stage of gravitational instability. One can obtain the gross parameters of galaxies and systems of galaxies at the stage of their isolation from the background before the transition into the non-linear regime. If we do not require high precision, these estimates may be used for comparison with the observational data.

First, let us consider the parameters of objects which correspond to the maximum of the spectrum of density perturbations, i.e. to objects with mass $M \sim M_d$. As can be seen from Figure 1, the spectrum near the maximum is rather flat. This means that at the instant of isolation of the mass M_d hierarchical fragmentation will take place. This process will continue up to the mass at which the spectrum diminishes by a factor e, i.e. of a mass approximately 10^2 times smaller than M_d.

A flat maximum near $M \sim M_d$ indicates that in addition to fragmentation of this mass into smaller pieces the opposite process of clustering will also proceed. In other words, from objects of mass $M \sim M_d$ both massive galaxies and agglomerates of galaxies with a mass $M \lesssim M_d$ and $M \gtrsim M_d$ may be formed. It is reasonable to assume that in this statistical process the maximum mass which a galaxy may attain coincides with M_d.

The principal parameters of the most massive galaxies (or of complexes of massive galaxies), which are first formed with spectrum of the form shown in Figure 1, are as follows:

Redshift of isolation	$Z_{isol} \simeq 28 \left(\frac{W}{0.2}\right)^{4/3} \left(\frac{\Omega h^2}{0.5}\right)^{-1/3}$
Mass	$M \simeq 5 \times 10^{12} \left(\frac{\Omega h^2}{0.5}\right)^{-7/2} M_\odot$
Mean density at isolation	$\rho_{isol} \simeq 6 \times 10^{-25} \left(\frac{W}{0.2}\right)^{4}$ g cm^{-3}
Virial radius*	$r_{vir} \simeq 26 \left(\frac{W}{0.2}\right)^{-4/3} \left(\frac{\Omega h^2}{0.5}\right)^{-7/6}$ kpc
Virial density*	$\rho_{vir} \simeq 5 \times 10^{-24} \left(\frac{W}{0.2}\right)^{4}$ g cm^{-3}
Specific angular momentum	$K \simeq 2 \times 10^{29} \left(\frac{M}{10^{12} M_\odot}\right)^{2/3} \left(\frac{W}{0.2}\right)^{2/3} \times \left(\frac{\Omega h^2}{0.5}\right)^{-1/3}$ cm^2 sec^{-1}

*Dissipationless collapse is assumed.

The last expression requires some comment. Since inhomogeneities with mass $M \lesssim M_d$, where internal motions are damped, participate in the rotation on larger scales, the galaxies formed will possess angular momentum. In these regions of turbulence where the specific angular momentum is less than the mean value elliptical galaxies will form and where it is larger than the mean spiral galaxies will originate. The dependence of specific angular momentum on the mass for spiral galaxies is the relation shown above and this is similar to the observed relation which is described by $M^{2/3}$ (Ozernoy 1967, Nordsieck 1973) or $M^{3/4}$ (Freeman 1970). It is tempting to note that a spatial velocity correlation in cosmological turbulence is able to explain a correlation of the morphological type of a galaxy with the type of cluster to which it belongs: ellipticals occur mostly in rich clusters, and spirals in irregular clusters.

As can be seen from these expressions, the above results resemble typical gross galactic parameters if we adopt W ∿ 0.2 - 0.4, Ω ∿ 0.5 - 1. The correspondence between calculated and observed parameters is surprisingly good if one remembers the simplicity of the model.

Now, let us turn to the parameters expected for systems of galaxies (Ozernoy 1971, Kurskov and Ozernoy 1975). As mentioned above, after recombination when the pressure drops, turbulent motions with a Kolmogorov spectrum generate small inhomogeneities with amplitude which is smaller the larger the scale. Their subsequent growth and isolation through gravitational clustering lead to the formation of groups and clusters of galaxies. The isolation of a system occurs the later the larger its mass:

$$Z_{isol} \simeq 9 \left(\frac{W}{0.2}\right)^{4/3} \left(\frac{\Omega h^2}{0.5}\right)^{-17/9} \left(\frac{M}{10^{15} M_\odot}\right)^{-4/9}$$

Assuming as above that the collapse of a system of galaxies into the virial state is dissipationless, one obtains the virial density of a system

$$\rho_{vir} \simeq 4 \times 10^{-26} \left(\frac{W}{0.2}\right)^{12/7} \left(\frac{\Omega h^2}{0.5}\right)^{-2} \left(\frac{r}{1\ \mathrm{Mpc}}\right)^{-12/7} \quad \mathrm{g\ cm^{-3}}$$

where r is its radius. This relation is shown in Figure 2 together with the corresponding observational data summarized by Karachentsev (1967).

