THE COSMIC MICROWAVE BACKGROUND SPECTRUM: THEORETICAL FRAMEWORK

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ABSTRACT

Preliminary analyses of COBE/FIRAS data have already produced a spectacularly accurate determination of the microwave background spectrum for $1\,\mathrm{cm} \leq \lambda \leq 500\,\mu\mathrm{m}$. The absence of detectable deviations from a blackbody spectrum sets strong constraints on physical conditions of the intergalactic plasma and, in particular, has ruled out the possibility of a truly diffuse thermal bremsstrahlung origin of the X-ray background. General arguments suggest that comptonization distortions due to heating of the intergalactic medium associated with the formation of cosmic structures, with hot protogalactic winds, or with the ionizing flux from AGNs, are likely to be very small (comptonization parameter $y \lesssim 10^{-4}$). A larger signal is expected from the integrated re-radiation from dust in external galaxies; to what extent this may conceal possible comptonization distortions depends on the maximum redshift at which galaxies contain substantial amounts of dust and on the temperature distribution of dust grains. In any case, a precise determination of either the y parameter or the background from distant galaxies requires a careful subtraction of the emission from the Milky Way.

The great success of COBE strengthens the need for a parallel improvement in the accuracy of spectral measurements in the Rayleigh-Jeans region, where imprints of physical processes occurring at very early epochs (such as, e.g., the dissipation of small scale density inhomogeneities) may show up.

1. INTRODUCTION

The impact of the cosmic microwave background (CMB) on cosmology is so well known and so widely discussed that we need not to go into details here. We refer to the superb lecture by Sciama (1990) for a comprehensive account of its significance for our understanding of the origin, structure and evolution of the universe, and of its influence on cosmological phenomena.

We will enter a little more into the use of the CMB spectrum as a probe of physical processes that may have occurred at early epochs (§ 2) and will briefly analyze (§ 3) astrophysical (as opposed to cosmological) implications of CMB measurements.

2. CMB SPECTRAL DISTORTIONS

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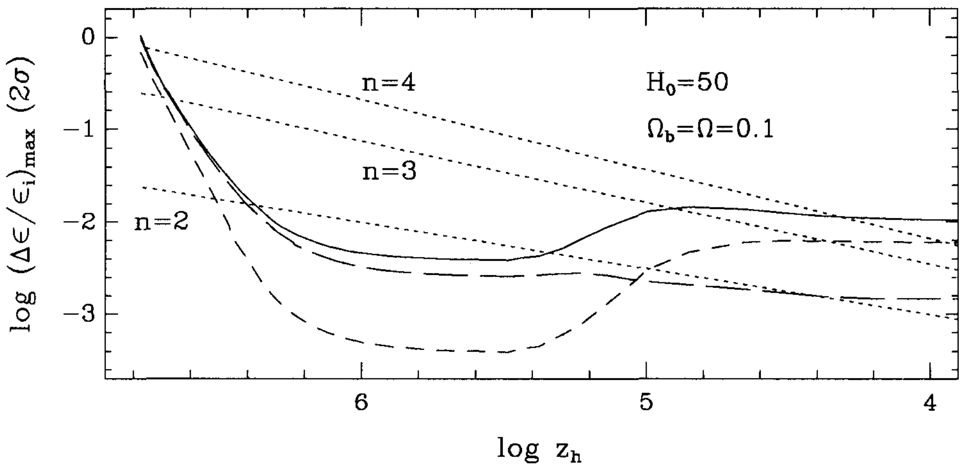

Figure 1. Upper limits (95% confidence) set by currently available data on the amount of energy that may have been dissipated, as a function of the redshift, z_h, at which the dissipation may have occurred, for the indicated values of cosmological parameters (solid line). Also plotted are the limits that may be expected from further analysis of COBE data (long dashes) and from new more accurate measurements in the Rayleigh-Jeans region (short dashes; see Burigana et al. 1991b). The dotted lines show the energy dissipation rate associated to damping of primordial adiabatic perturbations with power spectrum of index n.

