EXPLOSIVE ORIGINS OF LARGE-SCALE STRUCTURES

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1. INTRODUCTION

Large scale structures up to $5h^{-1}$ mpc, the galaxy-galaxy correlation length and the size of typical galaxy groups and clusters, can be produced quite naturally from explosions originating in young galaxies (Ostriker and Cowie, 1981: "OC") or quasars (Ikeuchi, 1981: "I") with energy output of 10^{61} ergs. But very large-scale structure in the 25 mpc -50 mpc range possibly indicated by cluster-cluster correlations (Bahcall, 1987a), can only be produced by much more energetic events of 10^{65} ergs which are far beyond the output of any objects currently known. This follows simply from the dimensional arguments which give $R = c(E\rho/ t^2)^{0.2}$ implicit in the classic Seldov-Taylor solution and cosmological analogs (cf Ostriker, 1986). Thus very large scale structure can only be produced by explosions if many small ones can coalesce suitably at early epochs (OC) or single giant events are produced by exotic objects such as superconducting cosmic strings (Ostriker, Thompson and Witten 1986: "OTW"). If however these large events do occur, then many specific properties of very large-scale structures will be produced quite naturally (cf Bahcall, 1987b, Weinberg, Ostriker and Dekel, 1987 "WOD"). Before discussing these points, it is appropriate to say a few words on the importance of hydrodynamics in general and explosions in particular, since the latter will certainly be a consequence of galaxy formation even if they are not the primary cause.

In the talk presented at this Symposium by Carlos Frenk (1987) summarizing some beautiful n-body simulations, the work was described as having a bearing on "halo formation," rather than "galaxy formation." This is correct. A large fraction of the work done in this field treats a collisionless, dissipationless fluid which would be appropriate if all matter were dark matter. We know that this is not true and that, in fact, the physical scales of mass and size for galaxies must be set (Rees and Ostriker, 1977; Silk, 1977) by just those processes ignored in the standard calculations. This fact is implicitly, if partially, accepted in pictures such as cold-dark matter where hydrodynamics is taken to act as a filter (Blumenthal et al, 1987) operating on non-linear perturbations to select out those producing bound objects or by those (Rees, 1987) invoking "bias" which either promotes galaxy formation in some regions or retards it in others.

J. Audouze et al. (eds.), Large Scale Structures of the Universe, 321–329.

There are two places where the charged baryonic nature of normal matter will be important. In the momentum equation and in the energy equation. With regard to the first, the collisional aspects of a real gas will produce on the large scale a network of caustic-like (Shandarin, 1987) shocks and on the small scale, a tendency for collapses to produce pancakes (Binney, 1977; Zeldovich, 1978) or thin shells (Ostriker, 1986). The same tendencies exist for collisionless matter, but the features produced are of course much less finely resolved and they will not persist, except insofar as they are reinforced by gravity. Furthermore, since shocks (with velocities > 30 km/s) will ionize matter, interactions with microwave photons or other electromagnetic phenomena become possible.

In addition, even a very low rate of ionization (e.g., as relect of the early, fully ionized state) suffices to couple the gaseous fluid to any ambient magnetic field that may exist. A brief word on this possibly important topic is appropriate.

The Galactic field of a micro-gauss is possibly of primordial origin and possibly generated by internal dynamo processes; decades of investigation have not provided convincing arguments for either alternative. If primeval, the galactic field corresponds to a current intra-galactic field of 10^{-9} gauss, which would be consistent with current observational limits and attractive for some other purposes. Such a field would have important dynamical consequences on scales of 10^{8} $M_{\odot}$ or less. Thus, a plausible magnetic field will affect formation of low mass galaxies, Lyman-alpha clouds, etc., but not directly influence large-scale structure. Two possible indirect effects are worth noting. In the conventional picture of explosive amplification for galaxy formation (I, OC, Bond, Carr and Arnett, 1984), the initial input is thermonuclear, but explosive energy may be transformed with high efficiency into a relativisitc fluid as seen in the Crab Nebula and other non-plerionic supernova remnants. Thus, the wind emanating from a galaxy having a high supernova rate or the jets emitted by active galactic nuclei may be dominantly composed of a cosmic-ray fluid. In order for this wind to drive, piston-like, a large hole into the intergalactic medium, some magnetic field is required to couple the cosmic ray fluid to the ambient gas. Superconducting cosmic strings require a magnetic field for two purposes: first to provide, by inductance, the current in the cosmic loop and, second, to couple the motion of the high energy particles within the giant nebula to the ambient medium. Again a field of 10^{-9} gauss is required.

