

DIFFUSE BARYONS IN GROUPS AND CLUSTERS OF GALAXIES

A. CAVALIERE

Astrofisica, Dipartimento Fisica, II Università di Roma, via Ricerca Scientifica 1, 00133 Roma, Italy

N. MENCI

Osservatorio Astronomico di Roma, via Osservatorio, 00040 Monteporzio, Italy

AND

P. TOZZI

Astrofisica, Dipartimento Fisica, II Università di Roma, via Ricerca Scientifica 1, 00133 Roma, Italy

Received 1997 September 8; accepted 1998 February 19

ABSTRACT

To predict the X-ray observables associated with the diffuse baryons in clusters of galaxies, we develop a new physical model for such a hot intracluster plasma. Our framework is provided by the hierarchical clustering cosmogony for the dark matter and by the standard FRW or Lemaître cosmologies constrained by cosmic ages. As to the plasma dynamics and thermodynamics we propose a semianalytical approach based on punctuated equilibria. This comprises the following blocks that we compute in detail: Monte Carlo “merging histories” to describe the dynamics of dark matter condensations on scales of order 1–10 Mpc and the associated evolution of the gravitational potential wells; the central hydrostatic disposition of the intracluster plasma (ICP), reset to a new equilibrium after each merging episode; conditions of shock, or of closely adiabatic compression at the boundary with the external gas, preheated by stellar energy feedbacks. Shocks of substantial strength are shown to prevail at the outskirts of rich clusters in a universe with decelerated expansion. From our model we predict the L - T relation, consistent with the data as for shape and scatter. This we combine with the mass distribution provided by the canonical hierarchical clustering; the initial perturbation spectra are dominated by cold dark matter but include enough baryons to account for the high abundance sampled by the X-ray clusters and are *COBE* normalized. Thus we predict the z -resolved luminosity functions, with the associated source counts and redshift distributions. We predict also the complementary contribution by the unresolved groups and clusters to the soft X-ray background. These results are compared to two recent surveys from *ROSAT*; one defines the local luminosity function over nearly three decades of L , and the other shows little or no evolution out to $z \sim 0.8$. Our results confirm that the critical cosmology coupled with standard cold dark matter (CDM) is ruled out by its overproduction of local clusters. On account of underproduction, instead, we rule out open cosmologies (the cheapest way to solve the baryonic crisis and to freeze evolution), except for a narrow range around $\Omega_0 = 0.5$; even there, we find the consistency with the full database to be barely marginal. For the CDM cosmogony with $\Omega_0 = 0.3$ but in flat geometry, we obtain acceptable fits. For the tilted CDM perturbation spectrum with high baryonic content in the critical universe, we obtain marginal consistency. The cosmogonical/cosmological sectors of the cluster history are independently testable by means of a lower bound to the evolved temperature distribution, as can be measured with *BeppoSAX* and *XMM* out to moderate z . Finally, we discuss the effective limitations of X-ray clusters and groups as cosmological signposts, and their brighter prospects toward the astrophysics of the ICP and the cosmogony of large, high-contrast structures.

Subject headings: cosmology: theory — galaxies: clusters: general — hydrodynamics — X-rays: galaxies

1. INTRODUCTION

Groups and clusters of galaxies constitute cosmic structures sufficiently close to equilibrium and with sufficient density contrast ($\delta \approx 2 \times 10^2$ inside the virial radius R) as to yield definite observables and possibly to offer reliable signposts for cosmology.

They stand out to substantial depths of spacetime not only in the optical band, but even more in X-rays. This is because their gravitational potential wells, shaped by a dominant dark mass M , contain not only baryons condensed into stars but also a larger amount of diffuse baryons. The latter, with densities $n \sim 10^{-3} \text{ cm}^{-3}$ and virial temperatures $kT \sim GM_{\text{H}}/10R \sim 5 \text{ keV}$ in rich clusters, satisfy the plasma condition $kT/e^2 n^{1/3} \gg 1$ exceedingly well—in fact by a factor 10^{11} , which is vastly larger than for the baryons inside the stars. Such a hot intracluster plasma

(ICP) emits powerful X-ray luminosities $L \propto n^2 R_{\text{X}}^3 T^{1/2} \sim 10^{44} \text{ ergs s}^{-1}$ by optically thin thermal bremsstrahlung from central regions of overall radius $R_{\text{X}} \sim 1 \text{ Mpc}$.

The temperature directly probes the height of the potential well, with the baryons in the role of mere tracers; on the other hand the luminosity, with its strong dependence on density, reliably probes the baryonic content. Statistically, a definite L - T correlation is observed (albeit with considerable scatter), and this provides the crucial link to relate the X-ray luminosity functions with the statistics of the dark mass M or with that of the corresponding T .

But groups and clusters are intrinsically complex systems. To begin with, their dynamical history is marked by extensive, repeated merging of clumps, both in the form of nearly isotropic accretion of small units and in the form of a few large, anisotropic coalescence events. This is shown in detail

by all N -body simulations (see, e.g., Schindler & Mueller 1993; Tormen 1997; Roettiger, Stone, & Mushotzky 1998), and is increasingly indicated by the data (see, e.g., Zabludoff & Zaritsky 1995; Henriksen & Markevitch 1996; Jones et al. 1997).

The timing of such a dynamical evolution (and specifically the present merging rate) is set by the cosmological framework. If we adopt the homogeneous isotropic FRW or Lemaître cosmologies, the expansion is parametrized by the Hubble constant h (in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and by the density parameter Ω_0 (to which the baryons contribute the fraction Ω_B); a possible additional contribution is given by Ω_Λ associated to the cosmological constant.

Given the cosmological framework, the cosmogony (i.e., the process of structure formation) is widely treated in terms of the standard hierarchical clustering scenario (see Peebles 1993), where all structures form by gravitational instability of initial density perturbations δ in the dark matter (DM). Important parameters are the shape of their power spectrum $\langle |\delta_k|^2 \rangle \propto k^n T^2(k)$ at the recombination and the normalization measured at large scales by COBE/DMR (Górski et al. 1998). The transmission function $T(k)$ depends on the specific model assumed for the DM; given this, the amplitude σ_8 (i.e., the normalization extrapolated down to the relevant scale $8 h^{-1} \text{ Mpc}$) and the effective spectral slope n_e depend on Ω_0 and h . These parameters also affect the growth factor $D(z)$ of the perturbations, which enters the actual form of the mass distributions of the condensed clusters or groups.

