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THE SOFT X-RAY BACKGROUND AND GALAXY CLUSTERS

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ABSTRACT

We show that the background flux observed in X-rays around 1 keV sets a tight upper limit to the evolution of X-ray–emitting clusters of galaxies, once the contribution of the sources now resolved is subtracted. Specifically, if the clustering proceeds up a scale-invariant hierarchy in a critical universe, the intracluster gas content must increase faster than the dynamical mass. We model such evolution in terms of infall of the intergalactic medium into the hierarchically growing potential wells, limited by the intergalactic temperature. Thus the soft X-ray background provides constraints to the dynamical clustering and to the history of the intergalactic medium, which extend those being provided by the z-resolved luminosity functions in X-rays and complement those expected from measuring the Comptonization parameter in the microwave and far-IR bands.

Subject headings: cosmology: theory — galaxies: clustering — X-rays: galaxies

1. INTRODUCTION

Baryons condensed in the form of stars (including educated extrapolations of the IMF at its faint end; see Stevenson 1991), or in the extreme form of massive black holes in active and in currently inactive galactic nuclei (Cavaliere & Padovani 1989), have been well studied.

Much less is known about *diffuse* baryons in the form of *intergalactic* medium (IGM). Widely spaced bounds (see Fabian & Barcons 1991) are provided on the one hand by the Gunn-Peterson test, which sets direct and severe limits to the neutral component. These are interpreted as evidence for electron temperatures $T \gtrsim 10^4$ K, and indirectly indicate a total $\Omega_b \lesssim 0.05$ at redshifts $z \approx 3$ (Giallongo, Cristiani, & Trevese 1992). On the other hand, the data from *COBE*/FIRAS (Mather et al. 1990) are yielding for the Comptonization parameter values $y < 10^{-3}$, implying local limits $\Omega_b T < 0.2 \times 10^8$ K that rule out a hot, uniform IGM such as produces most of the X-ray background (XRB).

Diffuse baryons *are* detected in X-rays in the form of an *intracluster* medium (ICM) concentrated to densities up to $n \sim 10^{-3}$ cm^{-3} in the deep gravitational wells provided by most local clusters and groups of galaxies (Burg et al. 1993). In rich clusters it is found that the total value of Ω_b is up to ~ 0.2 or more (White & Frenk 1991), considerably larger than the mean values $\sim 0.06 \pm 0.02\ h_{50}^{-2}$ provided by standard cosmological nucleosynthesis (Olive et al. 1990). In a critical FRW universe with uniform initial baryon distribution, as we adopt to § 4, such condition requires infall of diffuse baryons from a distance $\gtrsim 1.5$ times larger than the clusters' central region (Fabian 1991). The infalling baryons are heated up to virial temperatures T of several keV by the gravitational energy associated with the wells, while the electrons thermalize even by 2-body collisions (Loeb & Ostriker 1990). In this view the clusters are systems *open* to the IGM.

We stress that cluster statistics at different epochs can provide information concerning not only the gravitational condensations (initial distribution of peaks in the total matter distribution, and ensuing nonlinear dynamics), but also the density and the thermal state of the IGM at larger distances.

Such information may be extracted from several observables, and here we focus onto the cluster contribution to the *soft*; see also Setti 1992 (XRB). We will discuss also the *complementary* constraint provided in the microwave and far-IR bands by spectral distortions of the cosmic microwave background (CMB) caused by the Sunyaev & Zel'dovich (1972) effect.

2. SCALINGS

The above two observables depend directly on the ICM content, and this is related to the cluster dynamical properties.

The clustering dynamics based on direct hierarchical collapses (hereafter DHCs; see Peebles 1980 and Bardeen et al. 1986) envisages progressively larger structures to arise by pure gravitational collapse of peaks in a Gaussian field of density perturbations, with a power spectrum $\langle |\delta_k|^2 \rangle \propto k^\nu$ $(-3 < \nu < 1)$. The characteristic mass virializing at z in a critical universe is $M_c(z) \propto (1+z)^{-1/a}$ with $a \equiv \frac{1}{2} + \nu/6$, and it will prove convenient to use the normalized mass $m \equiv M/M_c$ to stress the scale invariance typical of gravitational instability per se. The internal density is proportional by a factor of $\sim 2 \times 10^2$ to the cosmic density $\rho \propto (1+z)^3$ at virialization.

