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On the agreement between COBE anisotropy results and specific predictions from clusters of galaxies

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ABSTRACT
The recent results from the first year of data from the COBE DMR experiment (Smoot et al. 1992) detect a large angle anisotropy in the Cosmic Microwave Background [CMB]. This first set of data seems to indicate that the scale–invariant ($n = 1$) spectrum is preferred, with an amplitude at the horizon crossing of $\epsilon_H = (5.4 \pm 1.6) \cdot 10^{-6}$ (Wright et al. 1992). This level is in remarkable agreement with the value of $\epsilon_H \simeq (1.5/b)\,(6 \pm 2.5) \cdot 10^{-6}$, which was *predicted* to be the relevant one from a study of the distribution of Abell clusters which sampled large scales which correspond to angles up to twice the COBE FWHM (Scaramella 1992), where the value $b \sim 1.5$ was suggested by agreement with the observed large scale peculiar velocities.

This observational agreement indicates that on the very large scales the peculiar gravitational potential has kept nearly constant from the epoch of last scattering to the present. This fact, together with the presence of large scale flows, suggests that we live in a spatially flat Universe of critical density, where optical galaxies are mildly biased with respect to the matter distribution, and with a power spectrum which, depending on the spectral index on small scales, has a turnover to $n = 1$ in the $100 - 200\,\mathrm{h}^{-1}$ Mpc scale range. We also considered a "tilted" ($n < 1$) CDM model, and find that this model would need a small spectral index ($n \sim 0.3$) to match the cluster normalization. However, such an index would yield a too large CMB anisotropy, even without the the possible additional anisotropy due to the presence of a significant background of primordial gravitational waves.

Key words: Cosmic microwave background — Large scale structure of Universe

1 INTRODUCTION

In the context of Friedmann–Robertson–Walker models, one expects that potential fluctuations at the last scattering surface will directly reflect into anisotropies of the observed CMB temperature pattern on several degrees, as discussed first by Sachs & Wolfe (1967). Clearly, the amplitude and the angular coherence of these anisotropies are related both to the global parameters of the cosmological model, and to the spectrum and amplitude of matter density fluctuations on large scales.

Now, a variety of large scale structures has been unveiled "locally" in the past few years by the recent wealth of data on the galaxy distribution (e.g. APM, COSMOS, IRAS, CfA slices; for a review see Kashlinsky & Jones 1991). These findings stressed the presence of more power in the spectrum of galaxy number density fluctuations on intermediate and large scales, up to $\approx 100\,\mathrm{h}^{-1}$ Mpc, than it was expected on the basis of the otherwise fairly successful Cold Dark Matter [CDM] scenario (Davis et al. 1992). However, still quite a large amount of extrapolation with the related uncertainties on models was needed to determine the amplitude and the coherence of CMB fluctuations on scales one order of magnitude larger, where one expects to recover the primordial features. The purpose of this paper, rather than to give an exhaustive discussion of a grid of different models with many possible choices of their parameters (Wright et al. 1992, Gouda & Sugiyama 1992), is to highlight a few points of discussion. So we show below how "here and now" (in a cosmological sense: $z \sim 0.1$) seems to agree well with "there and then" ($z \sim 10^3$).

2 PREDICTIONS FROM CLUSTERS' AND DMR RESULTS

As remarked above, astronomical samples in the past years have striven to cover as much volume as possible. Nevertheless, none of these recent result tested yet large volumes in the very large scale range, i.e. $\sim \mathcal{O}(1000)\,\mathrm{h}^{-1}$ Mpc. Indeed, in a canonically flat universe with standard reionization, these are the scales relevant for the large scale anisotropy experiments, since 1° corresponds to $\sim 100\,\mathrm{h}^{-1}$ Mpc on the