Further complexity is added by the physics of the ICP, and this constitutes our main aim here. Until now, the ratio of the ICP to DM, and specifically its central density n_0 and its effective radius, are poorly understood. But the former is especially important, as the factor n_0^2 enters the luminosities and amplifies the observed variance.

Observational information on the ICP and on the underlying DM dynamics is provided by the local L - T correlation. At higher z , further statistical information is provided by the evolution of the X-ray luminosity function $N(L, z)$, or by its integrals like the source counts or the z distributions. The problem is that the predictions of observables involve not only the ICP physics and the cosmogony (with their intrinsic variances) but also cosmology again (with its uncertainties), and so the various aspects are not easily disentangled.

The sharpest result obtained so far rules out the attractively simple assumption by Kaiser (1986) that the ICP amount be proportional to the DM's from groups to clusters at all z and M . A large number of subsequent works (of which we cite here the recent Mathiesen & Evrard 1998; Kitayama & Suto 1997; and Borgani et al. 1998) dealt with the combinations of these three sectors, namely, cosmology, cosmogony, and ICP physics. But most of these papers, following the start by Cavaliere & Colafrancesco (1988), approached the problem by parameterizing the dependences of the ICP/DM ratio on M and z , e.g., in the form $L \propto M^p(1+z)^s$. While the parameters p and s are constrained to some extent by the local L - T correlation, there still remains a substantial degeneracy (Oukbir, Bartlett, & Blanchard 1997) between ICP physics and cosmology/cosmogony. That is to say, different combinations of h , Ω_0 , Ω_Λ , Ω_B , σ_8 , n_p , s , p provide close fits to the observables. Conversely, when the ICP parameters are varied, different cosmologies appear to be preferred by the data; the trade-

off particularly concerns Ω_0 and s , which directly govern the global and the ICP evolution, respectively.

To go beyond such degeneracies a physical model is needed for the ICP, comprising the above complexities. Such a model must include: the histories of DM halos with their hierarchical merging events; the infall of the gas with the ensuing compression and shocks; the disposition of the ICP in the potential wells; its conditions at the boundary with the surrounding environment, which is modulated by the large-scale structures and by stellar preheating. A model accounting for all the above was missing until now. We stress that the simulations using advanced hydrodynamics coupled with N -body codes do not have at present enough dynamic range (as discussed by Bryan & Norman 1998) to describe DM and ICP over the full range from $\sim 50 \text{ Mpc}$ associated with the large-scale structures (which guide the mergers of DM halos) to the inner 50 kpc where the ICP still yields a considerable contribution to L . Nor do they include the stellar preheating with its crucial effects on the L - T relation.

This motivates us to develop here a semianalytical model that includes, although in a simplified form, the features listed above. We describe the cluster evolution as a sequence of "punctuated equilibria" (PE), that is to say, a sequence of hierarchical merging episodes of the DM halos (computed with Monte Carlo simulations), associated in the ICP to shocks of various strengths (depending on the mass ratio of the merging clumps), which provide the boundary conditions for the ICP to readjust to a new hydrostatic equilibrium. We show that our PE model predicts density and temperature profiles and the L - T relation for clusters and groups consistent with the recent data.

We then use our PE model to predict the counts of resolved sources $N(>F)$ for faint fluxes down to $F > 2 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$, now accurately measured by Rosati et al. (1998). We predict also the complementary observable constituted by the contribution of the unresolved groups and clusters to the soft X-ray background (XRB). We predict the z distributions and finally the full z -resolved luminosity functions to be compared to recent and forthcoming surveys.

This paper is organized as follows. In § 2 we present and discuss our approach to the ICP astrophysics. In § 3 we give the X-ray observables in the form suited to our hierarchical clustering computations; details are supplied in the Appendices A, B, and C. In § 4 we present the results from our approach. The final section (§ 5) is devoted to discussions and conclusions.

2. THE PUNCTUATED EQUILIBRIA OF THE ICP

The X-ray luminosity of a cluster with radial temperature profile $T(r)$ and density profile $n(r)$ is given by

$$L \propto \int d^3r n^2(r) T^{1/2}(r); \quad (1)$$

the integration is over the emitting region $r \lesssim R$. Expressing R from $T \propto M/R \propto \rho R^2$, equation (1) is recast into the form

$$L \propto [\overline{n(r)/n_1}]^2 T^2 \rho^{1/2}, \quad (2)$$

where ρ is the internal DM density, n_1 is the density just exterior to the cluster boundary, and the bar indicates the integration over the cluster volume normalized to R^3 . Note that equation (2) applies in the isothermal case; the corre-

sponding expression for a polytropic ICP is given in Appendix B.

The simplest approach to the ICP state is that adopted in the self-similar model (Kaiser 1986) where $n \propto \rho$ is assumed, independently of T ; then $L \propto T^2$ obtains from equation (2). The result conflicts with the observed correlation for rich clusters that is close to $L \propto T^3$ (Edge & Stewart 1991; Mushotzky 1994; Tsuru et al. 1996; Mushotzky & Scharf 1997). Also, when combined with the standard hierarchical cosmogony, the assumption yields unacceptable fits to the local luminosity function (see, e.g., Kitayama & Suto 1997). Finally, it would predict the clusters at higher z to comprise not only denser DM, but also equally denser ICP; since bremsstrahlung depends on n^2 , this would imply a strong positive evolution of $N(L, z)$, which is certainly *not* observed. Rather, the analyses of the *ROSAT* Brightest Cluster Sample (Ebeling et al. 1997, see also De Grandi et al. 1996) and of the *ROSAT* Deep Cluster Survey by Rosati et al. (1998), see also the data by Collins et al. (1997) and by Nichol et al. (1997), indicate no evolution out to $z \approx 0.8$ for $L < 10^{44} h^{-2} \text{ ergs s}^{-1}$; earlier surveys (Extended Medium-Sensitivity Survey [EMSS], Henry et al. 1992) suggested even a (marginal) negative evolution of the bright clusters.

So to derive the true scaling of L with T we need a closer analysis of the ICP disposition relative to the DM. We propose a new approach based upon two cornerstones: the profiles $n(r)$ and $T(r)$ are given by the hydrostatic equilibrium with the changing gravitational potential; their normalizations, and so the central density, are set by the conditions at the boundary with the external medium.