Since the pioneering works of Weymann (1966), Zeldovich & Sunyaev (1969), and Sunyaev & Zeldovich (1970), it has been widely recognized that distortions carry unique information on processes that might (or had to) occur in the primordial plasma after the thermalization redshift ($z_{therm} \approx 2 \times 10^6 \widehat{\Omega}_b^{-0.36}$, $\widehat{\Omega}_b = (H_0/50)^2 \Omega_b$, Ω_b being the present baryon density in units of the critical density). Recently Burigana et al. (1991a,b) carried out an extensive numerical study on the shape and evolution of CMB distortions that can arise over a broad interval of cosmic times.

A comparison with the available data allows us to set limits on the amount of energy that can have been dissipated, as a function of cosmic time. The solid curve in Fig. 1 shows, as an example, the 95% confidence limits set by current data, in the case $\widehat{\Omega}_b = 0.1$. COBE/FIRAS data (Mather et al. 1990) and the rocket experiment by Gush et al. (1990) have tightened by an order of magnitude the constraints for $z < z_1 \simeq 8.6 \times 10^4 \widehat{\Omega}_b^{-1/2}$. A further substantial improvement is expected from a fuller analysis of FIRAS data, although astrophysical foreground radiations may inhibit the detection of spectral distortions corresponding to $\Delta\epsilon/\epsilon \leq 10^{-3}$ (Wright 1991; remember that $\Delta\epsilon/\epsilon \simeq 4y$, y being the comptonization parameter). The dashed curve in Fig. 1 illustrates the bounds that would be obtained if FIRAS error bars were decreased to 10 mK and yet no distortions were detected.

On the other hand, the extraordinary success of COBE must not make us forget the importance of accurate measurements at longer wavelengths. In fact, distortions produced at high redshifts ($z > z_1$) show up in the Rayleigh-Jeans region, i.e. outside of the frequency range covered by the FIRAS experiment. Such distortions may be expected in different frameworks: decay of superconducting cosmic strings (Ostriker & Thompson 1987; Rudak & Panek 1987; Signore & Sanchez 1991), evaporation of primordial black holes (MacGibbon & Carr 1991), dissipation of primordial density fluctuations (Daly 1991; Barrow & Coles 1991).

The dotted lines in Fig. 1 show, as an example, the rate of energy dissipation due to damping of primordial adiabatic density perturbations in the case $\widehat{\Omega} = \widehat{\Omega}_b = 0.1$, for different values of the index n of their power spectrum ($\langle|\delta_{\mathbf{k}}|^2\rangle \propto k^n$). Our calculations follow Daly (1991) and take into account damping by both nonlinear dissipation and photon diffusion. The spectrum of density perturbations has been normalized assuming that the density contrast at the present epoch is unity on a scale $\lambda_m = 8(H_0/100)^{-1}$ Mpc. Clearly, stringent constraints are most efficiently obtained by means of accurate observations in the Rayleigh-Jeans region, especially in view of the likely astrophysical limitations to FIRAS results mentioned above (see also § 3). The dashed line in Fig. 1 illustrates the bounds that might be placed by a new set of measurements at cm wavelengths with typical uncertainties of 40 mK.

Accurate measurements at still longer (dm to m) wavelengths would also be very important. For example, we still do not have a firm, model-independent, upper limit on the reionization redshift (Bartlett and Stebbins 1991); free-free emission from a high redshift plasma with $T_e \gg T_r$ would be most easily detected at $\lambda \simeq 30$–50 cm where other backgrounds are minimum. Of course, an accurate knowledge of the emission from our own Galaxy would be required. The determination of the extragalactic background at meter wavelengths, which has, unfortunately, received little attention in the last 25 years, would also be of great value, both *per se* and to allow a better definition of the long wavelength portion of the CMB spectrum.

Distortions in the Wien region of the CMB spectrum are produced by comptonization of microwave photons by hot electrons and are usually characterized by the comptonization parameter $y = \int (kT_e/mc^2) n_e \sigma_T c\, dt \simeq 1/4(\Delta\epsilon/\epsilon)$. The parameter y is, in a sense, a measure of the kinetic energy density, $\epsilon_{IGM} \simeq 3n_e kT_e$, of the intergalactic medium (IGM). As is well known, a truly diffuse origin of the X-ray background would imply $\epsilon_{IGM}(z=0) \approx 10^{-13}\,\mathrm{erg\,cm^{-3}}$ and $y \approx 10^{-2}$ (Field & Perrenod 1977), a prediction ruled out by FIRAS data.

