TOWARDS UNDERSTANDING THE LARGE-SCALE STRUCTURE ?

Avishai Dekel
Racah Institute of Physics
The Hebrew University
Jerusalem 91904, Israel

ABSTRACT. Although some theories, such as that of cold dark matter, are quite successful in explaining certain aspects of the formation of structure, we seem not to approach a satisfactory theory which can easily account for all the observational constraints on all scales. Most difficult to explain are the indicated clustering of clusters and bulk velocities on very large scales, when considered together with the structure on galactic scales and the isotropy of the microwave background. If these observations are correct, the only scenarios that can work are hybrids of certain sorts, which involve somewhat *ad hoc* choices of parameters; they are not the theories that would have emerged naturally from first principles, and they do not satisfy the criteria of simplicity and elegancy. I will discuss the currently popular scenarios and the apparent difficulties they face.

1. INTRODUCTION

The current situation in the two front lines of physics is curiously very different; in particle physics there is one 'theory of everything' – superstrings – but no experimental constraints in the foreseen future, while in cosmology, to the contrary, we have a growing body of interesting observations of the large-scale structure, most of which are discussed in this symposium, but we also have *many* theoretical scenarios to account for them. It is not that there is an observation which we cannot explain; it is that each basic theory seems to explain a different subset of the observations, or it has to be modified or patched whenever a new observational constraint is reported. At each step we drift away from the simple, elegant theory we should wish for. Thus, although the field is very fruitful observationally, and despite the great effort and many ingenious ideas from the theoretical side, we do not seem to get closer to a 'theory of everything' for the formation of large-scale structure in the universe.

I would list the most relevant observational constraints as follows:

(a) Systematic properties of galaxies – relevant to galaxy formation on scales $\leq 1\ h^{-1}Mpc$ (for reviews see Silk 1987; Faber 1987; Efstathiou and Silk 1983).

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(b) Quantities that measure the clustering of galaxies on scales $1-10\ h^{-1}Mpc$; the galaxy-galaxy correlation function, $\xi_{gg}(r)$, with the associated galaxy pair velocity dispersion, $v_{gg}(r)$, and the galaxy number density contrast within the Local Supercluster (LSC), δ_g, with the associated peculiar infall velocity, v_p (for reviews see Davis and Peebles 1983; Dekel, Einasto and Rees 1987).
(c) The structure of superclusters of galaxies on scales $10-100\ h^{-1}Mpc$, described in different contexts as 'filamentary structure', 'pancakes', 'bubbles', etc. (see a review by Oort 1983; Tully 1986; de Lapparent, Geller and Huchra 1986; Giovanelli, Haynes and Chincarini 1986).
(d) The presence of 'voids' – regions of very low number density of galaxies with typical dimensions $10-50\ h^{-1}Mpc$ (perhaps limited only by the size of the available samples) (See Oemler 1987 for a review).
(e) The clustering of rich clusters on scales up to $\sim 100\ h^{-1}Mpc$, expressed in terms of superclusters of clusters or by the cluster-cluster correlation function, $\xi_{cc}(r)$, which, for Abell clusters of richness ≥ 1, becomes linear only beyond $25\ h^{-1}Mpc$ and stays positive out to $100\ h^{-1}Mpc$ (e.g. Bahcall and Soneira 1983) and the associated cluster pair velocities of $\sim 1000\ km\ s^{-1}$ (Bahcall 1986).
(f) On a similar scale, the reported 'bulk motion' of $\sim 600\ km\ s^{-1}$ relative to the microwave background of the whole body of galaxies, groups and clusters around us in a sphere of diameter $\sim 100\ h^{-1}Mpc$ (Rubin *et al.* 1976; Burstein *et al.* 1986; Collins, Joseph and Robertson 1986).
(g) The upper limits on temperature fluctuations in the microwave background, $\delta T/T$, on the various angular scales (1^o corresponds to $100\ \Omega^{-1}h^{-1}Mpc$) (e.g. Uson and Wilkinson 1984; Melchiorri *et al.* 1981).
(h) The indications for evolution of clustering in the distribution of high redshift objects such as quasars (Shaver 1987), Lyman-α clouds (Sargent 1987), and galaxies in very deep surveys (Koo 1987).

When constructing a theoretical scenario to account for these observational constraints, there is a large multi-dimensional parameter space available. Let me list just the options which are conservatively regarded as plausible:
(a) The values for the cosmological parameters: the density parameter Ω can vary roughly in the range $0.1-2$, the cosmological constant Λ may be zero or non-zero ($< 3H_0^2$), and the Hubble constant H_0 is 'either' 50 or 100 $km\ s^{-1}\ Mpc^{-1}$ (which is less important in the present context).
(b) The nature of the dark matter (DM): Is it *baryonic*? Is it made of *'hot'* particles like $10-100\ eV$ neutrinos? Is it *'cold'* particles like axions, or $> keV$ photinos? Is it some sort of *unstable* DM which decays on a time scale slightly smaller than the Hubble time? Is it some mixture of the above?
(c) The origin and nature of the initial density fluctuations: Have they originated in an *inflation* phase or were they induced by something like cosmic *strings*? Is the local distribution function, $p(\delta)$, *Gaussian*, as would be the result of the former, or *non-Gaussian*, as predicted by the latter? Is the initial spectrum a power-law, $\langle|\delta_k|^2\rangle \propto k^n$, and if it is, what is the power n? Are the fluctuations *adiabatic* or

isothermal (isentropic fluctuations or iso-curvature fluctuations)?
(d) Are physical processes other than gravity important in the formation of structure? In particular, do nuclear *explosions* dominate the cosmogonic process?
(e) What is the relationship between the spatial distribution of galaxies and the underlying mass distribution? If galaxy formation is *biased* – how is it biased?