The equilibrium profile may be effectively represented with a polytropic relation starting from the cluster boundary at r_2 , say,

$$n(r)/n_1 = g(T) \left[\frac{T(r)}{T_2} \right]^{1/(\gamma-1)}. \quad (3)$$

Here T_2 is the temperature just interior to the boundary; we conveniently use $g(T) \equiv n_2/n_1$ for the ratio of the interior to the exterior density, to include any shock discontinuity at the boundary. The appropriate values for γ will be discussed in §§ 2.1 and 2.4.

Actually, the ICP is reset to a *new* equilibrium after each episode of accretion or merging of further mass. In our PE approach, the history of such episodes is followed in the framework of the hierarchical clustering by Monte Carlo simulations, as explained in § 2.2.

Two relevant limiting forms of equation (3) are constituted by the “shock” model of Cavaliere, Menci, & Tozzi (1997, hereafter CMT97), and by the “adiabatic” models of Kaiser (1991) and of Evrard & Henry (1991). In both, the outer gas is taken to be preheated at $T_1 \lesssim 1 \text{ keV}$ (Ciotti et al. 1991; David et al. 1993; David, Jones, & Forman 1995; Renzini 1997) by $z \lesssim 2$, due to feedback energy inputs following star formation and evolution. Preheating temperatures $T_1 \gtrsim 0.1 \text{ keV}$ also would prevent the cooling catastrophe from occurring, see White & Rees (1978) and Blanchard, Valls-Gabaud, & Mamon (1992). In point of fact, Henriksen & White (1996) find from X-rays evidence for diffuse cool gas at 0.5–1 keV in the outer regions of a number of clusters. In the present context, preheating will inhibit the attainment of the universal baryonic density in gravitational wells with virial temperatures comparable to T_1 .

These limiting models differ in their treatment of the boundary conditions and of the merging histories.

2.1. Shocks and Hydrostatic Equilibrium

The key boundary condition is provided by the dynamic stress balance $P_2 = P_1 + m_H n_1 v_1^2$, relating the exterior and interior pressures P_2 and P_1 to the inflow velocity v_1 driven by the gravitational potential at the boundary. We expect the inflowing gas to become supersonic in the vicinity of R , when $m_H v_1^2 > 2kT_1$. In fact, many hydrodynamical simulations of loose gas accretion into a cluster (from Perrenod 1980 to Takizawa & Mineshige 1998) show shocks to form, to convert most of the bulk energy into thermal energy, and to expand slowly, remaining close to the virial radius for some dynamical times. So we take $r_2 \approx R$ (which follows the structure growth, since $R \propto M^{1/3}$), and focus on nearly static conditions inside, with $v_2^2 \ll v_1^2$.

The postshock state is set by conservations across the shock not only of the stresses, but also of mass and energy, as described by the Rankine-Hugoniot conditions (see Appendix B). These provide at the boundary the temperature jump T_2/T_1 , and the corresponding density jump g , which reads

$$g\left(\frac{T_2}{T_1}\right) = 2\left(1 - \frac{T_1}{T_2}\right) + \left[4\left(1 - \frac{T_1}{T_2}\right)^2 + \frac{T_1}{T_2}\right]^{1/2} \quad (4)$$

for a plasma with three degrees of freedom. Equation (4) includes both weak and strong shocks. For weak shocks with $T_2 \approx T_1$ (appropriate for small groups accreting preheated gas, or for rich clusters accreting comparable clumps), this converges to the truly adiabatic relationship $n_2/n_1 = (T_2/T_1)^{3/2}$ up to second order inclusive, see Landau & Lifshitz (1959). On the other hand, it is shown in Appendix B that for strong shocks (appropriate to “cold inflow” as in rich clusters accreting small clumps and diffuse gas) the approximation $kT_2 \approx -\phi_2/3 + 3kT_1/2$ holds, where ϕ_2 is the gravitational potential energy at $r_2 \simeq R$.

Inside R , the temperature and density profiles $T(r)$ and $n(r)$ are matched to T_2 and to n_2 by polytropic profiles or by their isothermal limit. We numerically compute such profiles using the hydrostatic support of pressure against gravity (see Appendix B); for definiteness, we use the Navarro, Frenk, & White (1996) representation for the potential and for the DM velocity dispersion (which varies slowly in the relevant region).

Let us consider first for reference the simple analytical approximation provided by the standard isothermal model

$$n(r)/n_2 = [\rho(r)/\rho_2]^\beta \quad (5)$$

(Cavaliere & Fusco-Femiano 1976), with the canonical exponent $\beta \equiv \mu m_H \sigma / kT_2$; here σ is the one-dimensional velocity dispersion at R , and μ is the average molecular weight. For the purpose of the analytical approximation we may use the strong shock limit for T_2 , and find numerical values for β increasing from about 0.5 for groups to 0.9 for rich clusters (a trend consistent with data being collected by M. Girardi et al. 1997, private communication). This implies that R_X/R is larger in the former than in the latter (see CMT97).

The full numerical computations using the expression for T_2 given in Appendix B, and $\sigma(r)$ and $\phi(r)$ from Navarro et al. (1996) confirm this trend and give results shown in Figure 1. Note that even in the isothermal case the