The ICM quantities are related to the dynamical ones as follows (see Cavaliere, Colafrancesco, & Menci 1991, hereafter CCM): the size $\hat{R} \propto (M/\rho)^{1/3}$, since the ICM is gravitationally dominated by the dark matter; the electron temperature $T \propto M/R$, from virial equilibrium with energy equipartition. The ICM mass, instead, may be *decoupled* from the dynamical mass in the form $\hat{M} \propto g(M, z)M$ as we discuss below; likewise, we will take here $n \propto g(M, z)\rho$. The bremsstrahlung luminosity from an individual cluster then reads

$$L \propto g^2(M, z) M^{4/3} \rho(z)^{7/6} . \tag{2.1}$$

The factor $g(M, z)$ will undergo an *intrinsic* evolution breaking the dynamical scale invariance. First, the scaling with M and z will include a dependence $g(M)$ in any physically "biased" condition (see Kaiser 1984; Bardeen et al. 1986), where light is more concentrated than dynamical mass. This is because in the developing hierarchy larger and darker regions are incorporated into more massive structures. Correspondingly, $M/L_{\rm opt}$ will scale up; in fact, an average behavior $M/L_{\rm opt} \propto M^{1/3}$ is consistent with observations; see Hoffman, Shaham, & Shaviv (1982). Then, from a uniform initial distribution of baryons one expects a complementary increase in the amount of *diffuse* baryons available to larger structures; CCM find that $g(M)$ will increase approximately as $g \propto M^{\alpha}$ with $\alpha \approx 0.2$–0.3. A consistent increase of the ICM content has been observed by David et al. (1990), in the form of the ratio of gas to stellar mass growing from poor to rich clusters. Conversely, such ratio drops to $\sim 10^{-2}$ in galaxies; see Fabbiano 1989.

All this may be interpreted starting from stellar energy outputs heating and expelling much of the initial baryons from galaxies (see also Ciotti et al. 1991), and building up nongravitational pressure sufficient to hold at bay the IGM from the shallower wells up to small groups. But a second factor must be included in g to describe the fraction of the available IGM which can infall and shock into the increasingly deeper potential wells; this depends on the ratio of the external to the virial temperature T_1/T (CCM). The full function g reads

$$g(M, z) = m^{\alpha} M_c^{\alpha}(z)\{2(1 - T_1/T) + [4(1 - T_1/T)^2 + T_1/T]^{1/2}\} \tag{2.2}$$

for sufficiently long-lived wells (lifetime $\gtrsim 1.5t$) and for an adiabatic exponent 5/3. Here the virial temperature rises toward us (see Peebles 1980) as

$$T(z) = T_{\rm co}\, m^{2/3}(1 + z)^{(\nu - 1)/(\nu + 3)} \, . \tag{2.3}$$

Combined with equation (2.1) these yield the relationship $L \propto n^p T^q$, with $q = (8 + 5\alpha)/2(2 - \alpha) \approx 2.5$–$2.8$ and $p = (1 - 2\alpha)/(2 - \alpha) \approx 0.3$–$0.24$; such a small value of p damps out any variance in density, leaving an $L-T$ correlation in agreement with the data reviewed by Mushotzky (1988) and Edge & Stewart (1991).

The external temperatures $T_1 \lesssim 10^7$ K tend to cool when the energy inputs die out, to the limit $T_1 \propto (1 + z)^2$ holding for outer baryons in pure Hubble flow. The key *physical* parameter will be the redshift $z_1 \sim$ a few, when $T(z_1)$ exceeds T_1. A definite value for z_1 is hard to establish a priori, partly due to the debated importance of delayed, Type I supernovae (cf. e.g., David et al. 1991 with Ciotti et al. 1991; Matteucci 1992). Additional energy inputs are contributed by partial collapses entraining the IGM. We will constrain z_1 in terms of the XRB.