If I had to sketch the simplest, most elegant scenario – a theorist's dream – I would probably choose the following:
(a) A flat Einstein-deSitter universe, with $\Omega = 1$ to a great accuracy and $\Lambda = 0$, as would naturally have emerged from inflation, without much fine-tuning. Otherwise, in the Friedmann equation

$$1 - \Omega - \Lambda/(3H^2) = -k/(aH)^2, \qquad (1)$$

the initial conditions would have to be fine-tuned such that the present curvature radius a is 'just' of the order of the horizon radius H^{-1}, or the cosmological constant has a very specific non-zero value.
(b) The DM is made of the only kind of massive particles we know – baryons. Obvious astrophysical candidates are 'Jupiters', such as this planet we live on, or some kind of dead stellar remnants.
(c) The structure have grown from inflation-generated fluctuations: their local distribution function is Gaussian, $p(\delta) \propto exp[-\delta^2/(2\sigma^2)]$, based on the central limit theorem, their power-spectrum is scale-invariant (Harrison-Zeldovich) with $n = 1$, and they are adiabatic (curvature) fluctuations, preserving the baryon to photon ratio as a constant of nature which is determined by microphysics.
(d) Gravitational processes are dominant and explosions do not complicate matters.
(e) Galaxies trace mass without a bias – this would allow a straight-forward comparison between theory and observation.

I will try to describe in this talk how the observational constraints force us to drift away from this ideal scenario.

2. THE NATURE OF THE DARK MATTER

Can the universe be purely *baryonic*? The observed abundances of deuterium and He^3 imply, in the standard big-bang nucleosynthesis scenario, that the contribution of baryons to the mean density is $\Omega_b < 0.2$ (e.g. Audouze 1987). Thus, unless we are willing to consider non-standad nucleosynthesis theories (e.g. Rees 1985; Hogan 1987) or some segregation mechanisms for certain elements (e.g. Braun, Dekel and Elitzur 1987, in progress), we have to assume that baryons cannot account for $\Omega = 1$. The other serious problem of a pure baryonic universe is that the required density fluctuations, especially if adiabatic, are inconsistent with the observation that $\delta T/T < 10^{-4}$ on scales of 4.5' (Uson and Wilkinson 1984); the latter indicates small amplitudes for the density fluctuations at decoupling which cannot make the observed nonlinear structure by the present time (see Kaiser and Silk 1986 for

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a review). The small-angle temperature fluctuations had to be smeared out by reionization of the intergalactic medium no later than $z \sim 30\ (\Omega_b h/0.1)^{-2/3}$ to provide an optical depth > 1 for Compton scattering. This would require early formation of stellar objects that could have ejected the required energy into the IGM. The simple adiabatic fluctuations cannot give rise to such objects because they damp out on the relevant scales due to photon diffusion and viscosity (Silk 1968); A special kind of ('isothermal'?) fluctuations that could survive damping on small scales is required. So, a model which is dominated by the simplest type of DM requires a special open universe, and non-trivial initial fluctuations.

The above difficulties can be eased if the DM is *non-baryonic* and only weakly interacting. It is then not subject to nucleosynthesis constraints so it can amount to $\Omega = 1$, and because it was never coupled to the radiation like the baryons, the fluctuations could start growing before decoupling ($z \sim 10^3$), when the universe turned matter dominated at $z_{eq} \simeq 2.5 \times 10^4 \Omega h^2$, and thus yield non-linear structure today with only small temperature fluctuations at the last scattering surface. The major types of non-baryonic particles are classified as 'hot' and 'cold', corresponding to whether they became non-relativistic at or much before z_{eq}. The fluctuations were damped out by free-streaming on all scales smaller than a critical coherence length, λ_{fs}, which is the horizon scale at the time when the particles became non-relativistic. Given the initial spectrum of fluctuations, the resultant spectrum at z_{eq}, after which gravitational growth occurs, can be calculated for each type of DM. The shape of this spectrum, and in particular the presence or absence of a critical coherence length, determines whether the subsequent formation of structure would be 'top-down' or 'bottom-up' respectively. The scenarios predicted for each type of DM can then be confronted with the structure as observed today and as evolving from $z \sim 3$. Before we proceed it should be born in mind that while particle theories can easily predict numerous candidates of either type, there is no actual detection of such particles; the scenarios of non-baryonic DM are therefore *a priori* based on a speculative assumption. The experimental effort directed at detecting such particles is therefore such a crucial development.

3. CAN Ω BE 1? DO GALAXIES TRACE MASS?

The mass estimates on scales of $\sim 10\ h^{-1}Mpc$ are based on on methods such as modeling our infall into the LSC, or applying a cosmic virial analysis to pairs of galaxies. In a linear, spherical model for the LSC, for a given observed infall velocity of the shell containing the Local Group towards Virgo, Ω is related to the mean density enhancement δ interior to this shell by $\Omega \propto \delta^{-1.7}$. For given *rms* pair velocities the cosmic virial theorem gives $\Omega \propto \xi^{-1}$, where $\xi(r)$ is the two-point correlation function. The observed results suggest $\Omega \simeq 0.1 - 0.3$. How can we then have $\Omega = 1$? The low estimates are obtained using the quantities corresponding to *galaxies*: their number overdensity δ_g or the galaxy correlation function $\xi_{gg}(r)$. If, however, the galaxies cluster more than the matter, such that (in the linear approximation)

$$\delta_g = f\delta \quad \text{and} \quad \xi_{gg}(r) = f^2 \xi(r) \tag{2}$$

(the latter is the obtained value of Ω is larger and compatible with $\Omega = 1$ if $f \simeq 2 - 3$. This requires *biased galaxy formation.*