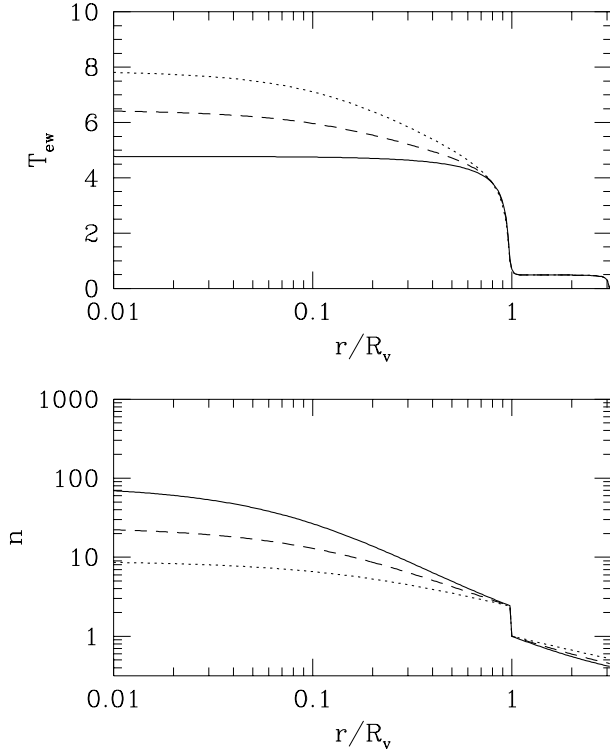


FIG. 1.—Temperature (*top*) and density (*bottom*) profiles for a single cluster of $10^{15} M_{\odot}$ at $z = 0$ in polytropic equilibrium; $\gamma = 1$ (*solid line*), 1.1 (*dotted line*) and 1.2 (*dashed line*), see eq. (B3); the dark matter potential is taken from Navarro et al. (1996), and critical cosmology with TCDM perturbation spectrum is used. The shock strength corresponds to $T_2/T_1 = 10$. The temperature is emission-weighted along the line of sight and smoothed with a filter width of 100 kpc.

emission-weighted temperature (integrated along the line of sight) declines outward but only very slowly.

The observed stronger decline requires a polytropic equilibrium, where the run of $T(r)$ steepens with the index γ increasing from 1. In Appendix B we recall the basic relations, and show that the variations induced in the volume-averaged luminosity by increasing γ are modest. Thereafter, we adopt the value $\gamma = 1.2$, which also yields for rich clusters an integrated baryonic fraction 0.15 out to R . The result for the emission-weighted $T(r)$ (see Fig. 1) is a mild decrease out to $r \sim 1$ Mpc in agreement with the observations (Hughes, Gorenstein, & Fabricant 1988; Honda et al. 1997; Markevitch, Sarazin, & Henriksen 1997), followed by a sharper drop as indicated by state-of-the-art simulations (e.g., Bryan & Norman 1998). Note that in Figure 1 the discontinuity at the shock has been smeared out to a smooth drop by the finite resolution, taken at 100 kpc for comparison with the simulations and with the forthcoming observations.

2.2. Merging Histories and the L - T Correlation

The luminosity $L \propto g^2 n^2(r)/n_1^2 T^2 \rho^{1/2}$ is statistically affected by the merging histories as follows. For a cluster or group of a given mass (or temperature), the effective compression factor squared $\langle g^2 \rangle$ is obtained upon averaging equation (4) over the sequence of the DM merging events; in such events, T_2 is the virial temperature of the receiving structure and T_1 is the higher between the stellar preheating

temperature and that from “gravitational” heating, i.e., the virial value prevailing in the clumps being accreted.

All that is accounted for in our model using Monte Carlo simulations of the hierarchical growth of the DM halos; these are based on merging trees corresponding to the excursion set approach of Bond et al. (1991), consistent with the Press & Schechter (1974) statistics (see CMT97). The averaging procedure is dominated by the events occurring within the last few dynamical times; this results in lowering $\langle g^2 \rangle$ compared to g^2 because in many events the accreted gas is at a temperature higher than the minimum preheating value $T_{1\ell} \approx 0.5$ keV. In addition, an intrinsic variance is generated, reflecting and amplifying the variance intrinsic to the merging histories.

The net result is shown in Figure 2 and discussed in its legend. In agreement with the observations (Edge & Stewart 1991; Mushotzky 1994; Tsuru et al. 1996; Ponman et al. 1996), the shape of the average L - T relation flattens from $L \propto T^5$ at the group scale (where the nuclear energy from stellar preheating competes with the gravitational energy from infall) to $L \propto T^3$ at the rich cluster scales. At higher temperatures the shape asymptotes to $L \propto T^2$, the self-similar scaling of pure gravity. Notice the intrinsic scatter due to the variance in the dynamical merging histories, but amplified by the n^2 dependence of L .

The average normalization rises like $\rho^{1/2}(z)$, where ρ is the effective external mass density, which increases as $(1+z)^2$ (Cavaliere & Menci 1997) in filamentary large-scale structures hosting most groups and clusters (see Ramella, Geller, & Huchra 1992). This implies a factor 1.3 at $z = 0.3$, consistent with the observations by Mushotzky & Scharf (1997). Further weakening of the z dependence will come from the increasing depth of the central ϕ_0 for distant structures of given M , as predicted by Navarro et al. (1996).

2.3. The Adiabatic Models

At the other extreme, the models by Kaiser (1991), and Evrard & Henry (1991) obtain from PE under two limits, appropriate only for rapidly expanding universes, as we discuss below. The first limit corresponds to no currently

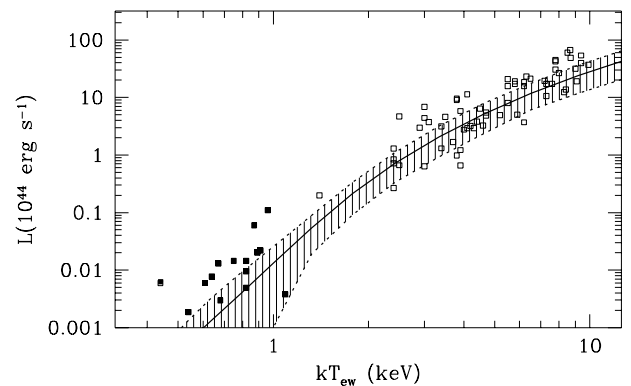


FIG. 2.—For the PE model and the TCDM cosmogony, we show the average L - T relation (in terms of the emission-weighted temperatures) with its 2σ dispersion (*shaded region*). The average and the scatter of the compression factor are computed by convolving g^2 in eq. (4) with the merging histories. The steepening at low T is due to the preheating temperature; this is uniformly distributed in the interval 0.5 ± 0.3 keV. Data from Ponman et al. (1996; *solid squares*) and David et al. (1993; *open squares*).

active merging, with shocks moving outward and vanishing. In such conditions, at the boundary $T_2 \approx T_1$ holds; with T_1 staying nearly constant after the dynamical freeze out, this implies $g \equiv n_2/n_1 \approx 1$. Correspondingly, the central density scales approximately as $n_0 \propto n_1(T_0/T_1)^{1/(\gamma-1)}$.