From equation (2.2) it is easily shown that when $z_1 \approx 1.5$–2 holds the z-dependence of g is strong near $z \sim 0$, and may be approximated in the form $(1 + z)^{-\xi}$ with $\xi \approx 1.5$–1. Then equation (2.2) reduces to

$$g(M, z) \approx m^{\alpha} M_c^{\alpha}(z)(1 + z)^{-\xi} \, . \tag{2.4}$$

The scaling for the X-ray luminosity correspondingly reads

$$L \approx L_{\rm co}\, m^{4/3 + 2\alpha}(1 + z)^{(5 + 7\nu)/2(\nu + 3) - 12\alpha/(\nu + 3) - 2\xi} \, , \tag{2.5}$$

which for $m = 1$ yields the characteristic $L_c(z)$.

For our statistics we shall also need the full distribution of masses (MD) around the characteristic value $M_c(z)$. Since in all DHC scenarios the mass collapsed at any z is conserved, the MD must have the self-similar form

$$N(M, z) \propto \rho(z) M_c^{-2}(z) \phi(m) \, . \tag{2.6}$$

We adopt the shape $\phi(m) = m^{a-2} e^{-(b^2/2)m^{2a}}$ (Press & Schechter 1974), motivated by the success of this model to describe the scanty optical data and the results of many N-body simulations (see, e.g., Carlberg & Couchman 1989). Here the bias $b \approx 1$–1.5 is primarily a parameter for the high-M shape, and we normalize the MD to the *optically* observed space density $N_{\rm obs} = 1.3 \times 10^{-6}\, h_{50}^3$ Mpc^{-3} of Abell (1958) clusters of richness ≥ 1 (Bahcall 1988; Scaramella et al. 1990). Most important in equation (2.6) is the factor $M_c^{-2}(z)$. This implies that in the past the ICM was in a more fragmented and denser state, but meanwhile the temperature decreased after the scaling (2.3).

3. CONTRIBUTION TO THE SOFT X-RAY BACKGROUND

ICM density and temperature combine to contribute at the *observed* energy $E_o = E/(1 + z)$ the integrated, monochromatic flux per unit solid angle

$$F(E_o) = \int dV \int dM\, N \frac{L(1 + z)}{4\pi D_L^2} \frac{e^{E/kT}}{T^{1/2}} \left(\frac{E}{kT}\right)^{-0.4} , \tag{3.1}$$

where $V(z)$ is the cosmological volume, $D_L(z)$ the luminosity distance, and the dependences of N, L, T on m, z are given in equations (2.6), (2.3), and (2.5); in the emissivity by an optically thin, thermal plasma (see Rybicki & Lightman 1979) the Gaunt factor has been given the form which is appropriate for $E \gtrsim kT$, and conservative for lower energies.

We normalize the emissivity to the luminosity of a typical richness 1 Abell cluster. We take $kT_{\rm co} = 4$ keV as the typical temperature at the present epoch. We then relate this fiducial temperature to the typical luminosity through the observed $L-T$ correlation, to obtain $L_{\rm co} \approx 2 \times 10^{44}\, h_{50}^2$ ergs s^{-1} in the *ROSAT* band. This agrees with the value found in the *Einstein* band by Burg et al. (1992a).

With the previous scalings inserted in equation (3.1), we find

$$F(E_o) = \frac{R_H}{4\pi} \frac{N_{\rm obs}}{\Gamma[(1/2) - (1/2a), (b^2/2)]} \frac{L_{\rm co}}{kT_{\rm co}} \left(\frac{E_o}{kT_{\rm co}}\right)^{-0.4} \int dm \int dz$$
$$\times\, m^{-1 + a + 2\alpha} e^{-(b^2/2)m^{2a}} e^{-m^{-2/3}(1 + z)^{4/(\nu + 3)} E_o/kT_{\rm co}} (1 + z)^{\beta} \, . \tag{3.2}$$