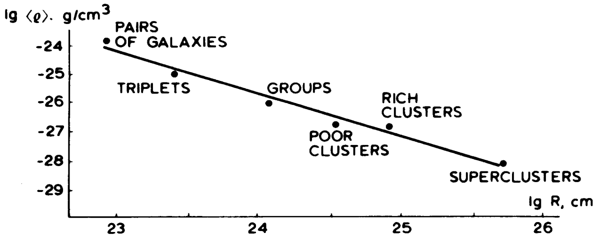


Figure 2

De Vaucouleurs (1971) gives an analogous relation for the virial mean density of systems of galaxies as a function of their size.

$$\langle\rho\rangle \simeq 10^{-26.4} \left(\frac{r}{1\ \mathrm{Mpc}}\right)^{-1.7} \quad \mathrm{g\ cm^{-3}}.$$

From extensive statistical analyses of catalogues of galaxies, Peebles (1974) obtained a similar value (-1.77) for the exponent of the spectrum. All these estimates are in rather good accord with the theoretical value 12/7 = 1.71 produced by the Kolmogorov velocity spectrum of cosmological turbulence. According to the theory the maximum scale of motions is of the order of 100 Mpc, and on larger scales the density contrast has a cut-off. Evidently this may be compared with the dimensions of superclusters as the largest scale of inhomogeneities in the Universe.

The theory predicts that the velocities of galaxies in groups and clusters are a mixture of primordial rotation and motions produced by subsequent gravitational instability. The ratio of chaotic and rotational velocities is expected to be $v_{chaot}/v_{rot} \sim (M/10^{12}M_{\odot})^{4/9}$ for gravitationally bound systems. For rich clusters of galaxies ($M \sim 10^{15}$ $M_{\odot}$) one obtains $v_{rot} \sim 10^{2}$ km/s. Applying the same formula at the limit of its applicability to superclusters, we have $v_{rot} \lesssim 10^{-2}$ v_{chaot}. Thus, for the Local Supercluster one expects $v_{rot} \lesssim 10\text{-}10^{2}$ km/s, in qualitative agreement with the recent revision by de Vaucouleurs (1976) of previous cruder estimates.

5. COSMOLOGICAL ASPECTS OF WHIRL COSMOGONY

First of all, let us consider what observational data limit the amplitude W of the initial whirl velocity on the largest scales of motion (this scale is naturally identified with the horizon scale at $t = t_{eq}$). The most interesting of these limits are shown in Figure 3.

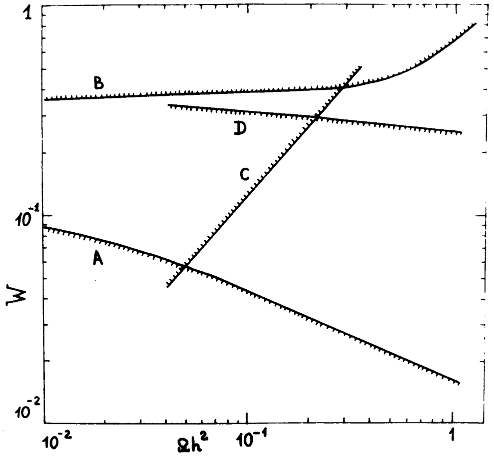


Figure 3

A lower limit to W (marked A) follows from the natural requirement that the scale containing most of the energy must not dissipate by the end of the recombination era. An upper limit to W (marked B) is provided by the fact that dissipation of cosmological turbulence must produce very small distortions (if any) of the Rayleigh-Jeans part of the spectrum of the relic radiation.

