A PROBE
OF PLANCK ENERGY PHYSICS

A Mechanism for the Formation of Large Scale Structure

F. OCCHIONERO, S. MONASTRA, C. BACCIGALUPI & L. AMENDO
Osservatorio Astronomico di Roma
Via del Parco Mellini 84, 00136 Roma - ITALY

1. Abstract

Large scale voids are a very prominent feature in recent redshift surveys: here we attempt an explanation in terms of a first order phase transition occurring during the slow roll epoch of a two field inflation, a process where one field drives the slow roll while the other undergoes quantum tunneling through a potential barrier. The ensuing bubble like perturbations – nucleated at a number of e-folds $N \approx 55$ before reheating – are thought to be the precursors of the voids we observe today, while the zero-point fluctuations of the inflaton are the small, Gaussian perturbations seen by $COBE$ on the large angular scales.

If this is so, primordial bubbles must have left a trace on the CMB, unless Silk damping and/or early reionization have erased it. We predict this imprint to have power on small angular scales, ≈ 10 arcmin or $\ell \approx 1000$. Therefore the physics at the Planck energy may be tested astronomically both indirectly through the large scale structure and directly through the forthcoming high resolution MAP and Planck satellites.

2. Introduction

The spectacular reconstructions of the galaxy distribution made available recently by (El-Ad et al. 1996) and by (El-Ad et al. 1997) have emphasized strongly once more that large scale voids are the most prominent features in the present sky. In particular, these voids are known to have diameters of the order of 40 h^{-1} Mpc and to be substantially empty of matter (Da Costa et al. 1996). Deep surveys indicate that strongly underdense regions,

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separated by walls of matter, can extend to very large distances (Cohen et al. 1996). As the canonical mechanisms of gravitational instability (Shandarin & Zel'dovich 1989) can (Shandarin 1997) or perhaps can not (Piran 1997) explain this, it is very important to have an alternative and to recall that La (La 1991, La & Steinhardt 1989) proposed long ago that large scale voids might be put in relation to the primordial bubbles that are formed during an inflationary phase transition.

The modern view of first order inflation, i.e. inflation with a first order phase transition, see e.g. (Kolb 1991), is that of two-field inflation (Adams & Freese 1991) where one field, say ω , is driving the slow roll down a false vacuum channel of the potential while the other field, say ψ, is performing the quantum tunneling toward a lower true vacuum channel (not necessarily of zero energy). In this scenario, two kinds of fluctuations are present: one consists of the canonical zero point small and Gaussian fluctuations of the inflaton ω, the other consists instead of the strongly non–Gaussian, bubble-like fluctuations imposed on ψ. At reheating the two fields release their energy in radiative, baryonic and dark matter: this imprint will remain in the present large scale structure expanding with the global inflation. Obviously bubbles nucleated earlier will grow larger and bubbles nucleated later will remain smaller and there is a one-to-one correspondence between epoch of nucleation and present size (aside from a factor of 2 between shallow and deep cavities; see later). In (Occhionero & Amendola 1994) we built a toy model based on fourth order gravity which realizes the above phenomenology and yields a simple expression for $S(N)$ (where S is the Euclidean action). In that toy model as well as in canonical General Relativity, Coleman's theory of bubble nucleation (Coleman & De Luccia 1980) can be used to evaluate the number of bubbles nucleated per unit time, and the fraction of volume, X, contained in bubbles of comoving radius L (Amendola et al. 1996). We assume that bubbles reentering the horizon before equivalence are erased by radiation inflow (Vadas 1993). The fraction of space occupied *at decoupling* by the surviving bubbles can now be evaluated (Amendola et al. 1996). It depends mainly on the value of N where the transition is culminating. We have in mind cases where X is definitely less than one. Correspondingly, at decoupling the $L > 10h^{-1}$ Mpc bubbles do not percolate, but are embedded in a background perturbed in two ways: by the small bubbles, almost completely thermalized, and by the ordinary zero-point fluctuations, seen by $COBE$ on large angular scales.