The m-integration is dominated by the range $M \sim M_c(z)$, and remains so for all realistic mass distributions yielding nearly constant numerical values. The scaling with $1 + z$ is most significant, and its exponent reads

$$\beta = -2.9 + (17.2 + 6.8\nu)/2(\nu + 3) - 2\xi - 12\alpha/(\nu + 3) \, . \tag{3.3}$$

The contributions to β break down as follows: -2.5 from cosmology ($\Omega_o = 1$); the intrinsic ICM evolution contributes $-2\xi - 12\alpha/(\nu + 3)$; the average luminosity $dM\, NL \propto L_c(z)/M_c(z)$ contributes $(17 + 7\nu)/2(\nu + 3)$; to this, we must add $0.1(1 - \nu)/(\nu + 3) - 0.4$ from the emissivity; the latter also contributes the exponential cutoff in E_o, the term that mixes the dependence on $1 + z$ with that on m.

We integrate equation (3.2) with the full expression (2.2) out to $z \approx 2.5$, the epoch for group formation in DHC, and from $m > 0.01(1 + z)^{-1.5 + 1/a}$, corresponding to group temperatures $kT > 0.5$ keV. Smaller masses (or earlier z) would fall in the domain of the galaxies for which the gas content drops to $\hat{M}/M \sim 10^{-2}$.

The results are shown in Figures 2 and 3. For comparison, Figure 1 shows the baseline model contemplating a uniform distribution of clusters with the same MD and ICM properties as are observed in the local environment. The resulting flux over the band 1–5 keV yields $F/F_{\rm obs} \lesssim 25\%$ relative to the *total*

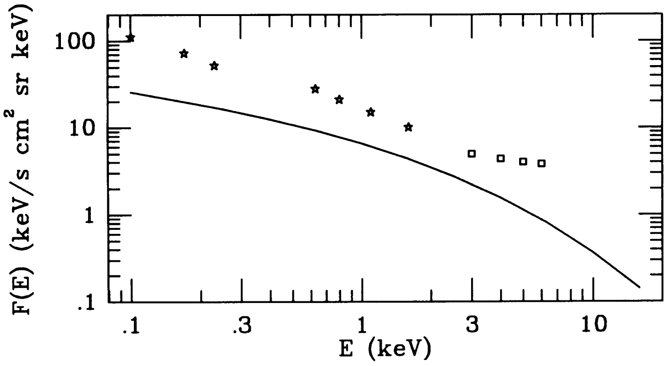

FIG. 1.—The contribution to the XRB from groups and clusters of galaxies uniformly distributed in a low-density ($\Omega_o = 0.1$) universe out to $z = 3$ retaining the local properties described by eq. (2.6) with $b = 1.5$. Data, with no subtraction of discrete sources, from *ROSAT* (Hasinger 1992; *open star* [☆]), and from Marshall et al. 1980, Wu et al. 1990 (□).

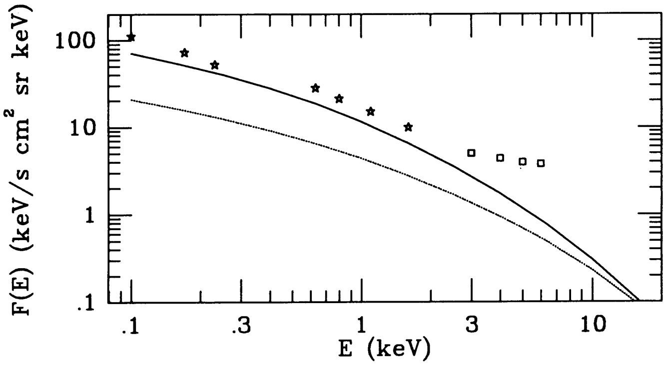

FIG. 2.—The contribution to the XRB by groups and clusters extrapolated from the same local distribution as in Fig. 1, but after a DHC scenario with $\nu = -1.2$ and $\Omega_o = 1$. The solid line refers to fully scale-invariant model with no ICM evolution, and the dashed one to ICM evolving after eq. (2.2) with $z_1 = 1.5$.