Recently Kurskov and Ozernoy (1977), using the available observational limits to the small-scale anisotropy of the relict radiation, improved considerably the constraints on W. A more stringent lower limit to W (marked D) follows from the temperature variations produced at recombination and then weakened by Thompson scattering as a result of secondary ionization of the metagalctic gas during the initial bright phase of galactic evolution (Ozernoy and Chernomordik 1976). A more stringent upper limit to W (marked C) follows from the temperature variations produced in the last scattering of the microwave background when the optical depth was $\tau \simeq 1$ at redshift $z_1 \sim 10$. From Figure 1 it follows that values $W \sim 0.3 - 0.4$, which provide a reasonable explanation of the parameters of both galaxies and systems of galaxies, do not contradict these more severe observational constraints. However, it should be stressed that a further improvement of the upper limit to angular variations of the relict radiation may be very dangerous for the present theory.

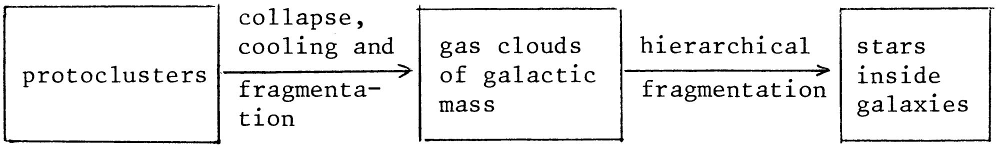
The whirl theory raises some problems not only for observational but also for theoretical cosmology. At early epochs, generally speaking, whirls make the cosmological expansion highly anisotropic, and we have some kind of "space-time curvature turbulence" (Tomita 1972). The transition from a Friedmann universe to an anisotropic one takes place at $t < t_F \simeq W^4\, t_{eq} \simeq 2 \times 10^7\ (W/0.2)^4(\Omega h^2)^{-2}$sec (Ozernoy 1971), and this means that helium and other light element production may be different from the standard picture. There is some controversy concerning estimates of the helium abundance produced in the anisotropic stage of cosmological turbulence (see, e.g., Tomita 1973, Barrow 1977), and further analyses are necessary. It is interesting to mention in this connection that the hypothesis of Chibisov (1976), who proposed that near the singularity the relativistic motions of both plasma and radiation were compensated for by oppositely directed vortex motions of free particles (for instance, of gravitons). Since the resulting vortex is zero, the metric is Friedmannian and such "zero vortices" do not influence element production at all; at the same time the whole picture of galaxy formation remains unchanged. "Zero vortices" do not lead to the problem of particle creation which may be serious for the usual whirl concept (Lukash et al. 1975). However, very special initial conditions are needed to have ab initio a total compensation of whirl motions for the normal and free particles.

6. DISCUSSION. COMPARISON OF THE WHIRL AND POTENTIAL CONCEPTS OF GALAXY FORMATION

Although a number of problems in the whirl theory remain unsolved, a test of the credibility of the theory in its present state consists in its ability to explain rather satisfactorily the main characteristics of galaxies and systems of galaxies. However, many of these features may be explained just as well according to the entropy or adiabatic theories. Evidently, a choice between different concepts should be made from some fundamental corollaries of these theories such as the mechanism for the formation of structure. The adiabatic concept is associated very closely with the fragmentation hypothesis, the entropy concept is based on the clustering hypothesis, whereas the whirl theory includes both. The situation is presented by the following scheme (cf Rees 1977):

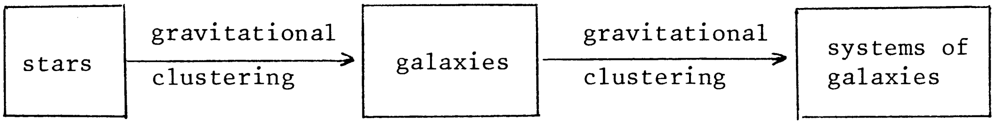
FRAGMENTATION HYPOTHESIS

(associated with adiabatic perturbations)