last scattering surface. This unsatisfactory situation led us to try to extract some information on these scales by studying an all sky sample of Abell clusters of diameter $600\,h^{-1}$ Mpc (Scaramella 1992; hereafter paper I). Details of the procedure, as well as discussion of the large uncertainties and possible sources of error are given in paper I. For completeness, however, we recall here the basic points. We studied the fractional anisotropy of the distribution of clusters belonging to a spherical shell of radii $R_a = 200$ and $R_b = 300\,h^{-1}$ Mpc. We evaluated the quantity $g_{AB} = 3\omega_s(R_B - R_A)\mathcal{R}_{AB}/(b_{cg}4\pi)$, where $\omega_s \cong 8\pi/3$ is the sample solid angle, and $\mathcal{R}_{AB} \equiv |\sum_i \hat{r}_i w_i/r_i^2|/(\sum_i w_i/r_i^2)$ is computed for the ~ 550 clusters in the shell (different choices for the weights w_i are discussed in paper I). Under the assumption of linear biasing of cluster with respect galaxy fluctuations (with a round value of $b_{cg} \approx 3$, as derived from the relative amplitudes of the two-point correlation functions), we obtained a tentative normalization of galaxy fluctuations on very large scales by equating the observed value to the square root of its ensemble average variance: $\langle|g_{AB}|^2\rangle = (9/2\pi^2)\int_0^\infty dk\,k^2\,\mathcal{P}_g(k)\,|\mathcal{W}_{AB}|^2$, where $\mathcal{W}_{AB}$ is a window function and $\mathcal{P}_g(k)$ is the power spectrum of galaxy fluctuations. In turn galaxies may still be biased by a factor of b with respect to the underlying mass fluctuations (Kaiser 1984). Customarily $b \equiv (\delta N_g/\bar{N}_g)_{rms}/(\delta M/M)_{rms}$ in a $8\,h^{-1}$ Mpc sphere for which galaxy counts have unit variance (Davis and Peebles 1983), so that for the power spectrum of mass fluctuations one has that $\mathcal{P}(k) = \mathcal{P}_g(k)/b^2$. The overall level of bias can then be derived for a given spectrum by requiring agreement with quantities related to the dynamics and the gravitational potential, such as the large scale flows as done in paper I, so predicting large scale anisotropies (now with the COBE data this path can be reversed).

The most important point to recall here is that the window function we adopted in paper I was purposedly conceived to act as a pass band filter so to look only at the primordial part of the spectrum. In fact this probed *directly* the very large scales such as those selected by the COBE beam: the maximum sensitivity corresponds to a $\lesssim 5^o$ scale, with a FWHM range which spans from $\gtrsim 2^o$ to $\sim 14^o$. These angles indeed confront well with those of the COBE beam (FWHM=7^0) and with the most fruitful angles (Scaramella & Vittorio 1992a) in the study of the autocorrelation function of the CMB temperature fluctuations. So, almost independently of what happens on small and intermediate scales, as we explicitly checked by considering phenomenologically very simple "kinked" spectra of density fluctuations [which have $P(k) = Ak$ for $k \leq 2\pi/\lambda_k$ and $P(k) = Ak(2\pi k/\lambda_k)^{(\nu-1)}$ for $k \geq 2\pi/\lambda_k$; for the assumed indices $\nu = -2, -1.4, -1.2$ we derived in Paper I the values $\lambda_k = 150, 220, 290\,h^{-1}$ Mpc, respectively], we then predicted that in an $\Omega_0 = 1$ universe the amplitude at horizon crossing, ϵ_H (Abbott & Wise 1984), would have been $\epsilon_H \simeq b^{-1}\,9 \cdot 10^{-6}$ for $-2 \leq \nu \leq -1.2$, with a nominal uncertainty of 40% (paper I). This level reflected into a predicted value for the expected "quadrupole" of $\langle\hat{Q}_2^2\rangle^{\frac{1}{2}} \simeq b^{-1}(30 \pm 12)\mu K$ [papers by the COBE team call (quadrupole)$^2 \equiv \hat{Q}_2^2$ what we call C_2, and which is smaller by a factor of 4π than the Q_2^2 used in paper I; see appendix C of Scaramella & Vittorio 1990 for definitions]. This re-