The importance of hydrodynamical processes in the energy equation is more obvious and dramatic, since in their absence a collisionless fluid is adiabatic and there are no naturally selected scales of mass or length. For an ionized gas, Compton cooling which (per atom) is independent of density, is usually the most important process for redshifts $z>8$ Radiative cooling is important for scales less than 10^{12} $M_{\odot}$ (Silk, 1977) and presumably sets the limit to the size of galaxies. It is not dependent on epoch, except of course indirectly through density, but is very sensitively dependent on metallic impurities.

Thus, in summary radiative processes are important on galactic and subgalactic scales at all epochs. On the scales approximate to a discussion of large-scale structure ($R > 5h^{-1}$ mpc), only processes involving a coupling with the cosmic background radiation are important and these only for redshifts greater than $z > 10$ (with respect to energy losses) and $z > 100$ (with respect to momentum losses).

Next a discussion of energetics is in order. Input via a feedback loop from galaxy formation can be estimated by noting that approximately 10^{51} erg per supernova is released or $2M_\odot$ of metals/SN. Since the typical giant galaxy contains 10^{11} M in baryons with a solar metalicity of $Z \sim 0.02$, this corresponds to $10^{9.3}$ M in metals or 10^{60} erg/galaxy. Translating this to an efficiency of transforming baryonic matter to supernova kinetic energy, one has $\Delta E/(\Delta Mc^2) \sim 10^{-5}$, so it seems plausible to adopt $10^{-4} > \epsilon > 10^{-6}$.

Next let us consider the possible size of the explosions in somewhat greater detail. A single explosion in an $\Omega_b = 1$ universe will reach a radius $R \sim 5E_{61}^{0.2}$ mpc (Ostriker and McKee, 1988), so that galactic explosions can produce fragmenting shells of moderate scale without difficulty. If we imagine that several generations succeed one another, large shells can in principal be made (cf Wandel, 1985 , and VOB, 1985) The present comoving radius of a detonation which ceases at a redshift zd is $R = 640\ \epsilon_{-4}^{1/2}\ (1 + z_d)^{-1.75} H_{100}^{-1.75}$ mpc (VOB) taking into account the extra expansion the shell approaches the comoving state. For $z_d = 8$ and $H_{100} = 0.75$, this gives $R = 18\ \epsilon_{-4}^{1/2}$ mpc which is marginally acceptable to produce the cluster-cluster correlations. The corresponding energy is $E = 9.8 \times 10^{65}\ \epsilon_{-4}^{3/2}$, which we note is about that released in a typical great cluster by thermonuclear means.

In addition it is necessary that the filing factor of the bubbles be significant. This is addressed in Schwarz et al, 1975, OC and Wandel, 1985, with the conclusion, for energies up to 10^{65} ergs, filling factors of order unity may be expected.

There is another way that relatively large individual events might occur other than by a chain thermonuclear reaction. Superconducting cosmic strings are a plausible consequence of symmetry breaking in grand unified gauge theories. The luminosity in electromagnetic radiation of an oscillating current-carrying loop may substantially exceed the luminosity in gravitational radiation (OTW). In the typical case considered, the energy released electromagnetically is 10^{49} erg s^{-1}, or 10^{66} erg in toto. Several consequences follow from this, the most interesting of which is the possibility that such loops may heat their surroundings, generating large, dense spherical shells of gas. Galaxies forming on these gravitationally unstable shells at moderate redshift will be seen at the present epoch to lie on bubbles having radii in the range 10-20h^{-1} Mpc if the initial ratio of luminosity in electromagnetic waves to that in gravitational waves is $> 10^{-3}$. In the parameter range of interest ($GM/c^2 \sim 10^{-6}$, $B^2/8\pi u_r) \sim 10^{-7}$), the bubbles will have a filling factor of order unity. Various possible tests for this extremely speculative but attractive scenario are proposed in OTW which utilize primarily non-optical detection methods. With the rough scales now outlined, let us look at an individual explosion in greater detail.

2. INDIVIDUAL COSMIC EXPLOSIONS

A general review is presented in Ostriker and McKee (1988, Chapters 9, 10) where references to earlier work are noted. There are several phases.