3. Dynamics in the Matter Dominated Era

Following (Occhionero et al. 1983) and (Occhionero et al. 1997), a spherical perturbation to the Hubble flow after it reenters the horizon in the MDE

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can be described by the line element

$$ds^2 = c^2dt^2 - \left(\frac{\partial R}{\partial m}\right)^2 \frac{dm^2}{\Gamma^2(m)} - R^2(m,t)(d\theta^2 + \sin^2\theta d\phi^2)\,, \qquad (1)$$

where m , the observable mass, is conserved and can be used as a Lagrangian comoving coordinate and $\Gamma(m)$ is the conserved energy,

$$\Gamma^2 = 1 + \frac{1}{c^2}\left(\frac{\partial R}{\partial t}\right)^2 - \frac{2Gm}{c^2R}\,. \qquad (2)$$

For a hyperbolic perturbation, i.e. an energy excess, $\Gamma^2(m) = 1 + \Gamma_+^2(m) \geq 1\,,\quad \Gamma_+(\infty) = 0$, the solution corresponds to an initial uniform density developing into a cavity *compensated* by a surrounding shell. Given an *ansatz* for $\Gamma_+^2(m)$ a density profile

$$\rho(m,t) = [4\pi R^2(\partial R/\partial m)]^{-1}\,. \qquad (3)$$

can now be evaluated. Unlike (Occhionero et al. 1983) here we concentrate on the cases where a singularity, $\partial R/\partial m = 0$, develops in (3) for the first time at a chosen redshift z_*. This implies the occurrence of shell crossing for (collisionless) DM and of shocking for (collisional) baryonic matter and signals – we assume – the first generation of galactic objects on the outer shells and the trigger of reionization of the intergalactic gas. Hydrodynamics plays a crucial role within the shell after the caustic formation: thereafter, we assume that a thin dense shell of galaxies (or of bound protostructures) is formed and that its position at any later time is given by the method (Berezin et al. 1987) (Sakai et al.1993) of the singular shell separating an inner Friedmann open model from an outer Friedmann flat model. This implies an amount of overcomoving growth, g, of the order of that derived from the Einstein–Sedov asymptotic self-similar solution (Bertschinger 1985), $L \propto t^{4/5-2/3}$. Interesting cases lie in the range $2 \leq g \leq 4$ (shallow and deep cavities, respectively). Clearly the second important observable is the density contrast at decoupling, δ_D. In fact, our solution contains only two parameters directly related to z_* and δ_D, (Occhionero et al. 1997).

The fraction of space occupied by bubbles is increased by the overcomoving expansion: an $X < 1$ at decoupling becomes $Y = g^3X > X$ by the present time. Whenever an $Y \gg 1$ results, an overpacking is implied: in this case the bubbles expand overcomovingly only until they touch each other, $Y = 1$, then stop their overcomoving growth and expand comovingly thereafter. For this reason, both $Y \leq 1$ and $Y > 1$ are interesting.

The relevant cases correspond to i) late caustics, $1 + z_* = 10$, $10^{-3} \leq \delta_D \leq 10^{-2}$, and ii) early caustics, $1 + z_* \geq 500$, $10^{-1} \leq \delta_D \leq 1$.

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4. CMB Constraints and Predictions

The structures described above introduce naturally anisotropies in the CMB, most efficiently when placed on top of the last scattering surface (LSS). The constraints for the case of an isolated bubble have been analyzed in detail in (Baccigalupi et al. 1997) and (Baccigalupi 1997): the main result is that the current whole-sky observations by *COBE* (Smoot et al. 1992) provide an upper limit of about $100h^{-1}$ Mpc to the present radius of the bubbles in both cases of early and late caustics (Occhionero et al. 1997).

A bubble-like perturbation on the LSS affects the CMB through the Sachs-Wolfe effect (SW) and through the acoustic oscillations of the photon-baryon plasma. On the contrary, the bubbles lying in front of the LSS are generating only the Rees-Sciama effect (from the temporal change in the gravitational potential) and are neglected because their signal is very small (Baccigalupi et al. 1997).

