DYNAMICS OF VOIDS AND CLUSTERS AND FLUCTUATIONS IN THE COSMIC BACKGROUND RADIATION

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1. INTRODUCTION

I want to "make propaganda" for some calculations carried out at Cornell; a detailed paper is available on this work (Hoffman, Salpeter and Wasserman 1982, hereafter HSW), so I only summarize it briefly (Sect. 2) and concentrate mainly on implications. Like previous work by Peebles (1982) and by Occhionero et al (1982), these calculations use spherically symmetric models without dissipation for the dynamical development of large voids and galaxy clusters (and superclusters) from small underdensities and overdensities, respectively, at the recombination era. We now know how this development depends on various parameters and on the asymmetries between over- and under-densities. I discuss conjectures for more complex geometries in Sect. 3.

With a detailed parameter study on the development of voids and clusters one can invert the process to infer the density fluctuations which must have been present just after the recombination era to produce some present-day configuration. Fluctuations in the present-day cosmic background radiation (on scales of ∿10 arcmin) are related to this and their inferred amplitude depends very strongly on the present-day value of the cosmological density parameter Ω. The relation to observed upper limits on these fluctuations are discussed in Sect. 4.

2. DYNAMICAL MODELS

We start with a small spherically symmetric density perturbation (but no perturbation in the Hubble velocity field) just after the proton-electron recombination era. We use a simple shape for the density profile (a "rounded-off stepfunction") so that the initial conditions are characterized by the (sign and size) density enhancement $\delta\rho_{rec}$, the radius of the enhanced (or depressed) region and the value of the dimensionless cosmological density parameter Ω at the initial time. We only consider regions small compared with the Hubble radius, so the size (or mass M_1) of the perturbed region only enters as a scalefactor; thus we have only two dimensionless parameters for a single, isolated, spherical perturba-

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tion. These two parameters can be expressed as the present-day value of Ω plus the ratio t/t_1, where t is the present epoch and t_1 the time (defined more quantitatively) when the perturbation "separated out from the rest of the universe."

Numerical results for the present-day density profile for models with different values of t/t_1 and of Ω are now available (see HSW); I only summarize the qualitative features, first for cases with (present-day) Ω appreciably less than unity. For $t/t_1 < 1$ the perturbations grow without change of shape (symmetrically for overdensities and underdensities) but the nonlinear growth for $t/t_1 >> 1$ is rather different: Once an overdensity has developed into a cluster it grows in mass only a little (from mass outside M_1 "falling in") and after a while the mass and radius of the cluster stays almost constant (in fixed coordinates, not in comoving coordinates). Since the density of the uniform outside background decreases continuously, the density contrast (expressed as the ratio of densities) continues to increase steadily. Two other features for dissipationless models for clusters are (a) the internal density decreases appreciably from the center of the cluster outward and (b) no ridges of underdensity develop outside the cluster. For an initial spherical underdensity, on the other hand, it is the density contrast (the ratio) which gets "frozen in" at the constant value reached as soon as t/t_1 exceeds unity and Ω decreases below ~ 0.4. Thus, a large value of t/t_1 is no guarantee for a large density contrast if $\Omega << 1$. Two other features for voids are (a) the internal density varies little and (b) dense ridges (spherical shells of high density) form outside of the void.

The formation of dense ridges is particularly important for applications to more complex geometries (Sect. 3). It is a rather general phenomenon, mathematically similar to the formation of a shock-front, where a positive density gradient outwards means that inner material is decelerated less and catches up with the slower matter further out. The time (in units of t_1) and the mass-shell (in units of the mass M_1 of the initial "density step") for the occurrence of the singularity depend on the details of the rounding off of the density step but qualitatively some dense ridge always forms after a few times t_1.

The redshift of the recombination era is known uniquely ($z_{rec} \sim 10^3$) which fixes the relationship between the cosmological density parameters then and now, Ω_{rec} and Ω respectively, but not their actual values. The numerical calculations for density ρ show that the ratio of $(\delta\rho/\rho)_{now}$ to $(\delta\rho/\rho)_{rec}$, increases quite considerably with increasing Ω. For an underdensity this trend is seen most easily by noting that the density contrast "freezes in" soon after Ω drops below ~ 0.4; for an overdensity by noting that $(1 - \Omega_{rec})$ increases with decreasing Ω and that the value of $(\delta\rho/\rho)_{rec}$ required for a bound cluster increases with increasing $(1 - \Omega_{rec})$. Although described differently, the trend is actually similar for clusters and voids with $(\delta\rho/\rho)_{rec} \sim 3\times10^{-3}$ and 3×10^{-2}, respectively, needed to give an "appreciable" contrast now if $\Omega = 1$ and 0.05, respectively.