Perhaps the strongest argument for the need of bias is provided by the common existence of *voids* (a review by Oemler 1987; Geller 1987). The number density of galaxies in these voids seems to be typically less than 10% of the mean. (This is only a crude estimate; in the Bootes void, for example, no bright galaxy was found in a volume which contains on the average 32 galaxies.) Based on spherical models (e.g. Hoffman, Salpeter and Wasserman 1982), a similar underdensity in the mass corresponds at decoupling to $|\delta| \geq 10^{-2}$ if $\Omega \simeq 1$, and $\geq 5 \times 10^{-2}$ if $\Omega \simeq 0.1$. This is incompatible with the microwave isotropy on angles $10' - 1^o$ in any of the cosmogonic scenarios, unless reionization has washed out the fluctuations. The large-scale N-body simulations demonstrate the difficulty: even in pancake scenarios (e.g. White, Frenk and Davis 1983; Centrella and Melott 1983; Dekel and Aarseth 1984) such large regions are not found with a density below 25% of the mean; they cannot be substantially evacuated dynamically by the present epoch, which is defined by matching the correlation functions of the simulated mass and the observed galaxies. The situation is worse if $\Omega < 1$, where the voids are evacuated even less efficiently. To estimate the real mass density in voids consider a 'toy' universe which consists of superclusters (sc) and voids of uniform densities both in the matter and in the galaxies. The relation

$$(\delta_g/\delta)_{void} = (\delta_g/\delta)_{sc} = f \tag{3}$$

results trivially from the definition of the density contrasts. Assuming that the LSC and the Bootes 'void' are typical, we can adopt the corresponding observed values for the *galaxies*: $\delta_g \simeq 2.5$ and -0.9 respectively. If $\Omega = 1$, the real mass overdensity in the LSC must be $\delta \simeq 0.85$ ($f \sim 3$), so we get for the *mass* in the voids $\delta \simeq -0.32$. (The fractional volume in the voids is then 73% and the mass fraction is $\sim$ 50%.) These mass densities in superclusters and in voids are both compatible with $|\delta| \simeq 9 \times 10^{-4}$ at decoupling. If most of the mass is non-baryonic, this corresponds to $\delta T/T \simeq 3.5 \times 10^{-5}(\Omega h^2)^{-1}$, which is compatible with the isotropy constraints if Ωh^2 is not much smaller than unity. An open universe with $\Omega \simeq 0.2$ would be in trouble: it would require no bias in the LSC, and therefore a real deep mass underdensity of 10% in the voids. The corresponding $\delta T/T \sim 5 \times 10^{-3}$ would be hard to reconcile with observations.

Further support for bias is provided by the N-body simulations which show that neither the scenario of cold DM (CDM) nor the neutrino scenario can reproduce the observed distribution of galaxies unless it is *biased.* In both cases the matter correlation function steepens in time, and the stage of the simulation to be regarded as the present epoch is determined by matching its logarithmic slope to the observed $\gamma \simeq 1.8$ of galaxies. The CDM correlation length at this time turns out to be only $r_0 \simeq 1\ (\Omega h^2)^{-1}$ (Davis *et al.* 1985). Hence, for the galaxies to match the observed

$r_0 \simeq 5\ h^{-1} Mpc$, with $\Omega = 1$, the galaxies must be biased by $\xi_{gg}(r) = (5-20)\ \xi(r)$ (for $h = 0.5 - 1$), in agreement with the required value of f. In the case of $\sim 30\ eV$ neutrinos, at the time when the slope is 1.8 the structure is still young (e.g. Dekel and Aarseth 1984); collapse to pancakes must have occurred at $z \sim 1$. This poses a timing difficulty for any 'dissipative pancake' scenario which assumes that galaxies are 'daughters' of pancakes, since various lines of evidence suggest that galaxies began to form at $z \geq 3$ (e.g. based on high-redshift quasars and galaxy candidates). The difficulty is also one of scaling: the neutrino correlation length, by the time when its slope is right, has already grown to be $r_0 \simeq 8\ (\Omega h^2)^{-1}$, which is too large in comparison with galaxies unless $\Omega h > 1$. If the galaxies form only in the collapsed regions the constraints become even tighter. But note that the bias required here is therefore of an opposite sense: the galaxies should somehow be *less* clustered than the neutrinos.

4. MECHANISMS OF BIASED GALAXY FORMATION

Biasing is motivated by theoretical considerations as well. Based on the observed correlation between galaxy type and environment (Dressler 1980), it would be astonishing if galaxy formation were not significantly affected by environmental effects which could segregate the galaxies from the underlying mass. After considering the physical processes that might be involved in galaxy formation, one can be easily led to the conclusion that a bias of one sort or another is expected in almost every cosmogony.

Counting the general possibilities, the bias could be determined in each protogalaxy *autonomously*, e.g. by its background density, or it may be a result of *feedback* from other galaxies. This feedback influence may propagate by gas transport to limited distances, or by radiation or fast particles to larger distances. The result might be *destructive*, suppressing galaxy formation *locally* (causing 'under-clustering') or *far away* (causing 'over-clustering'), but it could also be *constructive*, enhancing galaxy formation in the neighborhood of other galaxies (e.g. explosions). I will elaborate on this using several of the 'standard' scenarios as examples.

