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A BUILT-IN SCALE IN THE INITIAL SPECTRUM OF DENSITY PERTURBATIONS: EVIDENCE FROM CLUSTER AND CMB DATA

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We calculate temperature anisotropies of the cosmic microwave background (CMB) for several initial power spectra of density perturbations with a built-in scale suggested by recent optical data on the spatial distribution of rich clusters of galaxies. Using cosmological models with different values of spectral index, baryon fraction, Hubble constant and cosmological constant, we compare the calculated radiation power spectrum with the CMB temperature anisotropies measured by the Saskatoon experiment. We show that spectra with a spike at $120h^{-1}$Mpc are in agreement with the Saskatoon data. The combined evidence from cluster and CMB data favours the presence of a peak and a subsequent break in the initial matter power spectrum. Such feature is similar to the prediction of an inflationary model where an inflaton field is evolving through a kink in the potential.

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One of the crucial problems in cosmology is to determine the shape and amplitude of the initial (primordial) power spectrum of density perturbations. In the standard Friedman-Robertson-Walker cosmology this spectrum is arbitrary. It is specified as an initial condition at the cosmological singularity (the Big Bang). The only restriction is on the type of perturbations: they should belong to those modes which do not destroy the homogeneity of the Universe at early times, in particular, they should represent the growing mode in the case of adiabatic perturbations. For the scales of interest, the opposite assumption would result in the Universe being strongly anisotropic and inhomogeneous at the time of the Big Bang nucleosynthesis (BBN) that would completely spoil its predictions for the primordial abundance of light elements. On the other hand, the simplest inflationary models of the early Universe predict the power spectrum of the growing mode of adiabatic perturbations at present to be approximately scale invariant, i.e. Harrison-Zeldovich, characterised by a slope $n \approx 1$ on large scales [1]. In addition to processes during the inflationary era, the current power spectrum is determined by physical processes occurring during the radiation dominated regime that freeze out and damp the growth of density perturbations within the cosmological horizon.

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The final spectrum depends on values of cosmological parameters and on the exact nature of dark matter present in the Universe.

From the observational point of view, the current (evolved) power spectrum of matter density perturbations can be estimated by measuring clustering properties of galaxies and clusters of galaxies. Using the distribution of rich Abell clusters, the spectrum has been recently determined on scales from $k \approx 0.03$ up to $k \approx 0.3\,h$ Mpc^{-1} [2] (h is the Hubble constant in units of 100 km $\mathrm{s}^{-1}\mathrm{Mpc}^{-1}$). The observed power spectrum contains a spike at $k \approx 0.05\,h$ Mpc^{-1}. A similar feature on the same scale has been observed in the 1-dimensional deep galaxy redshift survey in the direction of Galactic poles, in the 2-dimensional power spectrum obtained from the Las Campanas Redshift Survey of galaxies, and from the deprojected power spectrum of the angular APM galaxy survey [3].

The purpose of this letter is to confront the power spectrum of matter density perturbations obtained from cluster data with measurements of CMB temperature anisotropies on different angular scales. We shall use the observations made at Saskatoon [4]. By using a synthetic antenna beam, the Saskatoon group was able to measure temperature anisotropies with five different angular resolutions corresponding to multipoles between $l \approx 80$ and $l \approx 400$. This range makes the experiment especially well suited for comparison with the cluster power spectrum [2] since it roughly corresponds to the wavelengths probed by the cluster data. We used the 4-year COBE data [5] to get the absolute normalisation and the shape of the matter power spectrum at scales close to the present cosmological horizon.

We calculate CMB temperature anisotropies for three different initial power spectra: (a) a scale free initial spectrum with a power index n, (b) a double power law approximation to the cluster spectrum, and (c) a spectrum based on the observed cluster spectrum. Outside the measured range, the latter was extrapolated assuming a scale free spectrum. At large wavenumbers ($k \geq 0.05\,h$ Mpc^{-1}) the shape of the observed cluster spectrum is similar to that of galaxies [6]. For the power spectrum (b), we used a slope $n = -1.8$ for small scales which is a smooth extrapolation of the cluster data. However, since this region of the power spectrum has little influence on multipoles above $l = 400$, this assumption will not affect our conclusions. At large scales the spectrum is poorly determined. Within observational errors, it is compatible with being the Harrison-Zeldovich spectrum. Furthermore, the COBE/DMR data indicate [5] that the power spectrum of matter density perturbations has $n \approx 1$ for $k \approx 0.003\,h$ Mpc^{-1}; more exactly, $n = 1.1 \pm 0.2$. Accordingly, we varied the slope at large scales in that range.