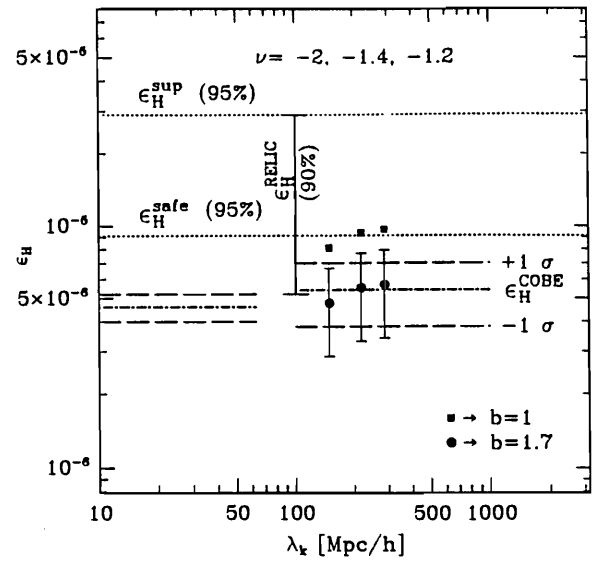

Figure 1. An update of Fig. 3 of paper I: predicted amplitude of fluctuations at the horizon crossing for three different kinked spectra. Squares correspond to the λ_k values derived in paper I with $b = 1$ and circles to values with $b = 1.7$, preferred by agreement with large scale flows (one sigma error bars). The values ϵ_H^{sup} and ϵ_H^{safe} denote the levels which would have or would have not given a detection in pre-COBE CMB large angle experiments at 95% confidence level (Scaramella & Vittorio 1990). The vertical range denoted by RELIC shows the interval derived by Strukov et al. (1992) through a reanalysis of the RELIC I data. The horizontal lines on the right side marked by ϵ_H^{COBE} denote the COBE value quoted by Wright et al. (1992), the ones on the left side are the values derived from Scaramella & Vittorio (1992b) from an analysis of the DMR cross-correlation function (Smoot et al. 1992).

ferred to the adiabatic models in a standard inflationary universe, while an open CDM model with $h\Omega_0 \sim 0.18$ (cf. Efstathiou et al. 1990) also satisfied the normalization on large scales, but then needed to invoke the presence of a cosmological constant (cf Kofman & Starobinskii 1985, Vittorio & Silk 1985, Gorski et al. 1992) to avoid excessive CMB anisotropies. Now, a value of $b \gtrsim 1.5$ gave good agreement for all the adiabatic spectra with the reported bulk flows on large scales, so that the suggested ϵ_H we derived in paper I (empty circles in Fig. 3 of that paper) for the standard case was $\epsilon_H \simeq (1.5/b)(6 \pm 2.5) \cdot 10^{-6}$, which reflected into the predicted value $\langle\hat{Q}_2^2\rangle^{\frac{1}{2}} \simeq (20 \pm 8)\mu K$. Our predicted values confront well with those derived from COBE, which are $\epsilon_H = (5.4 \pm 1.6) \cdot 10^{-6}$ and $\langle\hat{Q}_2^2\rangle^{\frac{1}{2}} \simeq (17 \pm 5)\mu K$ (Smoot et al. 1992, Wright et al. 1992), therefore validating the underlying assumption that fluctuations of the peculiar gravitational potential have kept nearly constant in time on these large scales. We show in Figure 1 an update of Figure 3 of paper I, with the new CMB data superimposed.

3 DISCUSSION

On the one hand, if we look at the good agreement between our predictions and COBE results with a safe, highly skeptical attitude, we could say that this agreement may be in part fortuitous: on the clusters' side there are crude assumptions