4.1. A Uniform Component

The universe may be dominated by 'ultrahot' weakly interacting particles which do not cluster because they have velocities $> 10^3\ km\ s^{-1}$. But if the 'ultrahot' particles are relics of an early epoch, their mass would have always been dynamically dominant over the baryons, and would have inhibited gravitational clustering altogether (e.g. Hoffman and Bludman 1984). This would also yield an unacceptably fast expansion timescale during nucleosynthesis. A way around this difficulty involves supposing that these particles arise from nonradiative *decay of heavy particles* with lifetimes only slightly shorter than the age of the universe (Turner, Steigman and Krauss 1984; Flores 1987 for a review). Assuming that these decay products are substantially lighter than their unstable parents, they would be very 'hot'. Galaxies (halos) and clusters would have formed during the era of matter domination by the

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unstable particles, but they then expanded or even became unbound as a result of the decay. An elaboration of this idea suggests that the universe finally becomes dominated by a stable primordial CDM species (Olive, Seckel and Vishniac 1985) which helps explain the survival of structure on both small and large scales; but this requires certain *ad-hoc* fine-tuning among various DM components. Several astrophysical considerations constrain the allowable parameters in this scheme, and they may already eliminate it all together. For example, the decay epoch is bound to be $1 + z_D \leq 0.5$ based on the isotropy of the microwave background (Silk and Vittorio 1986) and the requirement that galaxies and the cores of rich clusters remain bound after the decay (Efstathiou 1985). The observed gravitational lenses, if due to typical galaxies, require $1 + z_D \leq 3$ (Dekel and Piran 1986). A lower limit of $1 + z_D \geq 5$ can be obtained from the dynamics of the Local Supercluster (Efstathiou 1985; Hoffman 1986) but this limit is very model dependent. On the other hand, assuming a quite general scenario for galaxy formation, we find that galactic rotation curves would not have remained flat if the universe were dominated by relativistic decay products (Flores *et al.* 1986).

The universe could be flat ($k = 0$) with $\Omega < 1$ if a non-zero *cosmological constant* contributed to the curvature such that $\Omega + \Lambda/(3H_0^2) = 1$. In some respects this idea resembles the alternative discussed above, but contrariwise, the Λ-term is unimportant at early epochs and so it would not have had such a serious inhibiting effect on galaxy formation. It is found in N-body simulations (Davis *et al.* 1985) that the large-scale structure in a flat CDM scenario with $\Lambda \neq 0$ is quite successful in reproducing the two and three point galaxy correlation functions and their peculiar velocities (with no further biasing in the galaxy formation). It is also compatible with the isotropy of the microwave background (Vittorio and Silk 1986). However, for the Λ contribution today to be comparable to the ordinary matter, the required fine-tuning is as *ad-hoc* as the one we intended to avoid by adopting $\Omega = 1$ (Peebles 1984).

4.2. Biasing In Hierarchical Clustering (e.g. Cold Dark Matter)

An enhanced clustering of galaxies over the background matter can arise in a 'bottom-up' scenario if galaxies formed only from exceptionally ***high peaks*** of the density distribution smoothed on galactic scales; peaks with an overdensity δ above a threshold $\nu\sigma$, where $\sigma^2 \equiv \langle\delta^2\rangle$. If the local distribution function of δ has a steeply decreasing tail, like a *Gaussian*, and the power spectrum is not a white-noise, high peaks occur with enhanced probability in the crests rather than the troughs of a large-scale fluctuation mode, so they display enhanced clustering (Kaiser 1984). In a Gaussian process, in the region where $\xi(r) \ll 1$, the enhanced correlation function of high ν peaks is approximated by (Politzer and Wise 1984; Jensen and Szalay 1986)

$$\xi_{peaks}(r) \simeq exp[(\nu^2/\sigma^2)\ \xi(r)] - 1, \tag{4}$$

which becomes $\xi_{peaks}(r) \simeq (\nu/\sigma)^2\xi(r)$ where $\xi_{peaks} \ll 1$. The crucial question is what astrophysical mechanism prevents lower-amplitude peaks from also turning into galaxies, thereby neutralizing the effect. One has to come up with a mechanism that would produce a fairly sharp *cutoff* in the efficiency of (bright) galaxy formation at $\nu \sim 2.5$; the number density of such peaks in the case of CDM being comparable to that of bright galaxies.

N-body simulations (White 1987) suggest that the dissipationless dark halos which are the 'parents' of bright galaxies – those with velocity dispersions $> 200\ km\ s^{-1}$ – are themselves more clustered than the overall mass distribution. This is essentially because the linear growth rate of galactic-scale perturbations is significantly affected by whether they are embedded in a peak or a trough of larger fluctuations. The growth rate is boosted up or suppressed if the background mimics an $\Omega > 1$ or an $\Omega < 1$ model respectively. A weak point of this scheme is that the resultant bias would show up in the distribution of bright galaxies more than in the distribution of galaxies of lower luminosities – an effect which is not supported by observations (e.g. Eder, Schombert, Oemler and Dekel, in preparation).

The dissipative gas contraction to the centers of the dark halos and the subsequent star formation would have an important role in the final bias. As a simple example, the high-ν peaks would collapse earlier, and have higher density at turnaround, than more typical fluctuations on a given mass scale. This could, in principle, in itself account for the bias if star formation were highly sensitive to (for instance) Compton cooling on the microwave background (Rees 1985) – an effect that depends on time like $t^{-8/3}$.