The initial power spectrum is determined as follows:

$$P_0(k) = P(k)/T^2(k), \tag{1}$$

where $P(k)$ is the power spectrum of matter perturbations at the current epoch, and $T(k)$ is the transfer function for a particular CDM model. The transfer function depends only on physical processes taking place within the horizon. In the previous expression we assumed that the observed cluster power spectrum $P_{cl}(k)$ was proportional to $P(k)$ over the range probed by the cluster data: $P_{cl}(k) = b_{cl}^2 P(k)$, where b_{cl} is the bias factor for clusters of galaxies.

We assume the Universe has a flat geometry. We did not consider mixed dark matter (MDM) models here. They differ from CDM models mainly on small wavelengths which have little influence on our results. Furthermore, MDM models

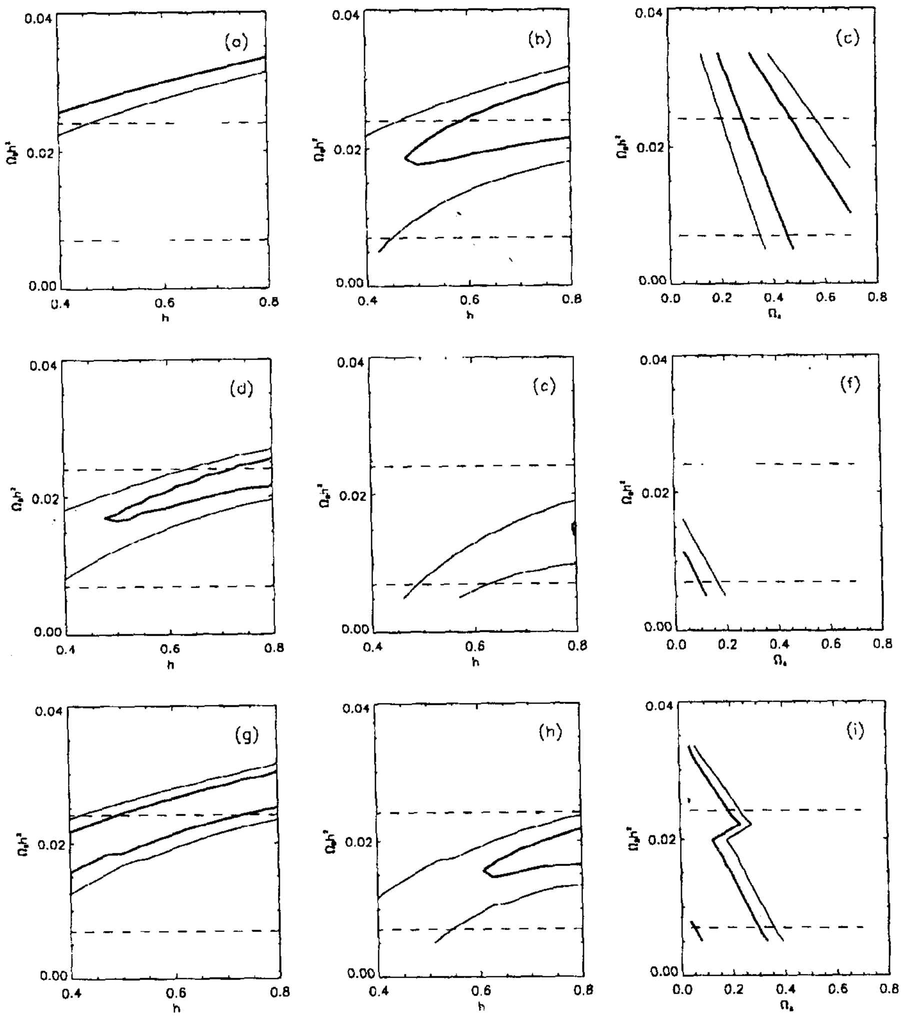

Fig.1.Goodness-of-fit contours of χ^2 at 68% (thick lines) and 95% (thin lines) confidence levels. The first row displays the results for the scale free model; the second row for the double power law model; and the lowest row for the cluster spectrum based model. In the first column we plot models with varying Hubble constant and baryon fraction for a spectral index $n = 1$ at large scales and zero cosmological constant. In the middle column the same diagrams are repeated for $n = 1.2$. The last column displays the results for models with different values of the cosmological constant