Initially, when the time since the event is less than the initial Hubble time, the explosion resembles a classic Sedov-Taylor blastwave with 70% of the energy in thermal form and 30% in kinetic energy. Then, as the effects of Hubble expansion are felt, a qualitative change occurs. Because of the declining density, the momentum picked up with swept up matter and self-gravity, a very thin shelled structure develops. If it reaches the self-similar state (for $\Omega = 1.0$), the shell thickness is only 3% of the radius with very little of the energy (2%) in thermal form. For this solution, the kinetic energy $(E_{kin}/E) = 1.58$ is nearly balanced by the gravitational energy $(E_{gr}/E) = -0.60$. Thus, the positive energy perturbation propagates like a nonlinear solitary wave, a special form of rearrangement of the Hubble flow. Numerical work (Bertshinger, 1983; White and Ostriker, 1988), supports the crude analytical stability theory forwarded in OC: such a shell is stable to large-scale modes but weakly unstable to small-scale modes which tend to fragment it into $\sim$300 pieces (cf Figure 1 from White and Ostriker, 1988). Normal dissipative effects such as ordinary viscosity or radiative losses have almost no effect once the nonlinear stage is reached. For example, the exponent y in the relationship $R \propto t^{\gamma}$ is reduced, from $4/5 = 0.8$ in the adiabatic case to $(\sqrt{17} + 15)/24 = 0.7968$ in the opposite, momentum-limited, snow-plow case. The reason for this is simple. Since the thermal energy is small, it does not matter much if it is kept intact or radiated away each doubling time. The reason for the small-scale of the unstable fragments is analogous. Large-scale modes are stabilized by the expansion of the shell and small-scale modes by the thermal energy. The mode of maximum instability corresponds to a wavelength which is characteristically the geometric mean between the shell thickness and its radius.

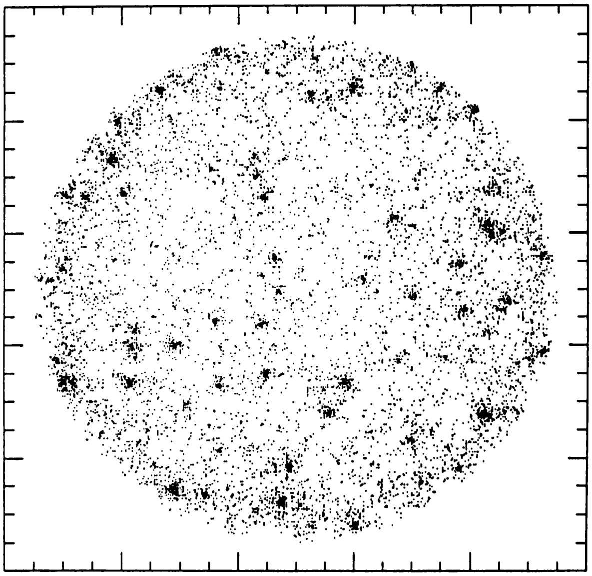

Figure 1: Appearance of the self-similar distribution of fluctuations established on a spherical shell expanding in an $\Omega = 1$ universe (from White and Ostriker, 1988)

3. INTERACTIONS BETWEEN SHELLS:CLUSTER-CLUSTER CORRELATIONS

As two shells cross, gravitational forces will tend to cause coalescense at the interface even without collisional shocks, and they will further tend to attenuate the membrane leading to, ultimately, a single shell with a dense equatorial ring of matter on which the interior parts have collected. While this process proceeds efficiently, if $\Omega = 1$ it is quite slow for $\Omega \ll 1$. Clearly interactions between three shells will cause matter to collect at the vertex where three surfaces intersect. If one envisions that the shells have fragmented into galaxy size objects as contemplated in OC and I, then at these points those galaxies which are near a forming vertex, whether singly or in the small groups which will preferentially be formed, will flow into it to make a great cluster. It is straightforward if complicated to ask what will be the statistical properties of the clusters so formed (Weinberg, Ostriker and Dekel, 1988: "WOD").