Conventional energy sources are expected to produce much lower values for ϵ_{IGM} (Daly & Turner 1988). The present average density of metals in observed galaxies is estimated to be (Songaila et al. 1990): $6\times10^{-5} < \widehat{\Omega}_Z < 2\times10^{-4}$. If the average density of helium synthesized in stars is $\Omega_{He} \simeq 3\Omega_Z$, the energy density produced by stellar nucleosynthesis would be $\epsilon_\star \simeq 0.7$–$2.5 \times 10^{-14}\,\mathrm{erg\,cm^{-3}}$; it is very unlikely that more than few percent of this contributes to heating of the IGM (Cowie 1989). If it does, as assumed in the explosion scenario for galaxy formation (Yoshioka & Ikeuchi 1987) which predicts $y \approx 10^{-3}$ and significant clumping on scales ≈ 10 Mpc, excessive small scale fluctuations of the CMB are also expected (Barcons et al. 1991): $\Delta T/T \simeq y/\sqrt{N_c}$, where N_c is the number of clumps per beam.

The binding energy of baryons in galaxies is $\epsilon_G \approx 1/2\rho_b v^2 \approx 2 \times 10^{-17}$ $(v/300\,\mathrm{km\,s^{-1}})^2(\widehat{\Omega}_b/0.01)\mathrm{erg\,cm^{-3}}$; the energy density associated with larger scale structure can be estimated to be of the same order.

Finally, the energy density produced by AGN's, estimated from counts in the B spectral band assuming a ratio between the bolometric and the blue flux