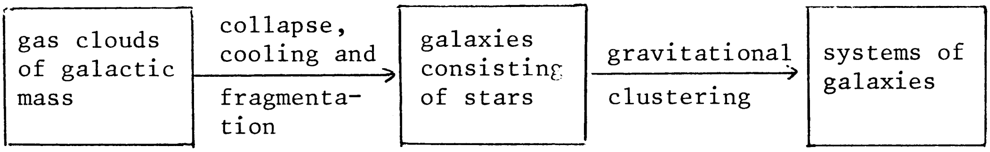
CLUSTERING HYPOTHESIS

(associated with entropy perturbations)



FRAGMENTATION-CLUSTERING HYPOTHESIS

(as given by the whirl theory)



Of course, the sequence of the formation of galaxies and clusters of galaxies depends also on the initial perturbation spectrum. In the adiabatic theory the natural choice of an initial white noise spectrum appears to be in contradiction with the observational data (Peebles 1974). The entropy theory is much better in this respect: it may be brought into agreement with the observed correlation function for a large interval of masses. One should recall that the whirl theory explains these data as well but with the principal difference that the spectrum of inhomogeneities is not designed initially to produce the observed result: it is calculated consistently and is independent (within broad limits) of the initial velocity spectrum. One can hope that further analysis, both observational and theoretical, of the fragmentation and clustering hypotheses may provide reliable tests for the choice between these different concepts.

7. CONCLUSIONS

During the last few years many theoretical problems which seemed to present difficulties for the whirl concept have been resolved. I mean, first of all, the evolution of cosmological turbulence immediately after recombination, which according to detailed calculations and contrary to simplified estimates turned out to be shockless and, at the same time, to be able to explain the main parameters of galaxies, not only their rotation. There are now two difficult problems for the theory: (i) creation of particles near the singularity and their influence on whirl motions, and (ii) the production of light elements in the whirl model with appropriate parameters W and Ω. Until much theoretical work is completed, these problems will remain unresolved as well as the main problem of the origin of the whirls themselves. By the way, the origin of primaeval perturbations is a problem common to all theories of galaxy formation. Some observational aspects of the theory seem to be more important at the moment. New measurements of the small-scale isotropy of the blackbody radiation leave only a narrow margin for the main parameter W of the whirl theory. At the same time it is worth noting that for values of W which do not contradict the observational constraints, the theory explains quite reasonably the main parameters of galaxies and systems of galaxies. Further observations and more detailed models will establish the plausibility of the whirl theory.

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DISCUSSION

Audouze: Could you comment in more detail on the nucleosynthetic implications of the whirl theory of the origin of the Universe? For instance, is helium produced in too large or in too small quantities compared to the canonical big-bang calculations?

Ozernoy: The problem is to produce a helium abundance which does not exceed the observed one. In order to calculate the expected abundance correctly, it is necessary to construct reasonable anisotropic cosmological models containing whirls at stages when the size of whirls exceeds that of the horizon.

Shandarin: I should like to stress that according to the adiabatic theory stars do not form in galaxies. Stars can form in gas glouds before galaxies have been formed.

Ozernoy: In most versions of the adiabatic theory (including the earlier version of the "pancake" concept) galaxies are formed in the course of fragmentation of protoclusters. It is true that another choice of free parameters makes it possible to obtain the picture you mentioned.

Silk: How do you account for the large number of dwarf galaxies in your model?

Ozernoy: I do not see any major difficulties with dwarf galaxies, which may be formed as a result of the fragmentation process on mass-scales $M < M_d$, where appreciable "entropy" inhomogeneities are present.

de Vaucouleurs: The low velocities you quoted for superclusters were for spherical systems. Do you have any estimate for the case of strongly flattened ("pancake") systems?

Ozernoy: If you consider a one-dimensional rather than a spherical character of the collapse for large scale systems you will obtain a smaller mean density for a system and, consequently, a smaller velocity for its rotation.

Jones: Before commenting I should stress that calculations in this kind of theory are extremely difficult and perhaps it is not surprising that various theoretical calculations disagree. However, two things are clear:

(a) the calculations of Barrow are better than those of Tomita and the nucleosynthesis problem must be taken seriously;

(b) turbulence, by its very nature, dissipates and one has to fight hard to overcome this natural decay.

We can only continue our attempts to evaluate this theory - it is very important to resolve the existing conflicts.