The mass that will accumulate at the two vertices where three equal sized shells intersect may be estimated by analytic argument. Expressing that mass as a fraction of the total mass within the three spheres, we (WOD) find that $\Delta M_b / M_b = (1/2)A^2$ and $\Delta M_\lambda / M_\lambda = (2/3)A^3$ where $A=(3\Omega_b/4) \times [1 + (3\pi/2)^{2/3} /(1 + z)\Omega_b]^{-1}$. For $\Omega_b = 0.05$ and shell overlap occurring at $z = 10$ this gives $A = 1/8$. So only .0013 of the dark matter collects but .0078 of the baryons accumulate with a "bias" of a factor of 6. It is interesting that the two particle correlation functions for randomly placed spheres approximates a power law of index (-2). This can be shown analytically (Kulsrud 1988). Furthermore, if a range of different sphere sizes is employed, then the mass which accumulates in the vertices, which will be proportional to $R_1 R_2 R_3$ will show a distribution in size (multiplicity function) which is attractive and a correlation function which scales with the indicative mass in the cluster in a way which mimics the observations. Figures 2 and 3 show the multiplicity function and the two particle correlating functions for the case where the distribution of sphere radii is $n(R)dR = \text{constant } R^{-4.5} dR$ with filling factor 0.3. These conditions are those appropriate to either the thermonuclear origin (Yashioka and Ikeuchi, 1987) or the superconducting string origin (OTW) for explosively driven large-scale structure. They fit the observations (Bahcall, 1987a) well as is also seen in the work of Bahcall, 1987b.

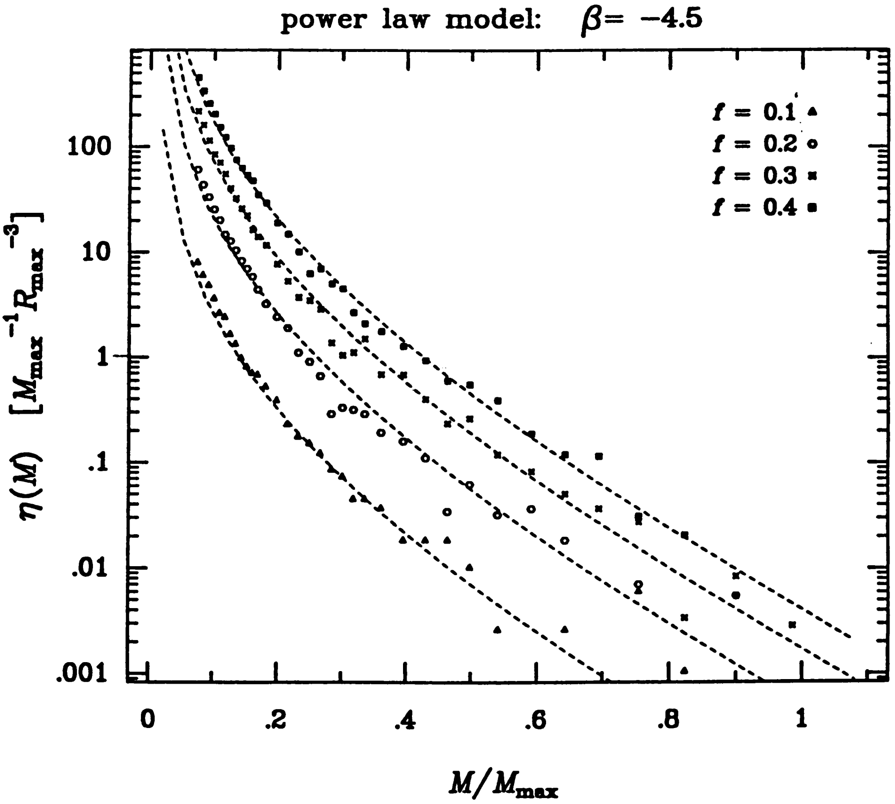

Figure 2a: Multiplicity functions for simulated clusters (and filling factprs f = 0.1 - 0.4) compared to the Schechter function with alpha = -2, dashed lines (from WOD, 1988)