The “adiabatic” models require also a second limit, concerning the internal gas distribution. The value $\gamma = 5/3$ is taken at the center, but an isothermal β profile is assumed (with a fixed β), based on a King-like DM distribution. A constant baryonic fraction at R is then required, and this forces the core radius to scale as $r_c \propto M^{1/3-1/3\beta}$. Thus $L \propto T^{2+3(2-1/\beta)/2}$ obtains, with the normalization $\rho^{1/\beta-3/2}(z)$.

Finally, the value of β is chosen as an input. The choice $\beta = \frac{2}{3}$ for both clusters and groups leads to the model of Evrard & Henry (1991), in which $L \propto T^{11/4}$ obtains, with constant normalization. The choice $\beta = 1$ leads to the somewhat different model of Kaiser (1991), in which $L \propto T^{3.5}$ obtains, with the normalization antievolving like $(1+z)^{-3/2}$; the exponent will become even more negative when the evolution of ϕ is taken into account, so conflicting with the data of Mushotzky & Scharf (1997).

2.4. ICP Models and Cosmology

Shock and adiabatic models can be characterized in terms of entropy (see Bower 1997). Actually, the modes of entropy production and distribution correlate with the global dynamics.

Collapses, merging, and the induced shocks are currently ongoing in the critical universe, so that strong shocks form close to the virial radius. Entropy is continuously generated in the outer regions, so that its radial distribution is raised outward. Then the effective γ will be close to one, leading to a roughly flat $T(r)$ inside the shock. The density is determined by the boundary conditions after equation (4). Shocks are weaker in groups, the density profile is shallower, and the L - T relation steeper.

Conversely, in an open universe most dynamical action is moved back to early times: merging and mixing occurred early on, and then subsided; shocks had time to expand beyond R and weaken; correspondingly, the accretion petered out under nearly adiabatic conditions for groups and for clusters as well. Then the effective γ will be closer to $5/3$, and this may be used to roughly scale the central densities with different virial temperatures T to obtain $L \propto T^{3.5} R_X^3$. The two adiabatic models adopt additional, and different, assumptions concerning r_c or R_X , i.e., $r_c \propto T^{-0.25}$, or $R_X = \text{const}$, as discussed in § 2.3.

For open cosmologies with $\Omega_0 \approx 0.5$, or for flat ones with $\Omega_\lambda = 1 - \Omega_0$, the present deceleration is intermediate between the two above cases, and the applicability of the shock or of the adiabatic model is not so clear-cut; we shall consider both, finding similar results as expected.

3. STATISTICS OF CONDENSATIONS, AND X-RAY OBSERVABLES

We use the dark mass $m \equiv M/M_0$ normalized to the characteristic mass $M_0 = 0.6 \times 10^{15} \Omega_0 h^{-1} M_\odot$ defined in the hierarchical clustering theory; see Appendix A and the analytical details given in Appendix C. The X-ray temperature T reads

$$T = T_0 m^{2/3} (1+z). \quad (6)$$

On the basis of § 2, the bolometric luminosity for the shock model is given by

$$L = L_0 \langle g^2(T) \rangle \overline{n^2(r)/n_2^2} (T/T_0)^2 (1+z); \quad (7)$$

the ratio $\overline{n^2(r)/n_2^2}$ (integrated over the cluster volume) and the factor $\langle g^2 \rangle$ (averaged over the merging histories) have been derived in § 2.2.

The constant kT_0 takes on the value $4.5\Omega_0$ keV (see Appendix C). The luminosity L_0 is calibrated on the height of the observed, local L - T correlation (see Fig. 2) rather than computed a priori, in view of the subtleties discussed in § 5. At 4.5 keV we find $L_0 = 1.6(1 \pm 0.25) h^{-2} 10^{44}$ ergs s^{-1} . The height of the local luminosity function provides an independent value for the normalization, which we find consistent with the former to within 15%.

The statistics at different z of DM halos in the hierarchical clustering theory is provided by the standard Press & Schechter (1974) formula, which in comoving form (ρ_0 being the local cosmological density) reads

$$N(m, z) = \sqrt{\frac{2}{\pi}} \frac{\delta_c \rho_0}{m_0^2} \left| \frac{d \ln \sigma}{d \ln m} \right| \frac{m^{-2}}{\sigma(m) D(z)} \times e^{-\delta_c^2 / [2\sigma^2(m) D^2(z)]}. \quad (8)$$

Here δ_c is the critical threshold for the collapses of the density perturbations (depending weakly on the cosmological parameters); on the other hand, $D(z)$ is the linear growth factor for the density perturbations, sensitively depending on the cosmological parameters (see Appendix A). The linear, time-evolved mass variance $\sigma(m) D(z)$ is usually represented in the form $\sigma_8 m^{-a} D(z)$ where $a \equiv (n_e + 3)/6$ contains the effective slope $n_e(M) \approx -1.3$ to -2 of the power spectrum $\langle |\delta_k|^2 \rangle$ at scales ~ 10 – 1 Mpc.

It is characteristic of equation (9) to comprise two kinds of evolution: the number increase of order $D^{-1}(z)$ at the low- M end, and the shift toward smaller M of the upper exponential cutoff. Such dynamical evolutions, modulated by cosmology, must combine with the ICP evolution to yield closely constant luminosity functions as observed. We conservatively adopt the Press & Schechter (1974) rendition of the hierarchical clustering, keeping in mind its problems and limitations (see Bond et al. 1991; Cavaliere, Colafrancesco, & Menci 1993) and deferring discussions to §§ 4.4 and 5.

From such statistics of dark halos using equation (8) we compute the luminosity function $N(L) = N(M) dM/dL$, the expected flux counts $N(>F)$ of X-ray clusters, and their contribution to the soft XRB. The latter two observables read (see Appendix C)

$$N(>F) = R_H \int_{m_1}^{\infty} dm \int_{z_F}^0 d\omega d\ell(z) N(m, z) dm, \quad (9)$$

$$\frac{d^2 F}{dv_0 d\omega} = \int_{m_0}^{m_1} R_H d\ell(z) N(m) dm [\overline{n(r)/n_1}]^2 \times \frac{L_0 m^{4/3} (1+z)^{5/2}}{4\pi \Gamma(0.6) k T_0 m^{2/3}} \left(\frac{h\nu}{k T_0 m^{2/3}} \right)^{-0.4} e^{-h\nu/(k T_0 m^{2/3})}. \quad (10)$$

Here the lower limit m_0 is set by the requirement that $T(m, z) > 0.5$ keV, the effective lower bound for group temperatures from preheating; smaller masses would correspond to galaxies, where the amount of diffuse baryons and

the emission (per unit total mass) drop sharply (Fabbiano 1996).