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I discuss next another hypothetical construct, a regular cellular structure (resembling a honeycomb) with a void at the center of each cell. In such a regular lattice the mean density inside each cell equals the mean cosmological density ρ_∞ and the cell boundaries expand with pure Hubble flow. Somewhat as in solid state physics, each polygonal cell can be approximated by a "Wigner-Seitz sphere" containing the same mass M_2 and having the same volume as the real cell. In the real lattice equal mounts of matter flow across each boundary-face in opposite directions; this is mimicked in a spherical calculation by using a single Wigner-Seitz sphere but with a perfectly reflecting spherical wall which expands precisely with Hubble flow (and internal mean density precisely ρ_∞). For such models there is an additional parameter, the ratio of the cell mass M_2 to the mass M_1 of the initial, central underdense region. For $M_2/M_1 \to \infty$ such models reduce to those for a single, isolated void. For $M_2/M_1 \sim 2$ to 10 the development of the central underdensity into a void is essentially unchanged by the reflection boundary condition, a dense spherical shell (a ridge) forms as before but in these models the dense matter remains "piled up" in a dense narrow shell just inside the boundary wall. Note that the permanence of these thin dense shells does not require any dissipation in the models.

3. MORE COMPLEX GEOMETRIES

Cellular honeycomb structures have been discussed before by Einasto et al (1980) and Doroshkevich et al (1980); the formation of "pancakes" with dissipation by Sunyaev and Zel'dovich (1970). As anticipated by Dekel (1982) and Peebles (1982), we have found dense spherical shells ("curved pancakes") which remain thin (but massive) even without any dissipation. We do not understand enough about the formation of individual galaxies to judge the importance of dissipation on theoretical grounds: (i) if galaxies can form easily from a modest density increase, they will have formed before any gaseous shock forms and there is little dissipation; (ii) if it is difficult to form galaxies, shock dissipation and radiative cooling will happen first. Our model results show that observations of "thin" pancakes (without a quantitative measure of "thin") do not necessarily prove the presence of dissipation.

A general discussion of density singularities has been given by Arnold, Shandarin and Zel'dovich (1982); but I only make some conjectures from generalizations of our highly symmetric models. Consider first a "slightly irregular lattice" of perturbations just after the recombination era, with some cells having overdensities at their centers and others underdensities. We saw that dense, thin ridges form easily surrounding an underdensity but deep, narrow holes do not form around overdensities. There is a further asymmetry: A slightly irregular underdensity develops into a void of similar shape, but (as previous work had shown) a slightly irregular overdensity develops into a dense, thin pancake (possibly with an even denser central core). Thus, if there were as many overdense as underdense centers initially, the final appearance may be closer to one of a hole-centered honeycomb with dense sheets (with cluster cores giving the sheet a mottled appearance) for boundaries. Ironically, it is because sheets of low density do not form readily that one "sees" cells dominated by (centered on) underdensities.

The distribution of galaxies today depends not only on Ω and on the initial density perturbations at $z \sim 10^3$ (including the amplitude, which controls t/t_1), but also on the "microphysics" of galaxy formation: If galaxies form easily and if t/t_1 is not very large, galaxies formed without dissipation and occupy a complex set of moving galaxy sheets, isolated superclusters, etc.; if a large compression ratio is required to form a galaxy and if t/t_1 is large, then the dense sheets, protoclusters and ridges merged (with dissipation of bulk motion and with radiative cooling) before galaxy formation and galaxies would now be seen only along well-defined, continuous, orderly cell-walls. The observational picture emerging at this Symposium does not seem to be well-ordered, which may be indirect evidence against the importance of dissipation.