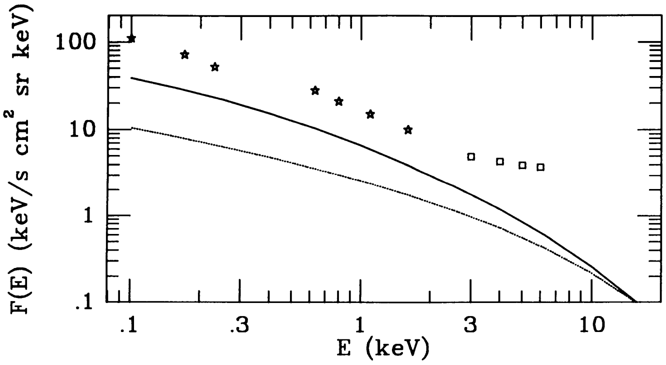

FIG. 3.—Same as Fig. 2 for $\nu = -2$

observed value. We expect a larger contribution from DHC models, with to an IGM denser in the past. More negative values of ν imply cooler temperatures and shallower depths that tend to suppress the flux, especially at higher energies.

It is seen that models with $\nu \approx -1.2$ for the dynamical structure and no intrinsic ICM evolution are ruled out. In fact, at $E_o \sim 1$ keV they would more than saturate the *residual* XRB flux, after subtracting from $F_{\rm obs}$ the contribution of the resolved AGN sources which amounts to at least 50% (Hasinger 1992). The result is stable by the following account.

The constraint is strengthened by including the emission lines (see Sarazin 1988) which yield an excess $\lesssim 5\%$ spread around $E_o \sim 1$ keV, since their flux is exponentially suppressed at the low temperatures where they have a large equivalent width. Changing our formal bias parameter b from 1.5 to 1 increases the result by $\lesssim 6\%$, since in this range the denominator and numerator changes nearly balance in equation (3.3). Likewise, partially virialized structures or 2D and 1D collapses will increase the flux, although only by minor amounts if these structures are too tenuous or short-lived to allow electron thermalization (Loeb & Ostriker 1990). Similarly for the inclusion of a larger number of faint or cool groups like Burg et al. (1992) are finding. Conversely, changing the integration limit to $z = 2$ only causes a few percent decrease since cosmological volumes saturate for $z \gtrsim 1$. Changing $kT_{\rm co}$ to 5 keV, the result is lowered only by 3%. Finally, the results are independent of H_o because equation (3.3) maps individual fluxes into an integrated flux. The spectrum from our model is softer than Loeb & Ostriker's (1990) due to our typical $kT_{\rm co} = 4$ keV. It is consistent with the spectra derived by Blanchard et al. (1992) for corresponding parameters in their phenomenologically extended grid, considering our normalization, Gaunt factor, and conservative evaluation of the contribution from very faint and cool sources.

4. DISCUSSION

The *residual* XRB at ~ 1 keV is easily exceeded by the integrated emissions contributed by clusters and groups, extrapolated backward from the *local* numbers following *fully* scale-invariant evolutions of the DHC kind.

For perturbation power spectra with $\nu > -2$ additional *anti-evolution* of the ICM is required. Two implications then follow. The scale invariance so characteristic of the pure gravitational instability must be broken; one likely cause is stellar energy released from supernovae in galaxies matching down to $z_1 \sim 1.5$ the energy gained by the ICM from structure formation, with help from partial collapses. Alternatively, power spectra with $\nu \lesssim -2$ (implying that structures on all scales involved form only late) are still compatible at 1 keV with no intrinsic ICM evolution. This may be expressed in terms of $z_1 > 2.5$, and implies an early and low energy input.

We stress that the constraint provided by the XRB data is more reliable for extended sources than limits from either number counts or z-resolved luminosity functions. In fact, both may easily miss—unless the survey is specifically designed—sources which are cool or with low surface brightness, as are being observed locally by Burg et al. (1992) and are expected to increase in number at larger z.