The limit m_1 in equation (10) is set by the maximum between $T(m, z) > 0.5$ keV and the limiting flux of cluster or group sources, for which we conservatively adopt 4×10^{-14} ergs s $^{-1}$ cm $^{-2}$. On the other hand, m_1 also constitutes the upper limit for the unresolved sources contributing to the XRB.

Thus a complementary relationship holds between the counts and the contribution to the XRB. If one limits the number of resolved sources in the counts by assuming, e.g., a stricter surface brightness selection, as discussed later on, then all sources pronounced unresolved will contribute to the XRB. The joint consideration of these two observables is thus expected to give robust constraints.

4. RESULTS

In the luminosity functions $N(L, z)$ the luminosities are reduced to the *ROSAT* band for comparison to the data. The derivation of the temperature function $N(T, z)$ involves only equations (6) and (8), corresponding to the mere passive role played here by the ICP.

The results depend on cosmology and are sensitive to the values of the normalization L_0 and of the amplitude σ_8 . To a weaker extent, they depend also on the full shape of the power spectrum, which is determined in turn by Ω_0 and (weakly) by Ω_B , but does not depend directly on Ω_λ (although its normalization does).

We note that L_0 and σ_8 decrease with Ω_0 decreasing, and by themselves tend to decrease all numbers; however, this is delicately balanced by the increase of the distances and by the slower (negative) evolution, as discussed in more detail in § 4.4. With $\Omega_\lambda \neq 0$ the amplitude σ_8 is larger, and this also enters the results as discussed in § 4.3.

As for the values of h and Ω_0 , we conservatively adopt combinations yielding for the present age of the universe $t_0 = 13 \pm 2$ Gyr (see Ostriker & Steinhardt 1995). As for Ω_B , many X-ray measurements in clusters give a considerable ratio ≈ 0.15 – 0.20 of the baryons to dark matter; as rich clusters are likely to constitute fair samples of the universe, an abundance ratio $\Omega_B/\Omega_0 = 0.05 \pm 0.02$ $h^{-3/2}$ is indicated (White et al. 1993; White & Fabian 1995; Markevitch et al. 1996). So for $\Omega_0 \approx 0.3$ a sufficient value $\Omega_B = 0.0125 \pm 0.0025$ h^{-2} is predicted by the standard cosmological nucleosynthesis with canonical abundances of light elements (Walker et al. 1991); but in the critical case (with $h = 0.5$) this must be stretched up to $\Omega_B = 0.15$.

The full $\sigma(m)$ for cold dark matter (CDM) cosmogonies in different cosmologies, normalized to the 4 yr *COBE* results (Górski et al. 1998), is given by Bunn & White (1996), and White et al. (1996). In conclusion, we focus on three popular CDM cosmologies/cosmogonies, which provide acceptable values for σ_8 : the tilted ($n_p = 0.8$) spectrum in a critical universe with high baryonic content (TCDM); the scale-invariant spectrum at large scales ($n_p = 1$) either in a flat universe with $\Omega_0 = 0.3$ and $\Omega_\lambda = 0.7$ (Λ CDM), or in an open universe with $\Omega_0 \approx 0.5$ (OCDM). But in the last subsection, the full set of CDM cosmogonies will be discussed in a more synthetic way.

Our results will be compared to the data from two recent surveys with *ROSAT*: the relatively local brightest cluster sample by Ebeling et al. 1997, and the higher z sample by Rosati et al. (1998).

4.1. Tilted CDM with High Baryon Content in the Critical Universe

For the TCDM, we adopt the tilted primordial spectral index $n_p = 0.8$ and the amplitude $\sigma_8 = 0.66(1 \pm 0.08)$, with a high baryonic fraction $\Omega_B = 0.15$, in the critical universe with Hubble constant $h = 0.5$.

The tilt is chosen following White et al. (1996) so as to minimize one of the main problems of the standard CDM, namely, the excess of small-scale power, still retaining a value for h rather low but still not inconsistent with current observations. In addition, such a cosmogony includes the high baryonic fraction referred to above. We recall that such a parameter set is hard pressed in terms of the low value of $h \approx 0.5$ and of the primordial abundance implied for light elements, with that of He exceeding many recent measurements; the debate is still hot on the related issue of the D/H ratio, with recent signs of convergence, see Tytler, Fan, & Burles (1996) and Songaila, Wampller, & Cowie (1997).

After § 2.4 we consider here only the PE model with the full range of shock strengths. In Figure 3a we compare the local luminosity function to the current data; it is seen that an acceptable fit obtains only at the lower 2 standard deviations in σ_8 . It is also seen that the evolution of $N(L, z)$ is predicted to be virtually nil out to $z \approx 0.8$, consistent with data by Rosati et al. (1998).

The evolution of the temperature function is characterized by a fast decrease out to a moderate z in the number of high- T (massive) clusters. This is within the reach of *BeppoSAX* (Piro et al. 1995) and *XMM* (Mason et al. 1995), and is shown in Figure 3b.

The counts are shown in Figure 3c. The fit of the predicted counts to the bright data reflects the acceptability of the fit to the local luminosity function. Note that the slope of predicted counts is sufficiently flat to fit both the bright and the faint data by lowering σ_8 within the *COBE* uncertainty. Alternatively, a similar result is obtained on using the central value of σ_8 from *COBE*, but the higher baryon abundance $\Omega_B/\Omega_0 = 0.20$.

Our computation of the soft XRB (see Fig. 3d) comprises, as said above, the sources fainter than $h \times 10^{-14}$ ergs s $^{-1}$ cm $^{-2}$. Our predictions are compared to the residual XRB from *ROSAT*, once the AGN contribution ($\approx 70\%$ at 1 keV, see Hasinger 1996) has been subtracted out. The computed curve lies below the upper bounds.