With redshifts known for several thousand galaxies we can now map (at least crudely) the nearest few superclusters as well as our own Local Supercluster (centered on the Virgo cluster). These superclusters are by no means arranged in a regular lattice network, but one can nevertheless attempt to fit models for a cluster-centered lattice to the data (I refer now to clusters closer than the nearest large void (Kirshner et al 1981, Davis et al 1982) and not to large hole-centered cells with many clusters in their walls). One interesting feature of such fits is that M_2, the mass of a Wigner-Seitz sphere (total mass per supercluster but also including galaxies outside the supercluster) is very much larger than M_1, the mass of the initial overdense region. The total supercluster region which has a noticeable density enhancement (e.g. a Virgo-centered region extending out to our location for the Local Supercluster) is more massive than M_1 (closer to the traditional Virgo cluster itself), yet even this region has a mass of only about 0.1 M_2. At the moment it is not clear if this feature is due to (a) a property of the initial density perturbations; (b) a tendency for rare, strong fluctuations to "swallow up" more common, weaker fluctuations during the dynamic development; or merely due to (c) the greater ease of identifying a rare, strong feature from an imperfect observational data base. Whichever the cause, we know fairly reliably that of order 10% of the mass of the universe is made up of regions like that extending from the Virgo cluster to our location, with a mean density about three times ρ_∞. We shall use this knowledge in the next section.

4. ANISOTROPIES IN THE COSMIC MICROWAVE BACKGROUND

Disregarding smearing by radiative diffusion, an adiabatic perturbation of baryonic density contrast $(\delta\rho/\rho)_{rec}$ at the end of the recombination era gives rise to temperature perturbation of $\delta T/T \approx (1/3)(\delta\rho/\rho)_{rec}$ in the present-day cosmic background radiation (the situation is qualitatively similar for isothermal perturbations). The models relate the present-day density perturbation $(\delta\rho/\rho)_{now}$ to $(\delta\rho/\rho)_{rec}$ and predict the temperature perturbations from an observed $(\delta\rho/\rho)_{now}$. Previous work (see Silk 1968, Peebles 1981) emphasized sinusoidal perturbations, whereas I will concentrate on the consequences of presently observed

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clusters, superclusters and voids. Present-day regions of density $\sim 3\rho_\infty$ (containing ~10% of all mass) lead to predictions for $\delta T/T$ slightly larger than the observational upper limit (Partridge 1980) if $\Omega = 1$, but much larger if Ω is small (multicored superclusters and large voids might add appreciably to $\delta T/T$).

If most of the mass of the universe is in the form of massive neutrinos, the predicted $\delta T/T$ would be smaller because (a) $\Omega_{tot} \approx \Omega_\nu$ is large, (b) the baryon density is small and (c) "neutrino clusters" have larger radii (less dissipation, more thermal motion) than inferred from galaxies and thus a smaller density contrast. I hope we shall soon have detections (instead of upper limits) of δT. We predict a non-Gaussian distribution, with "hot-spots" of ~(5 to 10) arcmin over ~10% of the sky mimicking "discrete, extended sources", but with a blackbody spectrum. This work was supported in part by NSF grant AST81-16370.

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Discussion

Shandarin: When you considered the evolution of overdensities and underdensities, did you assume that the scale of perturbation is much larger than Jeans mass?

Salpeter: Yes. The models are for zero-temperature matter.

Hoffman: What fixes the scale of the holes and why don't we see holes on scales smaller than ~ 10 Mpc?

Salpeter: The model calculations themselves are dimensionless for zero temperature and consequently they have no scale. For real matter with a finite temperature, the models do not apply for scales less than the Jeans mass.

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Occhionero: In a poster paper shown here, we outline a simple algorithm by which the density profiles and velocity fields for holes can be evaluated straightforwardly. In particular, we call attention to two parameters which define: 1) the depth of the hole, and 2) the shape of the surrounding mass ridge.

Giovanelli: From the picture of evolution of inhomogeneities that you presented, could you comment on how filaments arise from the cell structure and would structures preferentially form that resemble filaments rather than cells?

Salpeter: Our spherical models are only an approximation to models for a lattice cell. If filaments are the intersections of two cell walls, they CANNOT be approximated by our models.

B. Jones: Do the ridges formed around the holes meet before or after they have had time to attain a sufficient density contrast to fragment into galaxies? This is important if you want galaxies to lie on thin sheets around the voids.

Salpeter: This depends mainly on the "microphysics" of galaxy formation: If only a moderate density increase is required, the ridges may already contain galaxies before they merge into "cell walls."

Vignato: I do not understand why it is not possible to obtain void structure by simply supposing the presence of a number of elliptical perturbations.

Salpeter: No comment.

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