The bias may result from processes intrinsic to the protogalaxies, which depend only on the local background density. For example, Dekel and Silk (1986) have argued that in a bottom-up scenario the 'normal' bright galaxies *must* originate from high density peaks ($2\sigma - 3\sigma$) in the initial fluctuation field, while typical ($\sim 1\sigma$) peaks either cannot make a luminous galaxy at all because the gas is too hot and too dilute to cool in time, or, if their virial velocity is less than $\sim 100\ km\ s^{-1}$, they make diffuse dwarf galaxies by losing a substantial fraction of their mass in supernova-driven winds out of the first burst of star formation. This would lead to a *selective bias*, in which the normal bright galaxies are biased towards the clusters and superclusters, while the dwarf galaxies do trace the mass, and should provide an observational clue for the real distribution of the DM. The evidence for such a segregation between the high and very low surface-brightness galaxies is still inconclusive (see Haynes 1986).

There are several ways whereby the first galaxies ($> \nu$) could have influenced their environment so as to modify the formation of later galaxies ($< \nu$), but many of the physical processes that have been considered would not seem to do the job very convincingly (e.g. Bardeen 1985; Peebles 1986). In order to unbind a protogalaxy one has to heat the intergalactic gas to temperatures above $\sim 100\ eV$, corresponding to the potential well of a typical galaxy. Unfortunately, photoionization by available sources (like quasars) is capable of heating the gas only to a few eV, the binding energy of hydrogen. Furthermore, in order to be relevant, any feedback influence must propagate sufficiently fast over large distances, from proto-clusters to proto-voids, and maintain a continuous suppression of galaxy formation for a long time. It would be hard to expect that any mechanical heat source, such as explosive winds, would be capable of doing the job.

UV radiation is capable of carrying the influence and perhaps affecting the IMF in protogalaxies after the redshift $z \sim 3$ corresponding to the (apparent) peak of activity of quasars (Silk 1985). The first generation of protogalaxies might have fragmented efficiently via H_2 cooling into a 'normal' stellar population, but the radiation then photodissociated the H_2 molecules, making the fragmentation less efficient and thus leading to massive stars. The latter would be highly disruptive via supernova-driven winds, eliminating bright galaxies and leaving behind only diffuse 'failed galaxies'. However, an anti-bias might arise instead, if the fragmentation via H_2 were so efficient that it led to a population dominated by unseen 'Jupiters', while the later inefficient fragmentation ended up with a 'normal' visible population. Also, a similar suppression of H_2 may result from shock heating in the vicinity of luminous objects, so perhaps more likely is a local negative feedback effect, which would produce 'under-clustering'.

Alternatively, 'cosmic-ray' particles from first generation galaxies may raise the Jeans mass by heating the gas (if $< 0.1c$) or raising its pressure (if relativistic), provided that they can diffuse appropriately (Rees 1985). A constant pressure gradient may produce a constant drift of the baryons which, if larger than the escape velocity from the DM potential wells, would be sufficient to prevent further galaxy formation (see more in Dekel and Rees 1987).

To summarize, the 'standard' CDM scenario must be biased, and the origin of the bias can be understood. The biased CDM scenario is very successful in explaining observed properties of galaxies such as the $L - -\sigma$ type relation for 'normal' galaxies (Blumenthal *et al.* 1984), the galactic angular momentum (White *et al.* 1986), and the properties of dwarf galaxies (Dekel and Silk 1986). It can even marginally account for the observed filamentary structure and voids in the galaxy distribution on scales up to a few tens of megaparsecs (Frenk *et al.* 1986; but see a reservation in Dekel 1984a based on alignmemnt of clusters).

4.3. Biasing in Pancake Scenarios (e.g. Neutrinos)

A bias is generated automatically in any 'top-down' scenario where the perturbations below a critical length of a few tens of megaparsecs have all damped out, as in the neutrino scenario or in the case of adiabatic perturbations in a baryonic universe. First, there are motions from 'proto-voids' to 'proto-pancakes' associated with the large coherence length; collapse into flat pancakes accompanied by streaming toward their lines of intersections ('filaments'), and toward the 'knots' where rich clusters form. The gas then contracts dissipatively into the high density regions, within which the conditions become ripe for cooling and galaxy formation; galaxies are thus limited to very specific regions.

However, if the efficiency of galaxy formation were similar in all the collapsed regions, this natural bias would make the timing-scaling difficulties described in §3 more severe; how can 'pancakes' collapse soon enough to form galaxies at $z > 3$ without producing large-scale clustering of excessive amplitudes? Galaxy formation must be *suppressed* in the high density regions (or, less likely, enhanced in the low density regions). for instance, galaxies might have formed preferentially in the sheet-like pancakes and not in the denser filaments and clusters, maybe because cooling was more efficient behind shocks of planar geometry, or because galaxy formation was, for some reason, more efficient at later times when most of the pancake galaxies form. N-body simulations in which the formation of a galaxy at a given position and time is determined taking into account suppressing feedback effects from nearby quasars (Braun, Dekel and Shapiro 1987) demonstrate that the required anti-bias could be easily obtained with a reasonable choice of values for the physical parameters such as the quasar output energy and lifetime and the cooling rate of the heated gas.

A complication arises because while an anti-bias can eliminate the timing problem, it has to be reconciled with the indications for a positive bias summarized in §1. The solution may be a complicated combination of anti-bias on scales of clusters and bias on scales of superclusters and voids. Another difficulty is the big clusters formed by the neutrinos; the gas must be prevented from concentrating in their cores to avoid producing excessive x-ray sources (White *et al.* 1984)

In Summary, the 'standard' neutrino scenario must be 'anti-biased'. Its great appeal is in explaining the distribution of galaxies in 'pancakes', 'filaments' and the 'voids' between them. This scenario is less specific as far as galaxy formation is concerned; although the timing problem might be solved by anti-bias, it may still be hard to explain certain facts such as the existence of galaxies away from pancakes, the failure to detect any alignment between the orientation (and angular momentum) of a galaxy and its parent pancake (Dekel 1985), and the possible presence of dark halos in dwarf galaxies (Tremeine and Gunn 1979).