4.2. Open CDM with $\Omega_0 \approx 0.5$

As said, open universes with $\Omega_0 \lesssim 0.3$ apparently constitute the simplest way out of the baryonic crisis. However, it is seen in Figure 4 that *COBE*-normalized cosmogonies with $\Omega_0 \leq 0.4$ using the adiabatic model for the ICP suffer from the fatal flaw of severely underpredicting both the local functions of temperature and luminosity. The blame stays mainly with the dynamical sectors; specifically, the low spectral amplitude σ_8 yields a severe deficit in $N(L, 0)$ and correspondingly a deficit in the bright counts. Similar dynamical reasons yield in aimed N -body simulations a percentage of complex morphologies lower than observed in the local clusters (West, Jones, & Forman 1995; Mohr et al. 1995).

On the other hand, intermediate values of Ω_0 are still a possibility. After Liddle et al. (1996), the range allowed to the class of open cosmologies by a set of observational

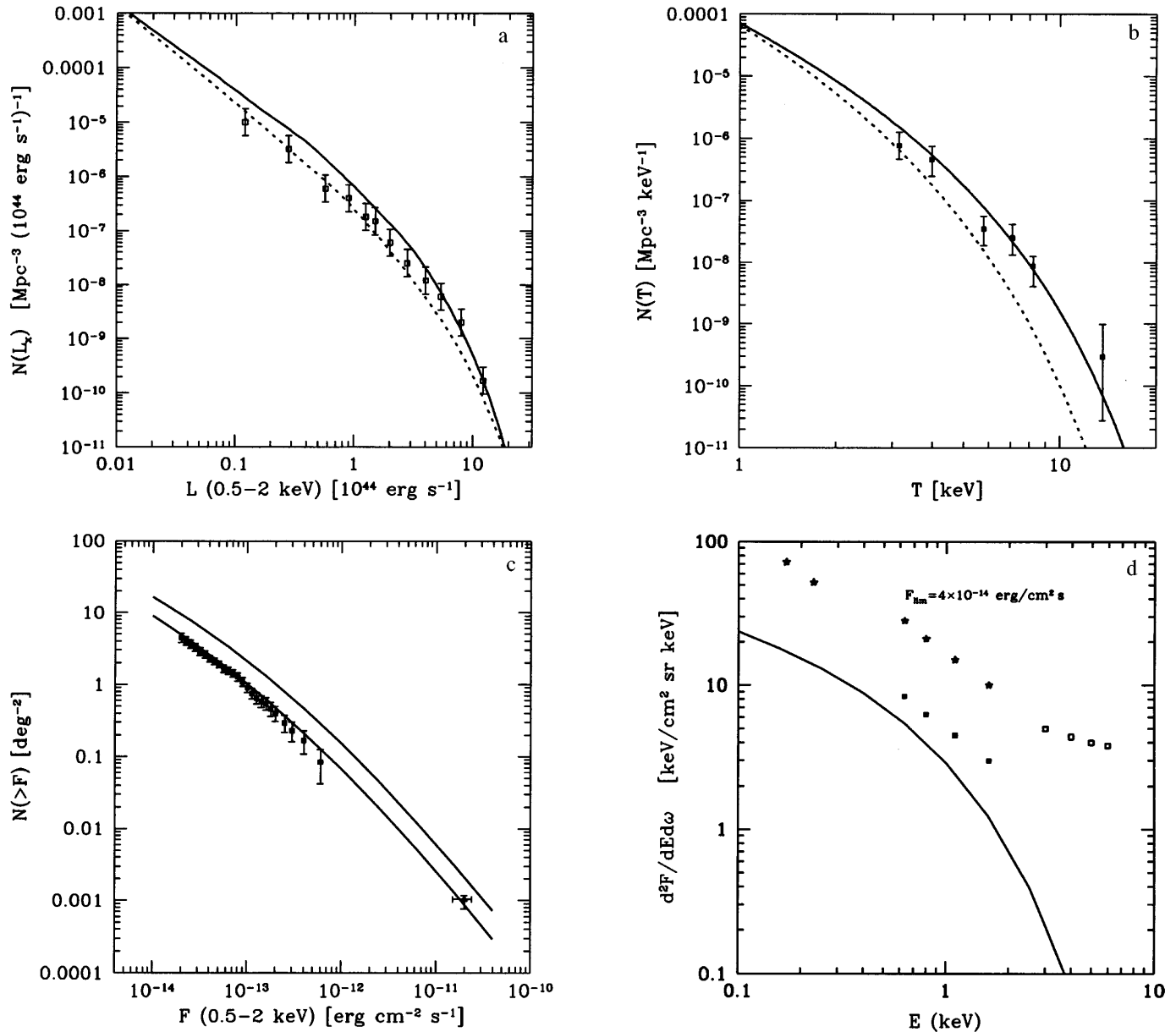


FIG. 3.—(a) Local luminosity function (solid line), and that evolved out to $z = 0.7$ (dashed line) are computed for the shock model and TCDM cosmogony. The data are from Ebeling et al. (1997). (b) Same as (a) for the local temperature function (solid line), and that evolved out to $z = 0.5$ (dashed line). The data are from Henry & Arnaud (1991). (c) Predicted source counts are compared to data by Rosati et al. (1998; solid squares) and by Piccinotti et al. (1982; solid triangle). Solid line: $\sigma_8 = 0.66$; dotted line: $\sigma_8 = 0.55$. (d) Contribution of the sources with $F < 4 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ to the XRB, compared to the observed values (open stars, Hasinger 1996) with a 70% contribution from the sources resolved by ROSAT subtracted out (solid squares).

constraints, including $h \geq 0.5$ and the COBE normalization, is narrowed down to the vicinity of $\Omega_0 \approx 0.5$. We focus first on the representative OCDM cosmogony with $\Omega_0 = 0.5$, $h = 0.65$, and $\Omega_B = 0.07$, which yield $\sigma_8 = 0.76(1 \pm 0.08)$.

Here it is not easy to decide a priori whether the PE or the adiabatic model applies better to the ICP, so we use both, ending up with similar results as expected. These are shown in Figures 5a, 5b, 5c, 5d. It is seen that the local distributions are well fitted, but the integrated observables show excesses over the data.

These persist when other values of Ω_0 around 0.5 are used and when the uncertainties in σ_8 and L_0 are considered, as discussed in § 4.4.