The SW effect has been evaluated by integrating null geodesics in the Tolman metric (1) backwards in time from the observation point to the interaction with the bubble. The line-of-sight distortion naturally depends on the angle between the photon direction and the bubble center direction, on the density profile, and on the position of the bubble center with respect to the LSS. A similar approach can be found in (Vadas 1995). For the width of the LSS as a function of z we have taken the probability of last scattering (Jones & Wyse 1985). The larger is the perturbation amplitude $|\delta_D|$, the stronger is the overall distortion; for shallow cavities this dependence is linear. Varying the bubble's radius the signal scales as R^2 for shallow cavities, as expected for linear perturbations (Padmanabahn 1993), and as R for the deep ones (precisely, in this case it is of order $R/H^{-1}/10$ (Baccigalupi et al. 1997)).

The adiabatic and Doppler effects derive from the fact that the size of our bubbles is comparable to the sound horizon at decoupling. In other words our perturbation involves scales where the pressure gradient of the photon-baryon plasma is comparable with gravitational forces. The general treatment of this situation for linear perturbations (Hu & Sugiyama 1995) consists in solving the Boltzmann, Euler and continuity equations for the $\mathbf{k}-$mode of $\delta T/T$ using the Fourier transformed gravitational potential of the perturbation as a source. These equations, solved in the tight coupling approximation, account for pressure and gravitational terms, for Silk damping and for the LSS finite width. From the $\mathbf{k}$-spectrum of $\delta T/T$ we can obtain the anisotropy profile. The dependence of the results on the details of the shells is only minor, because of Silk damping. The visual appearance of an inflationary bubble is a central hot spot surrounded by a series of concentric rings of alternate colors reaching out to the sound horizon at decoupling ($\approx 1^o$) (Baccigalupi 1997).

In (Amendola et al. 1997) we consider a distribution of bubbles on the LSS and we find that their global effect is to introduce an excess power on the subdegree scales, $500 \leq \ell \leq 1000$. The high resolution ($10'$), high sensitivity ($\delta T/T \approx 10^{-6}$) MAP and Planck missions of the near future will therefore confirm or reject this scenario.

5. Conclusions

Under the pressure of the new observations (El-Ad et al. 1996; El-Ad et al. 1997) we propose a new cosmogony of which large scale voids of tens of Mpc at present, originating as the primordial bubbles of a first order phase transition, are the dominant factors. By using a specific biparametric model for bubble evolution in the MDE, we have shown the compatibility of the new scenario with the CMB anisotropy known from $COBE$'s data. On the other hand, a definite prediction for the anisotropy produced by an inflationary bubble has been computed in (Baccigalupi 1997): the visual appearance is that of a sequence of concentric rings alternatively hot and cold on the sub-degree scale. The entire CMB angular spectrum to be compared with the forthcoming high resolution experiments contains excess power with respect to CDM at $\ell \approx 1000$ (Amendola et al. 1997).

We have analyzed the MDE dynamics of bubbles formed through a primordial phase transition: we have shown that they are capable of generating caustics and therein galaxies at any chosen z_*, provided the parameters are adjusted suitably. In fact, from δ_D and z_*, it is possible to relate the microphysics of bubble nucleation to astronomical observations (Amendola et al. 1996).

In the light of recent debates on homogeneity vs. fractality (Pietronero & Sylos–Labini 1995) (Pietronero et al. 1996), it is worthwhile to point out that the present scenario is compatible with fractality, but only up to a definite scale, of the order of hundreds of Mpc, because homogeneity is restored thereabove. Perhaps not coincidentally, this scale is reminiscent of the redshift periodicities (Broadhurst et al. 1990).

In this cosmogony, the formation of galaxies occurs on the shells as described above and possibly like in conventional scenarios from the zero–point fluctuations of the inflaton in the interbubble space; the latter galaxies, however, will be gradually swept up by the overcomoving shells and will add to the galaxies already there. For $Y < 1$ most shells will fully exploit all their available overcomoving growth without ever interacting with their neighbors. For $Y \geq 1$, as the observations (El-Ad et al. 1996; El-Ad et al. 1997) suggest, very commonly will a shell collide with a close neighbor; in this case the resulting scenario is reminescent of classical work (Yoshioka & Ikeuchi 1989) and suggests to relate the observed bulk flows (Lauer & Postman 1992) (Strauss et el. 1996) to the flowing of matter on the bubble collision planes. The present scenario is therefore rich of astronomical implications which warrant further investigation.

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