What may help alternatively is the non-dissipative pancake scenario, such as would arise from a *hybrid* picture (Dekel 1981; 1983; 1984a; Dekel and Aarseth 1984): If galaxies form independently of pancakes, from another component of density fluctuations, the timing constraint becomes irrelevant: galaxies could have formed at $z > 3$ and large-scale pancakes at $z \sim 1$. Galaxies would not be limited to pancakes but rather be present everywhere, subject to the biasing mechanisms that are relevant in general 'bottom-up' scenarios. Such hybrids could involve two types of DM, baryonic and/or non-baryonic, or two types of initial fluctuations, adiabatic and isothermal. The hybrid scenarios can be successful where the single-DM models fail, e.g., in reproducing simultaneously the observed structure on galactic scales and on supergalactic scales, and in smearing the anisotropies in the microwave background (see also §5.1).

4.4. Useful Observations and Conclusions Rgarding Biasing

A few key observations may be helpful in distinguishing between the possible biasing mechanisms. In relation with the voids one would like to answer questions like:

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(a) How big are the voids and how empty are they? We need to quantify the data using a meaningful statistic, to confirm (or disprove) our suspicion that no theory can account for the voids without biasing.
(b) Are voids empty of galaxies of all types, or only those types that are most conspicuous? Any evidence that galaxies of different types display unequal degrees of large-scale clustering would be relevant here, and most interesting would be the spatial distribution of very low surface brightness dwarfs.
(c) How much gas is there in the voids? Absorption systems along the lines of sight to quasars passing through voids may be detectable. If the gas is at $10^5 K$, too hot for 21-cm and too cold for x-ray, perhaps some features characteristic of neutral He may reveal its presence.

The relationship between 'parent' halos and 'daughter' galaxies could also have interesting implications on the biasing scheme (Rees 1985):
(d) Are there any 'barren' galactic-mass dark halos with no luminous galaxy within them? Such objects may be associated with either small halos of a shallow potential wells or with halos too big to let the gas cool in a Hubble time. (They may, perhaps, be candidates for invisible gravitational lenses.)
(e) Are there any galaxies which lack dark halos? Such galaxies may form from regions where the baryons had been compressed to ~ 10 times the DM density, indicating a certain type of biasing mechanism.

I have tried to argue here that the idea of biasing is not just an *ad-hoc* idea introduced by theorists to save the attractive $\Omega = 1$ model when confronted with apparently conflicting evidence. A bias is essential in order to understand the large-scale structure, in particular the big voids and the superclustering of galaxies, and to reconcile any of the above cosmogonic scenarios with the observed universe. What might have looked at first as a frustrating idea for astronomers became an interesting observational search which requires non-trivial interpretation. On the theoretical side, the biasing mechanism is intimately related to the cosmogonic scenario and the nature of the DM. Although some of the proposed biasing mechanisms may seem *ad-hoc*, others are very plausible. In some cases the bias improves the consistency of the cosmogonic scenario and the observations, and in others it introduces new problems. The moral is, in any case, that the default assumption to be made is *not* necessarily that galaxies trace the mass. Instead, a physical 'biasing' scheme should be considered and the possible scenarios are numerous (Dekel 1986; Dekel and Rees 1987 for more details).

5. DIFFICULTIES ON VERY LARGE SCALES

In contrast to the successes on galactic scales and up to $\sim 10\ h^{-1}Mpc$, the recent indications for significant structure on scales $\sim 100\ h^{-1}Mpc$ introduce a non-trivial difficulty for any of the 'standard' scenarios discussed so far. In the case of CDM, the cluster-cluster correlation function is expected to be proportional, in the linear regime, to the matter two-point correlation function, ξ (see eq. 4). But, with a Zeldovich spectrum, ξ becomes negative at $\simeq 20\ h^{-1}Mpc$, while ξ_{cc} is observed to be positive out to $\sim 100\ h^{-1}Mpc$. In the case of neutrinos ξ_{cc} was found numerically (Barnes *et al.* 1985) not to be much larger than ξ, and to be independent of the cluster richness – in disagreement with the observations.

The observed large scale bulk velocity, if real, introduces a similar difficulty. The mean-square mass fluctuation and bulk velocity in a spheres of radius R are both related to the power spectrum via

$$\left(\frac{\delta M}{M}\right)^2_R \propto \int_0^\infty dk\ k^2\ \langle|\delta_k|^2\rangle\ W_R(k), \tag{5}$$

and

$$v_R^2 \propto (a_o H_o)^2\ \Omega^{1.2} \int_0^\infty dk\ \langle|\delta_k|^2\rangle\ W_R(k), \tag{6}$$

where the window function $W_R(k)$ can be approximated by the step function: $W_R(k) \simeq 1$ for $0 < k < 1/R$ and it vanishes elsewhere. The *rms* fluctuation of the number of galaxies is observed to be $\delta N/N = 1$ in spheres of radius $8\ h^{-1}Mpc$. So for a given spectrum, assuming $\delta M/M \leq \delta N/N$ as is appropriate for CDM, one can predict an upper limit for the *rms* bulk velocity on any given large scale. For spheres of $100\ h^{-1}Mpc$ in diameter in the 'standard' CDM the predicted velocity is $< 150\ km\ s^{-1}$ – way below the observed value of $\sim 600\ km\ s^{-1}$.