with one stable neutrino and $h \geq 0.5$ have problems to create small scale structure. In these models galaxy formation occurs too late [7], and considering scale-free MDM models with $n > 1$ does not help [8]. In what follows we shall consider $\Omega_b + \Omega_c + \Omega_\Lambda = 1$, with Ω_b, Ω_c, and Ω_Λ being the fraction of the energy density in baryons, cold dark matter and vacuum energy (cosmological constant), respectively.

To calculate the radiation power spectrum we used the packages COSMICS and CMBFAST [9]. The radiation power spectrum was normalised to the COBE/DMR

4-year data [5] using the multipole $l = 10$ as a central value instead of the quadrupole [10]. The comparison to the cluster power spectrum gives $b_{cl} \approx 3$ for $n \approx 1$. We have performed the integration for the three primordial spectra and parameters: $n = 1.0, \ldots, 1.4$; the Hubble constant from $h = 0.3$ to 0.8; the baryon density from $\Omega_b h^2 = 0.005$ to 0.033 centered on the range suggested by BBN [11]. We also considered models with the cosmological constant. In these models we chose a Hubble constant that makes the Universe 14 Gyr old. It ranged from $h = 0.5$ for $\Omega_\Lambda = 0.1$ to $h = 0.7$ for $\Omega_\Lambda = 0.7$, in agreement with the recalibration of the Hubble constant and cosmic ages made by [12] using the new determination of distances to subdwarfs and Cepheids based on the Hipparcos data. The amplitude of a temperature anisotropy expected on a given angular scale was found using the window function that best models the synthetic beam pattern of the Saskatoon experiment for that scale [4]. Finally, for each model we calculated the χ^2-deviation between the theoretical prediction and the Saskatoon data. In Fig.1 we plot the intervals in the parameter space at 68% and 95% confidence level. The dashed lines indicate the range $0.007 \leq \Omega_b h^2 \leq 0.024$ favoured by BBN [11].

Fig.1 shows that CMB data alone exclude a large range of parameter space for each of our three basic models. The standard CDM model is compatible with the CMB data for values of the Hubble constant and baryon fraction that are almost out of the range of astronomical interest. An increase of the power index n helps, but such models are not viable because they overproduce mass fluctuations on scales of $8\,h^{-1}$ Mpc (σ_8). Actually, it is well known that even the scale-invariant CDM model normalised to the COBE data is excluded for that reason. The best scale free model has a fairly large cosmological constant, $\Omega_\Lambda \approx 0.6$. A CDM model with a large cosmological constant and a high baryon fraction was suggested in [13] to explain the presence of large walls and voids in the distribution of galaxies. Energy densities of baryon and dark matter fractions are comparable in this model that results in the appearance of noticeable Sakharov oscillations in the transfer function for cold dark matter and baryons after recombination. As for the cluster based and double power law spectra, both fit the results of the Saskatoon experiment rather well in the range of parameters of astronomical interest. The best agreement with the CMB data is obtained for a low or vanishing cosmological constant, and for a spectral index $n = 1$. The allowed range of the Hubble constant is rather large for a reasonable baryon fraction.

In Fig.2 we compare matter power spectra and temperature anisotropy spectra for our three basic models with the data. The cosmological parameters were chosen to reproduce the CMB data within the 68% confidence level. As expected, the temperature anisotropy spectra are very similar. In other words, the present CMB data alone is not sufficient to discriminate between models. By contrast, the matter power spectra are very different. The scale free model with a large cosmological constant has a broad maximum at large wavenumbers ($k \approx 0.01\,h$ Mpc^{-1}); the maximum of the first acoustic oscillation occurs at $k \approx 0.1\,h$ Mpc^{-1}, and is of a rather small relative amplitude. Both scales are well outside the allowed range of the observed spike in the spectrum: $k_0 = 0.052 \pm 0.005\,h$ Mpc^{-1} [2]. Therefore we conclude that, contrary to the expectation of [13], this spike is not related to acoustic oscillations in the baryon–photon plasma. The scale free model spectrum agrees with the observed cluster (and galaxy) spectrum on short wavelengths up to the peak. However, no combination of cosmological parameters reproduces the spike at $k = k_0$. The existence of a broad maximum is an intrinsic property of all scale free models and such maximum cannot produce a regular supercluster-void network as shown in [14]. On the other hand, the cluster and double power law spectra fit the observed cluster spectrum by construction and reproduce the CMB data, i.e. they fit equally well both datasets. Therefore, the present combined cluster and CMB data favour models with a built-in scale in the *initial* spectrum.