Below 1 keV the observational constraint may be even tighter. *ROSAT* shadowing observations (Snowden 1992) together with the *ROSAT* Deep Survey (Hasinger et al. 1992) are providing evidence that the *residual* XRB at $\sim \frac{1}{4}$ keV may be no more than 20% of the extragalactic flux. Such levels are even less compatible with fully scale-invariant models. With $\nu \lesssim -1.2$ they will require $z_1 \lesssim 1.5$, and values $z_1 < 2.5$ even for $\nu = -2$. A similar bound holds for the CDM perturbation spectrum (Blumenthal, Pagels, & Primack 1982; Peebles 1982) which, if still normalized to the local clusters, yields for $F(E_o)$ values that at $E > 1$ keV approach those we computed for $\nu \approx -1.2$, and at lower energies those for $\nu \approx -2$.

Both constraints at 1 and at $\sim \frac{1}{4}$ keV do not rule out yet the uniform distribution, realistic in low-density FRW universes. Such cosmogonies, in turn, are constrained by the SZ effect.

TABLE 1

EFFECTS OF THREE BASIC MODELS ON XRB AND INTEGRATED SUNYAEV ZEL'DOVICH EFFECT

Model	Contribution to XRB	S-Z Effect
Uniform	Low $F/F_{\rm obs} \simeq 25\%$, 1-5 keV	High $y \simeq 2 \times 10^{-4}$
Hierarchical, $\nu \lesssim -1.2$	High $F/F_{\rm obs} \simeq 100\%$, 1 keV	Low $y \simeq 1 \times 10^{-5}$
Hierarchical, with evolving ICM	Low $F/F_{\rm obs} \simeq 25\%$, $\frac{1}{4}$ keV	Very low $y \lesssim 5 \times 10^{-6}$

NOTE.—Hierarchical models with evolving ICM yield about the level of the residual XRB at $\sim \frac{1}{4}$ keV.

This probes the other combination of n and T given by $y \propto \int dl\, n\, T$ integrated along the line of sight, and is complementary to the above in two ways. First, the *linear* dependences imply a stronger dependence on the dynamical quantity T, but a milder dependence on $n \propto g\rho$ which embodies the ICM evolution. Second, y averaged over angles larger than cluster diameters saturates with z slower than fluxes, in fact following $y(<z) \propto (1+z)^{(7+5\nu)/2(\nu+3)} g(z)$, or even increases as $y(<z) \propto (1+z)^2$ in the limit of a uniform distribution in an empty universe (Cavaliere, Menci, & Setti 1991). So y is generally more *sensitive* to the presence of structures at sizable redshifts providing they are not too cool, with the uniform distribution yielding the largest y values.

The spectral distortion of the CMB by distant clusters, given by $\Delta T/T = 2\langle y \rangle$ in the microwave band, is computed in detail by Cavaliere, Menci, & Setti (1991) (and also by Markevitch et al. 1991). The updated *COBE* result $y < 4 \times 10^{-4}$ is close to ruling out the uniform distribution for $\Omega_o \lesssim 0.1$. Angular fluctuations both from the SZ effect and in the XRB constitute generally shallower probes, as they tend to favor nearby objects.

The overall picture is summarized in Table 1, which shows how the two observables are *maximized* in turn by *different* models for cosmogony and for ICM evolution spanning the domain of interest. We may add the information carried by the z-resolved luminosity functions which, from the pre-*ROSAT* surveys (see Henry et al. 1992), also indicate out to $z \lesssim 0.5$ some dearth of bright sources consistent with a fast antievolution of the ICM content.

In conclusion, the two integral observables in terms of the XRB and the CMB probe different combinations of n and T at different epochs. Together they begin to constrain mass (or density) and temperature of the ICM, and the dynamical spectral index ν. The model envisaging long-lived, uniformly distributed clusters and groups is still compatible with the XRB limits, but it is closely constrained by the SZ spectral effect. A model consistent with all these constraints is clustering by DHCs, with ICM *preheated* by stellar or even by gravitational energy and gradually concentrated since the epoch of group formation. Such a model offers the additional prospect of complementing the AGN contributions so as to saturate the soft extragalactic XRB.

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