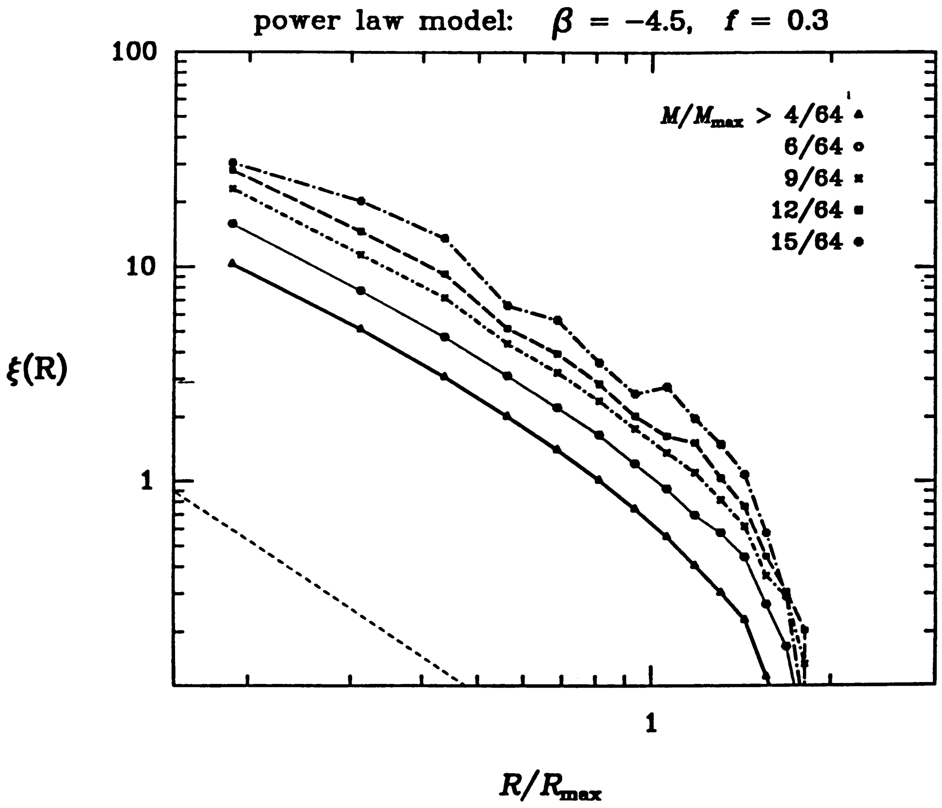

Figure 2b: Two particle cluster-cluster correlations for different cluster masses, with dashed line showing the observationally estimated slope (from WOD, 1988).

4. OTHER LINES OF EVIDENCE

While it is traditional to look for clustering of optically detected objects as signs of cosmological structure, other means are available. Surveys in X-ray, infrared and microwave wavelengths all afford opportunities. In the microwave, the cosmic background radiation (CBR) will be shifted to the blue (Zeldovich-Sunyaev, 1969, effect) when scattered off intervening hot electrons. When large structures form either explosively or simply by gravitational clustering, it is ineviable that large volumes of heated gas will be produced that will eave a signature on the CBR. This issue, first addressed by Hogan (1984) and Vishniac and Ostriker (1986), has lead to the realization that explosive galaxy formation (on the $R < 5$ mpc scale) will lead to the fluctuations at the $\Delta T/T \sim 10^{-5}$ level on arcminute angular scales that are not in contradiction with present observations, and even perhaps tentatively indicated by some recent studies. However, if larger scale structure ($R > 10$mpc) were made at recent epochs ($z < 10$) a definite contradiction to extant observations would be found. More recently Yashioka, Ikeuchi (1987) and Ostriker and Thompson (1987) have independently noted, however, that large explosions at a relatively high redshift ($z \gtrsim 40$) would not only produce appropriately large bubbles but also produce an isotropic shift in the CBR with a Compton "y-parameter" of about 0.01 which is in accord with the important recent Nagoya-Berkely rocket measurement (Matsumoto et al, 1987) of the CBR in the Wien part of the spectrum. The reason for a large isotropic shift with small angular fluctuations is that subsequent scattering off of the ionized IGM smoothes over the small angular scales. Both works investigate explosions of magnitude 10^{65} ergs appropriate either for cluster size explosions, detonations of thermonuclear origin or superconducting cosmic strings.

In the latter case there should be significant fluctuations detected in the gamma-ray (MeV) sky due to direct observations of the Crab Nebula-like loop containing regions.

In these pictures most early galaxy formation would occur at redshifts near $z = 5$-10 where dust obscuration would prevent the easy visual detection of the young galaxies. At far infrared wavelengths the emitted optical should be seen and mm wavelengths the dust emmision seen from these young galaxies should show patchy ring-like structures on the sky from the fragmenting overlapping shells of galaxies. The primary optical test will involve velocity measurements since, as noted by Peebles (1987), there may be a contradiction locally bewteen explosive formation of our supercluster and the apparently small deviations from a smooth Hubble flow.

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