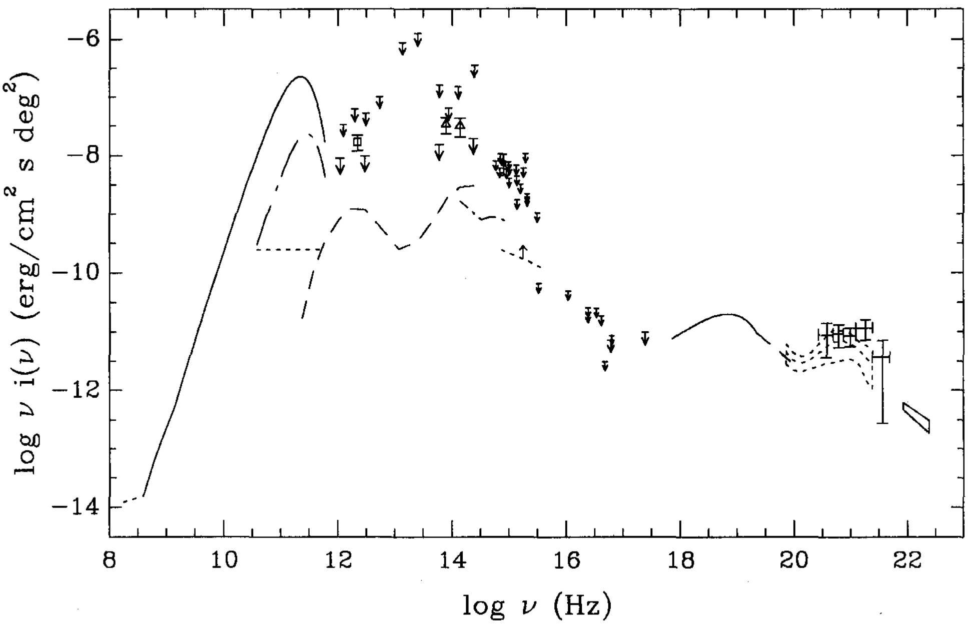

Figure 2. The microwave background shown in comparison with measurements or limits on the diffuse radiation in other wavebands. The data reported by Mather et al. (1990) imply that the brightness temperature of any additional component must be < 60 mK (dot-dashed line). The dotted line shows the expected final accuracy of FIRAS data ($\leq 10^{-3}(\nu I_{nu})_{\rm peak}$). Also plotted are the DIRBE upper limits (Hauser et al. 1991) corresponding to the total observed sky brightness in a dark direction plus 1σ; local diffuse sources, which are probably dominating the observed signal, are not subtracted. On the contrary, the results by Lange et al. (1990), also shown, refer to the isotropic residuals. For limits in the other wavebands, see Bowyer & Leinert (1990). The dashed line is the estimated contribution of galaxies to the IR background (Franceschini et al. 1991); the dot-dashed line summarizes the contributions from galaxy populations to the deepest available limits at optical and near-IR wavelengths.

$\kappa = 30$, is $\epsilon_{\rm AGN} \approx 5 \times 10^{-16}\,{\rm erg\,cm^{-3}}$ (Padovani et al. 1990), about 1/6 of which in the form of ionizing photons (Padovani 1989).

Although all these figures are highly uncertain, it appears very likely, also in view of the cosmic nucleosynthesis constraint on the baryon density ($\Omega_b \lesssim 0.1$), that the amount of energy that can have been released to heat up the IGM is $\epsilon_{IGM} \lesssim 10^{-15}\,{\rm erg\,cm^{-3}}$, so that $y \lesssim 10^{-4}$. Detailed calculations of distortions from gas heated by the release of gravitational energy during the formation of large scale structure indicate that y may range from few$\times 10^{-4}$ to below 10^{-5} (Cen et al. 1990; Cavaliere et al. 1991), in general agreement with the above estimates. The lowest distortions correspond to cold dark matter scenarios, implying low power on large scales which are characterized by high virial temperatures.

A high temperature plasma would also manifest itself by its bremsstrahlung emission. Current upper limits on extragalactic backgrounds, shown in Fig. 2,

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are again indicating $\epsilon_{IGM} \lesssim 10^{-15}\,\mathrm{erg cm^{-3}}$, i.e. $y \lesssim 10^{-4}$. On the other hand, a *lower* limit may also be derived (e.g. Miralda-Escudé & Ostriker 1990) from the absence of Gunn-Peterson troughs in the spectra of high redshift QSOs, implying that the IGM is highly ionized up to $z > 4$; the associated y-distortion is however expected to be very small: $y \simeq 10^{-7}[(1+z)/6]^{3/2}(\widehat{\Omega}_{IGM}/0.01)(T_e/10^5\,K)$.

We may then conclude that there is no compelling reason for expecting $y \gtrsim 10^{-4}$. As discussed in the next section, FIRAS measurements might rather detect astrophysical foreground radiation. In any case, a serious limitation is set by emission from dust in our own Galaxy, which might hamper a firm detection of comptonization distortions if $y < 3 \times 10^{-4}$ (Wright 1991).

3. ASTROPHYSICAL FOREGROUNDS

Background measurements are usually perceived as a tool to recover information on sources beyond the detection limits. In a more positive vein, we may note that just because the information on unresolved sources that can be extracted is intrinsically of integral type, so that fine details are lost, one is driven directly to the important astrophysical parameters and to model-independent conclusions.

A particularly intense far-IR/sub-mm background is predicted by models ascribing a large fraction of the X-ray background (XRB) to starburst galaxies (Griffiths & Padovani 1990). *Einstein Observatory* data indicate that these objects have X-ray to far-IR luminosity ratios generally below a few $\times\, 10^{-4}$ (Fabbiano 1990). Thus, if they make up much of the XRB, we would expect a far-IR background intensity far in excess of constraints based on current estimates of nucleosynthesis in galaxies and also exceeding the upper limits on the isotropic far-IR flux derived by Lange et al. (1990). COBE will undoubtedly provide a conclusive test of this possibility.