These observations indicate that we need more power on very large scales. But on the other hand, the observed upper limits on $\delta T/T$ constrain the amplitude of the spectrum from above on various scales. Finding a scenario that would satisfy simultaneously the opposite constraints is a non-trivial task. I consider below two possible solutions.

5.1. A Hybrid Open Universe

Lowering Ω may be helpful; the spectrum shifts to larger scales roughly in proportion to $(\Omega h^2)^{-1}$, like the scale corresponding to the horizon at z_{eq}. In particular, there are two possible characteristic scales of relevance. Baryonic fluctuations, if $\Omega h^2 > 0.05$, develop a secondary peak on a very large scale corresponding to the baryon-photon Jeans scale just prior to recombination,

$$\lambda_J \simeq 25\ (\Omega h^2)^{-1}Mpc. \tag{7}$$

Neutrinos develop a critical coherence length due to free streaming within the horizon until z_{eq}, at a comoving length

$$\lambda_\nu \simeq 14\ (\Omega h^2)^{-1}Mpc. \tag{8}$$

If $\Omega h^2 \sim 0.1$, the resultant 'feature' is on a very large scale; with the normalization $\delta M/M \leq 1$ at $8\ h^{-1}Mpc$ there is more power on large scales, as required.

Consider, for example, an *open* CDM model where $\Omega_{cdm} \simeq 0.1$. Baryons, based on nucleosynthesis arguments, are likely to contribute a comparable density, $\Omega_b \simeq$

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0.1. This is, therefore, a natural *hybrid*, where CDM fluctuations are responsible for the formation of galaxies while baryonic fluctuations, because of λ_J, give rise to the structure on very large scales (Dekel 1984a; 1984b). The properties of galaxies and their distribution on scales $\sim 10\ h^{-1}Mpc$ are reproduced very well in such a model (Blumenthal *et al.* 1984; Davis *et al.* 1985). No bias in the formation of galaxies is required, which would be consistent with the formation of big voids only if we have overestimated the emptiness of the voids in §2. We have recently looked at the formation of large scale structure in this model in some detail (Dekel, Blumenthal and Primack 1987). The cluster correlation function comes out right (confirming Dekel 1984); the clusters are 'super-biased' into forming in 'superpancakes'. The predicted *rms* bulk velocity is $\simeq 600\ km\ s^{-1}$ (calculated independently by Bond 1987). There is no difficulty with the $\delta T/T$ isotropy on large angular scales (also Silk and Vittorio 1987), but there is a marginal difficulty on small angles. This difficulty can be removed by reionization, which could naturally occur in this hybrid model due to the early formation of subgalactic objects from the CDM component of the fluctuations. Another way out would be invoking a non-zero cosmological constant (Vittorio and Silk 1986).

Other options for hybrids that may work in a similar way are a mixture of CDM and $\sim 10\ eV$ neutrinos each contributing $\Omega \simeq 0.1$, or an open baryonic universe with a mixture of adiabatic and isothermal fluctuations.

Thus, here are scenarios which seem to work, but they were patched up to do so. The choice of parameters is somewhat *ad hoc*; it is not the choice which arise naturally from first principles, or based on simplicity and aesthetics arguments.

5.2. Non-Random Phases – Cosmic Strings

An alternative way to produce large scale density fluctuations without producing large thermal fluctuations involves non-Gaussian statistics. If the density fluctuations began as quantum fluctuations of a free scalar field during the era of inflation they are indeed expected to be Gaussian (Bardeen *et al.* 1985), but it is also possible that the fluctuations arose from a different mechanism, in which they would not in general be Gaussian, and have non-random phases. A specific model that incorporates this feature is the scenario in which the density fluctuations were induced by *cosmic strings* (see a review by Vilenkin 1985). The strings are generic objects which form in a phase transition in many potentially plausible theories of the microphysics of the early universe. They are curvature singularities which are born with a topology of random-walks. They turn into closed smoother 'parent' loops on entering the horizon and then chop themselves into (possibly) stable 'daughter' loops, all in a scale-free self-similar fashion. The spectrum of fluctuations represented by the loops is scale-invariant ($n = 1$), which is quite appealing. It was argued, based on pioneering low-resolution string simulations (Albrecht and Turok 1985), that the loop-loop correlation function has a general shape close to that of galaxies or clusters (Turok 1986), $\xi(r) \propto r^{-2}$, as expected from 'beads' along locally-linear 'strings'. Density fluctuations (whose spectrum is determined by the nature of the DM) are

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induced in the DM by accretion onto the loops, so the galaxies and clusters that form are expected to be aligned in space along the same 'parent' linear structures. Studying a 'toy' string model that incorporates DM gravity (Primack, Blumenthal and Dekel 1986), we found the *phase-correlations* to have a very pronounced effect on the correlation functions of galaxies and clusters that are defined as peaks above a density threshold, while the matter correlation function (and the fluctuation spectrum), and therefore the temperature fluctuations, are of low amplitude. It seemed to provide a natural galaxy biasing mechanism, as well as an appropriate excess of cluster clustering on very large scales.

I do not think, though, that the clustering of loops is well understood yet. First, contrary to previous claims, the correlations on scales larger than the horizon are found to be negligible because the strings' random walk is self-avoiding (E. Vishniac, private comm.; Blumenthal, Dekel and Primack 1987, in preparation). Second, it is not obvious that the notion of 'beads along strings' is at all relevant; newer simulations (Albrecht 1987) show no such effect. Also, high loop velocities tend to smear out their correlations on scales slightly smaller than the original parent loops ($\sim$ the horizon). It is therefore crucial to study this fragmentation process and the associated velocities in more detail before a serious attempt is made to understand the formation of large scale structure from cosmic strings. We are currently running high resolution string simulations for this purpose.