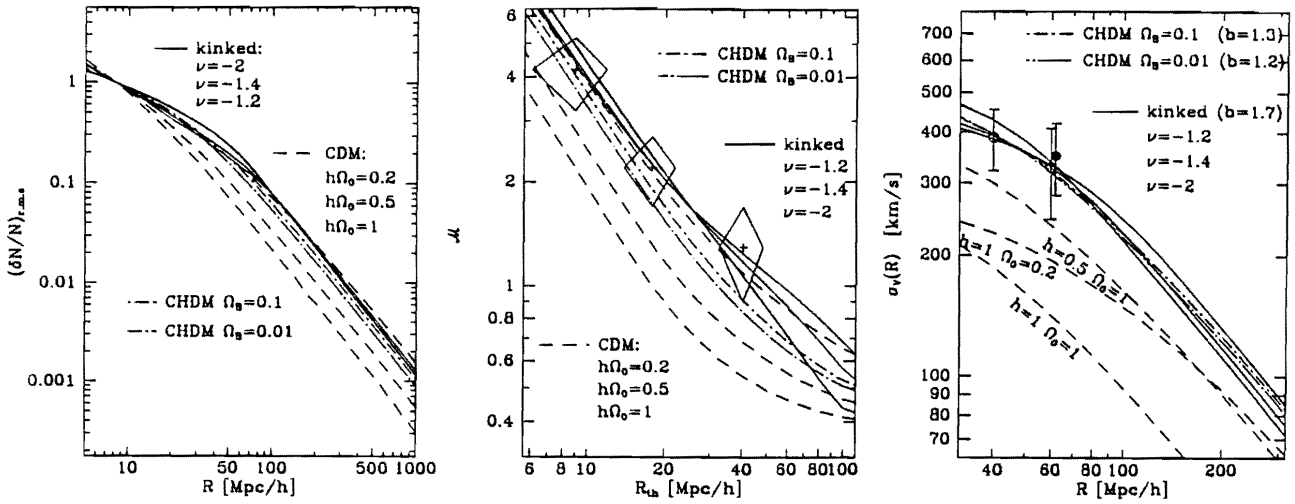

Figure 2. Comparisons of kinked phenomenological spectra of exponent ν (the vertical ordering of the solid lines is that at the abscissa of the labels) with CDM models with different values of $h\Omega_0$ (dashed lines), and hybrid models. Left panel: dispersion of the fluctuations in the number of galaxies in a sphere of radius R, normalized to unity at $8\,h^{-1}$ Mpc [the CDM $h\Omega_0 = 0.2$ and all kinked spectra are also normalized on large scales according to paper I]. Middle panel: cosmic Mach number for top-hat spheres of radius R. Diamonds denote the rather uncertain experimental points (Ostriker & Suto 1990). Right panel: peculiar velocities averaged in spheres of radius R. The open points are from Bertschinger et al. (1990), the slightly displaced solid point is an update from Dekel (1992).

on biasing and large uncertainties in the data plus the one due to the cosmic variance (see paper I), while on the CMB side as well there are results which, at the present time, when considered alone allow still quite a range of amplitudes and primordial spectral indices (Smoot et al. 1992; Scaramella & Vittorio 1992b). On the other hand, for the time being the agreement *is* good and, if one would have not had a scale-invariant spectrum (see also below), nor a flat universe, nor a direct link of fluctuations seen "today" with those present on the last scattering surface via the Sachs–Wolfe effect, it is likely that the COBE values would have been very discrepant with our predictions, which were derived from experimental data plus these assumptions. Therefore at present time we are led to seriously consider the above canonical framework to be valid.

The COBE result has prompted the search and investigation of possible spectra which can link both the customary normalization on small scales and the large scale anisotropy. One way is to keep the CDM transfer function but to have a primordial spectrum of index smaller than unity, $n < 1$, which can arise in some inflationary scenarios (Lucchin & Matarrese 1985, Abbott & Wise 1985, Liddle Lyth & Sutherland 1992, Cen et al. 1992). In some of these models a non-trivial contribution to the level of CMB anisotropy comes from a primordial background of gravitational waves, so that the level of matter density fluctuations on large scales inferred by the anisotropy is lower (Abbott & Wise 1985, Starobinskii 1985, Lidsey & Cole 1992, Liddle & Lyth 1992, Lucchin, Matarrese & Mollerach 1992). Then, in this scenario one can set lower bounds on the spectral index (Liddle & Lyth 1992, Scaramella & Vittorio 1992b) as a function of the bias value, b. In order to match results from paper I by tilting the CDM spectrum, however, one would need the rather low value of $n \simeq 0.30^{+0.45}_{-0.35}$, where the interval reflects the nominal 40% uncertainty in the cluster datum. From direct analysis of the DMR data (Smoot et al. 1992), however, we find from Fig. 5 of Scaramella & Vittorio (1992b) that when $b = (1, 1.5, 2)$, then one expects $n \simeq (0.97 \pm 0.03, 0.88 \pm 0.03, 0.80 \pm 0.03)$ for CDM if a gravitational wave background contributes to anisotropy, and $n \simeq (0.95 \pm 0.05, 0.85 \pm 0.05, 0.70 \pm 0.05)$ if there is not such contribution (one sigma uncertainties). Therefore for a pure CDM model we see that this comparison suggests that one would need the presence of a strong bias, of a low tilt and the absence of significant contribution from gravitational waves (cf. Cen et al. 1992).