The contribution to the optical/near–IR background of galaxies directly detected in ultra deep surveys (Tyson 1990; Cowie et al. 1990) is is $(\nu I_\nu) \simeq 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,deg^{-2}}$ (see Fig. 2), i.e. about 0.5% of the peak νI_ν of the CMB. The observed flattening of the counts suggests that the global contribution of galaxies is not larger by more than a factor of a few, although Noda et al. (1991) find that the residual isotropic component of the observed near-IR sky brightness could be about 20 times higher. Since the local far-IR luminosity density of galaxies is about 1/3 of the optical luminosity density (Saunders et al. 1990) and IRAS counts at $60\,\mu$m suggest substantial cosmological evolution (Hacking et al. 1987; Danese et al. 1987) we expect a far-IR background due to galaxies of intensity $(\nu I_\nu)_{\mathrm{FIR}} >$ few $\times\, 10^{-3}(\nu I_\nu)_{\mathrm{CMBpeak}}$, and peaking at $\lambda \simeq 100(1+z_{\mathrm{eff}})\,\mu$m, i.e. detectable by COBE. Obviously, measurements of the spectrum of this background would provide important insights into the birth of galaxies, their chemical and photometric evolution, the evolution of interstellar dust, the average density of metals in the universe.

Detailed calculations have been worked out by several authors (Désert & Puget 1990; Hacking & Soifer 1991; Beichman & Helou 1991; Wang 1991; Franceschini et al. 1991); the results are in generally good agreement. In Fig. 2 we show, as an example, the results by Franceschini et al. (1991). Predictions in the near-IR and mid-IR (1–12 μm) are based on models taking into account the observational information on chemical evolution of disc and spheroidal galaxies and allowing

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for luminosity evolution of Seyfert nuclei; such models were found to be consistent with deep source counts in the K band (Cowie et al. 1990). On the whole, predictions in this spectral region appear to be well grounded.

Reliable estimates at longer wavelengths are made difficult by our poor knowledge of the evolution of interstellar dust, discussed by Wang (1991). Valuable constraints are set by the 60 μm IRAS counts, as well by the very deep radio (VLA) counts (owing to the tight correlation between radio and far-IR emission). The results shown in Fig. 2 rely on the evolution models by Danese et al. (1987), fitting the counts, and exploit the mean observed spectra of spiral, active star forming, and Seyfert galaxies. The estimated contribution to the sub-mm background turns out to be very close to the observed dust emission in our own Galaxy, towards the galactic poles. Careful modelling will be required to disentagle the two components.

To what extent the far-IR background from galaxies may interfere with the possibility of detecting true distortions of the CMB depends primarily on the redshift distribution of galaxies and on the temperature distribution of dust grains as a function of z. The results shown in Fig. 2 assume that there is a significant dust emission up to $z_D = 5$ [in fact, $\simeq 70\%$ of the background intensity at $\lambda \geq 500\,\mu$m is produced in the redshift range $1 \lesssim z \lesssim 3.8$ ($q_0 = 0.05$)], but that the contribution of active star-forming galaxies, with their higher dust temperatures, dominates at the higher z.

The possibility that early structures, at $z \sim 5$–100, could have lead to copious star formation, producing both an intense background and dust capable of reprocessing it, has been extensively discussed by Bond et al. (1991). In this case, essentially all the energy produced by nuclear reactions comes out at far-IR/sub-mm wavelengths. The peak wavelength depends on the redshift and temperature distributions of the dust but, for a relatively broad range of parameter values, occurs at $\lambda \sim 600\,\mu$m, where the amplitude ($\nu\Delta I_\nu$) of y-distortions also peaks.

Finally we note that the estimated energy density of known AGNs, $\epsilon_{\rm AGN} \approx 5 \times 10^{-16}\,{\rm erg\,cm^{-3}}$ (see § 2), is $\approx 10^{-3}\epsilon_{\rm CMB}$ and corresponds to a mass density of collapsed nuclei of $\widehat{\Omega}_{\rm AGN} \simeq 3 \times 10^{-6}(\kappa/30)(\eta/0.1)^{-0.1}$, where η is the mass-energy conversion efficiency (Padovani et al. 1990). A similar mass density of dust-enshrouded AGNs accreting with the normally adopted efficiency $\eta \simeq 0.1$ could yield a far-IR background detectable by COBE. Already available data on diffuse backgrounds (Fig. 2) rule out the possibility that the dark matter consists of black holes built up by accretion with such efficiency (Bond et al. 1991).

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