It turns out that the string theory yet suffers from further difficulties. Peebles (unpublished 'screed') have listed a number of problems concerning the properties of galaxies such as the origin of their angular momentum and their luminosity function. There are ideas of how to overcome these difficulties (e.g. Turok 1987), but they involve *ad hoc* 'patching' of the theory. Another problem is that the most appealing string model where the DM is 'cold' cannot reproduce the large bulk velocity. Only if the DM is 'hot' can string-induced fluctuations be associated with high velocities on the order of 500 $km\ s^{-1}$ (R. Brandenberger, private comm.). Thus, the cosmic-strings picture seems to follow the familiar route: after it emerged as a very appealing elegant theory which can 'naturally' explain a certain set of observations that are in conflict with the other scenarios (e.g. the cluster correlations), it has reached a stage where a quantitative confrontation with the various aspects of the observed structure forces *ad hoc* 'patching', which is not very satisfactory.

6. THE EXPLOSIONS SCENARIO

The theories discussed above all assume that the present structure arose from small amplitude density fluctuations which originated in the early universe, and that it is determined by the spectrum and statistics of these fluctuations. An alternative approach, based on the concept that the present structure is determined by physical processes in late cosmological epochs and is not sensitive to the exact initial conditions, is represented by the picture of explosions (Ostriker and Cowie 1981; Ikeuchi 1981). Here, nuclear energy from first generation objects helps gravity in forming further galaxies and enhancing their clustering. The exploding galaxies

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produce spherical blast waves that push the gas out of their interiors. The shells expand, cool and fragment into a new generation of galaxies, the last generation forming at $z \simeq 7$, after which the shells cannot cool efficiently anymore. Based on several astrophysical constraints it has been argued that the individual 'bubbles' of galaxies cannot be bigger than $\sim 10\ h^{-1}Mpc$ in radius (e.g. Carr and Ikeuchi 1985). But, the subsequent interaction of the bubbles with each other generates clusters and superclusters and makes the empty interiors of the shells grow significantly. Contrary to previous worries, it turns out that the resultant structure on scales $1 - 30\ h^{-1}Mpc$ resembles the observed structure quite well (Saarinen, Dekel and Carr 1986; Weinberg, Dekel and Ostriker 1987); it can reproduce the galaxy correlation function, the appearance of sharp edges in the distribution of galaxies and the occurrence of big voids. It can even account for the required 'bias' of the galaxy distribution (which arise from gas that was swept out into shell surfaces) relative to the DM (which partly still fills the shell interiors).

However, it is not clear how the explosions can be responsible for the clustering of clusters and the high velocities on scales as large as $\sim 100\ h^{-1}Mpc$. The only plausible way out is again 'patching' the theory with a component of primordial fluctuations on large-scales – a hybrid. For example, 'wakes' behind cosmic strings can give rise to the 'seeds' required for triggering the explosion scenario, which would be correlated appropriately on very large scales (Rees 1986). Also, superconducting strings combined with primordial magnetic fields can give rise to explosion-like phenomenon (Ostriker, Thompson and Witten 1986).

7. CONCLUSION

The field of the formation of large scale structure is, to my mind, in a dissatisfactory phase. Our 'standard' scenarios, which are sometimes very successful in explaining some of the observations, need 'patching' and *ad hoc* fine-tuning when confronted with the whole set of observations on all scales. This, by no means, indicates a breakdown of conventional physics; just that we should look for better ways of applying it. Quoting two of the participants in this symposium, Dr. Norman's conjecture is that: "Some observations must be wrong!", while Dr. Yahil says: "Theoreticians should think harder!". My feeling is that either, or both, are correct! This situation is not necessarily frustrating, considering the fact that the observational constraints accumulate rapidly and continuously improve qualitatively. It implies that, on the contrary, there is much more (and better) work to be done in this field, by all of us, and that there is a hope for significant improvement in our understanding of the large scale structure in the near future.

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DISCUSSION

BAHCALL: In the hybrid model of cold dark matter plus baryons, are there problems with the observed isotropy of the microwave background radiation?

DEKEL: There are no difficulties on scales of a few degrees and up - those which should directly reflect initial density fluctuations. There is a marginal discrepancy on the scale of a few arc-minutes, which can be avoided if either 1) reionization by the first objects that emerged from the CDM fluctuations has smeared out temperature fluctuations on scales of a few degrees and less, or 2) there is a non-zero cosmological constant.

SILK: You used an upper limit of 10 percent on the void density contrast in reaching an important conclusion about justifying the need for biasing. However the observed 2σ limit on luminous galaxies in one of the largest voids in Bootes is 25 percent; moreover the void contains at least six emission line galaxies.

DEKEL: The statistics certainly need to be done better, with better data. Nevertheless, in the Bootes void, 32 galaxies were expected and none found! The situation is similar in the other voids that are found very frequently in every redshift survey. Ten percent mean number density is, I believe, a reasonable estimate for what we observe in voids. But this will become clearer in the future.

NORMAN: For biasing and anti-biasing theories, to make these truly scientific they need to be falsifiable! What are the best tests for these concepts that observers here should go out and measure?

DEKEL: I agree that this is crucial, and have listed suggestive tests in my paper. But the point is that, based on the numerous possibilities for biasing processes, it would be astonishing if they did not affect the distribution of galaxies relative to the matter. I refer you to a Nature review by Rees and myself for a more comprehensive discussion.

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