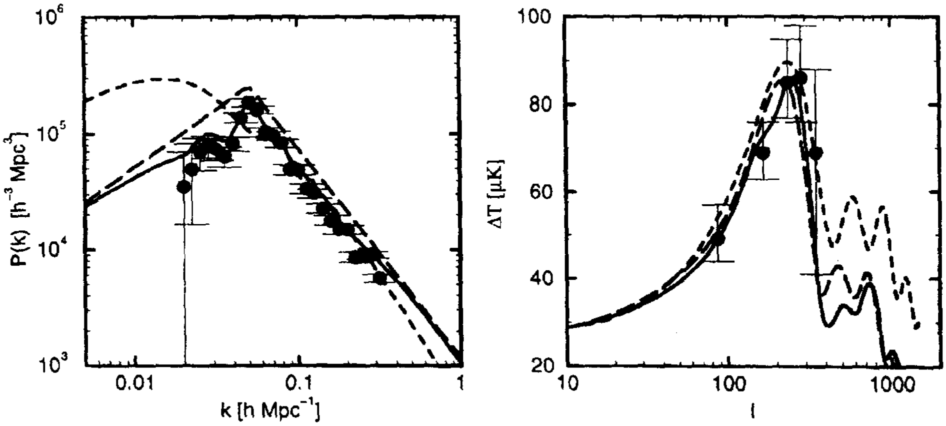

Fig2. Comparison of matter power spectra and radiation temperature anisotropies with cluster and CMB data. Dots with 1σ error bars present the observational data: the measured cluster spectrum in the left panel and the Saskatoon data on CMB temperature anisotropies in the right panel. The scale free model spectra (short-dashed lines) are computed using the following parameters: $h = 0.6$, $\Omega_b = 0.07$, $\Omega_c = 0.23$, and $\Omega_\Lambda = 0.7$ (short-dashed lines). The cluster spectrum (solid lines) was calculated using $h = 0.6$, $\Omega_b = 0.08$, $\Omega_c = 0.92$, and $\Omega_\Lambda = 0$; and the double power law models (long-dashed) using $h = 0.6$, $\Omega_b = 0.05$, $\Omega_c = 0.95$, and $\Omega_\Lambda = 0$

Double inflation models provide a possible scenario where the formation of a spike could have taken place [15]. The presence of two scalar fields driving the evolution of the Universe has a built-in scale defined by the moment when the inflaton field that initially drove inflation becomes subdominant. Another possibility which does not require a fine tuning of the initial energy density of different scalar fields is when the inflaton field evolves through a kink in the potential. A quick change in the first derivative in the inflaton potential generates a sharp spike in the matter power spectrum followed by a break in amplitude [16]. Note that this effect is beyond the slow-roll approximation to the motion of the inflaton field or any adiabatic correction to it. The initial power spectrum found in [16] is very similar to the empirical initial power spectrum that follows from the measured cluster spectrum plotted in the left panel of Fig.2, the relative amplitudes of the spike and break are also close to the observed values.

The main conclusion we can draw from our study is that, within the accuracy of present measurements, the combined cluster and CMB temperature anisotropy data suggest the existence of a break in the initial power spectrum of matter density perturbations. The spike found earlier in the cluster power spectrum [2] accounts for the observed high amplitude of the first Doppler peak in the CMB spectrum, if the baryon fraction is not too high ($\Omega_b h^2 < 0.024$ for $h \simeq 0.6$). On the other hand, if the cosmological constant is large ($\Omega_\Lambda > 0.4$), then it would be difficult to reconcile a built-in scale in the initial matter power spectrum with the present CMB data. Only new and more accurate observations of the power spectrum, both optical and CMB, can discriminate between these two alternatives.

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