Another physical model which yields the required amount of power is the "hybrid" model "cold+hot" [CHDM]. A CHDM model with 2/3 of C and 1/3 of H confronts COBE observations well (Wright et al. 1992). This is also in agreement with the early findings that the fraction of matter in the H component had to be at most 1/3 of the total in order not to delay too much the galaxy formation epoch (Achilli, Occhionero & Scaramella 1985, Occhionero & Scaramella 1988). The CHDM model has been reanalized and confronted again well with more recent observations by Shaefer, Shafi & Stecker (1989) and a number of authors (see below). In Figure 2 we compare three kinked spectra against CDM with three different values of $h\Omega_0$, and two versions of the CHDM model. The kinked spectra and the $h\Omega_0 \simeq 0.2$ CDM model were constrained in paper I to agree with our normalization on large scales. These models and one CHDM (Holtzmann 1989) yield very similar answers for fluctuations on large scales (Figure 2 , left panel), and their spectral shapes are such that they show agreement with the Cosmic Mach number as well (Ostriker & Suto 1990, Suto, Cen & Ostriker 1992; Figure 2 middle panel; the agreement of the CHDM models, however, worsens if one uses Gaussian spheres). However, the magnitude of peculiar flows penalizes the low density model, even with the presence of a cosmological constant (Lahav et al. 1991, Kofman et al. 1992), while the adiabatic kinked spectra agree well with a biasing value of $b = 1.7$ (Figure 2, right panel). This value is in the range preferred by several studies on intermediate scales

(see e.g. Kaiser & Lahav 1988), but smaller than the value $b \sim 2.5$ originally advocated by nonlinear studies on small scales (Davis et al. 1985). Also the CHDM model agrees well with some biasing, although for a slightly smaller factor. We also recall here that we expect local bulk flow values on larger scales to be on the high side of the probability distribution, because of the unusual alignment of nearby huge "attractors" (Scaramella et al. 1989), which gives coherence to the flow, and this should reflect as well in a locally large cosmic Mach numbers on larger scales.

A couple of additional interesting point are given by confronting kinked spectra with properties of rich clusters. The first concerns the biasing level, which is the one apt to match the number density of rich clusters, for the canonical threshold value for collapses (Bardeen et al. 1986, Bardeen, Bond & Efstathiou 1987). The other point is the agreement, in the case of $\nu = -2$, we find between our normalizations and the one derived in an independent way by Henry et al. (1992), who studied properties and evolution of X-ray clusters. Henry et al. (1992) found that a good description of present data on X-ray clusters is given by the spectrum $P(k) = (k/k_0)^\beta/k_0^3$ in the range relevant to cluster scales. The values they found are $\beta \simeq -2.10$ and $k_0 \simeq 3 \cdot 10^{-2}\,\mathrm{h\,Mpc^{-1}}$, with uncertainties of $\sim 10\%$ and $\sim 30\%$, respectively. For $\nu = -2$ kinked case we found that $k_0' \simeq b^2\lambda_k^3/(2\pi^3 A) \simeq b^2/100 \simeq 3 \cdot 10^{-2}\,\mathrm{h\,Mpc^{-1}}$, with a good agreement. Such a red spectrum, however, predicts a very fast evolution of cosmic structures and a dearth of rich clusters already at moderate redshifts, a fact which may be in contrast with optical results (Peebles, Daly & Juszkiewicz 1989, Kaiser 1991).

In summary, we see that at the present moment that the level of anisotropy we predicted from the level of fluctuations we derived on very large scales agrees well with COBE results, and seems to yield a consistent picture over a very large range of scales, favoring mildly biased spectra which turn to $n = 1$ in an $\Omega_0 = 1$ universe. Now the stress is put on CMB anisotropy experiment on the degree scale (Bond et al. 1991, Vittorio et al. 1991), which, if no anisotropy is found soon, may suggest that a reionization of the Universe has taken place.

After this work was completed, we saw some recent papers of relevance to the present discussion: the CHDM model is considered with favour by linear (Taylor & Rowan-Robinson 1992, van Dalen & Shaefer 1992) and non-linear (Davis, Summers & Schlegel 1992, Klypin et al. 1993) studies, while Efstathiou, Bond & White (1992) study in detail consequences of moving the break in a CDM spectrum by varying the value of $h\Omega_0$. Their conclusion that for $\Omega = 1$ a mildly biased model ($b > 1.4$) is preferred is in agreement with the above discussion. Interestingly, Fisher et al. (1993) from an analysis of the 1.2 Jy IRAS survey find a spectral index $\nu = -1.4$ (cf. Peacock & Nicholson 1991) from small scales up to wavelenghts $\lesssim 200\,\mathrm{h^{-1}}$ Mpc, which is consistent with the value of the break, $\lambda_k \sim 220\,\mathrm{h^{-1}}$ Mpc, we derived in paper I for this case and used in Figure 1 and 2.

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