4.3. CDM with $\Omega_0 = 0.3$ in Flat Geometry

“Intermediate” conditions for the cosmic deceleration also obtain when $\Omega_\lambda \neq 0$ is accepted, with a flat geometry as

in most variants of inflation. The values $\Omega_0 = 0.3$ and $\Omega_\lambda = 0.7$, with $\Omega_B = 0.05$ and $h = 0.7$, match many observational evidences (see Ostriker & Steinhardt 1995). Following Klypin, Primack, & Holtzman (1996), we adopt the normalization $\sigma_8 = 1.1(1 \pm 0.08)$.

Here as in the previous case we have to consider both the PE and the adiabatic model. We show in Figures 6a and 6b the local luminosity and temperature functions, while in Figures 6c and 6d we plot the predicted counts and the contribution to the soft XRB.

4.4. A Synthetic Presentation

Here we give results covering the full set of COBE-normalized CDM cosmogonies. For a synthetic presentation, in Figures 7a and 7b we compare the predictions for the counts at bright ($F = 2.5 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$) and at faint fluxes ($F = 4 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$) to the data. We

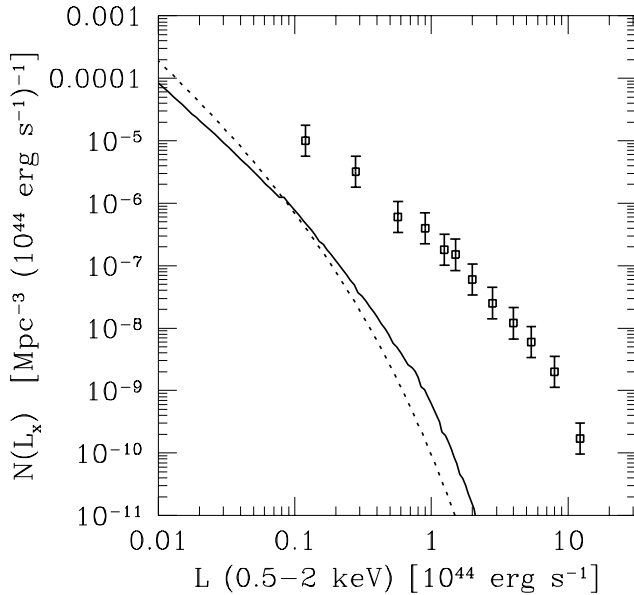


FIG. 4.—Local luminosity function with OCDM and $\Omega_0 = 0.3$ for the shock model (solid line) and for the adiabatic model (dashed line). Data as in Fig. 3a.

also show the effects of varying σ_8 within the uncertainty associated with *COBE* data, and L_0 within the minimum dispersion intrinsic to the L - T relation. Note in the figures that the strips corresponding to the uncertainties narrow down at the upper edge because σ_8 (entering inversely the expression for $\Delta N/N$) increases with Ω_0 . Similarly, $\Delta N/N$ is larger for the TCDM cosmogony compared to standard CDM, due to the smaller value of σ_8 .

Our results agree with Liddle et al. (1996) in ruling out $\Omega_0 < 0.45$ and $\Omega_0 > 0.55$. Even in the remaining range our results compare critically to the data because on fine tuning Ω_0 toward ≈ 0.4 the local luminosity function and the bright counts turn out to be underestimated; on the other hand, as soon as $\Omega_0 \approx 0.5$ is approached, an acceptable fit to the local luminosity function is recovered, but an excess in the faint counts is generated (see Fig. 5), especially with the adiabatic model. In summary, agreement with both the bright and the faint data is marginal; the underlying reason is that in open cosmologies long lines of sight and slow dynamical evolution conspire to yield a slope of the counts too steep to account for both the faint and the bright counts.

We note that such a slope would be even increased on considering that the formation z is always larger than z at observation, which has the affect of steepening, if only slightly, the luminosity functions (Cavaliere et al. 1993; Kitayama & Suto 1997). Note also that the addition of $\Omega_\lambda = 0.7$ to $\Omega_0 = 0.3$ implies a higher value of σ_8 and hence higher levels of faint counts, although still lower than in the $\Omega_0 \approx 0.5$ case.

In Figure 7 we also show that the counts in TCDM critical and in Λ CDM cosmogonies/cosmologies can be made consistent with the observations on considering not only their uncertainties, but also those in the present *COBE* normalization and the intrinsic uncertainty in the L - T relation, see the discussion following equation (7).

Overall, a common feature of all the above models based on canonical hierarchical clustering is constituted by some

excess in the counts; only in the critical and in the flat geometry can this be brought to consistency with the data. This may indicate some nontrivial incompleteness in the canonical hierarchical clustering worth keeping under scrutiny.

We also show in Figure 8 the results for the contribution to the soft XRB, e.g., at $E \approx 1$ keV. Once again, CDM with $0.55 < \Omega_0 \leq 1$ is ruled out, while $\Omega_0 \approx 0.5$ is marginal also in this respect.

Could excess faint counts be reduced by considering a stronger selection due to surface brightness? On the contrary, we stress that the complementarity with the contribution to XRB makes any such excess even more significant. In fact, a solution cannot be sought in terms of surface brightness selections without increasing the excess contribution to the XRB from the unresolved groups and clusters.

5. CONCLUSIONS AND DISCUSSION

In this paper we have computed the X-ray observables for groups and clusters of galaxies. As anticipated in § 1, we use—rather than continuous and possibly degenerate parametrizations—only discrete combinations of physical models appropriate for the dark matter and for the intra-cluster plasma. We first summarize our approach and then list our results.

1. We have developed the punctuated equilibria model for the ICP state and dynamics. This is comprised of the following two components.

2. As for single clusters, we have used a polytropic β model that yields temperature profile $T(r)$ (see Fig. 1) in good agreement with the observations. We predict the ICP density profile $n(r)$ and the brightness profile to be flatter for groups than for clusters, corresponding to a larger extension of the ICP relative to their gravitational radii.

3. As for statistics, we convolved the ICP equilibria with the histories of DM halos and predicted the L - T correlation to take the form shown in Figure 2, in agreement with the data. In addition, we predicted an intrinsic variance with the minimum value of 25% (1 σ) also represented in Figure 2.

4. We then proceeded to compute for various standard cosmological frameworks the local and the evolved luminosity functions of galaxy clusters, which we compared to the data (Figs. 3a, 4, 5a, 6a). We derived also the number counts (Figs. 3c, 5c, 6c), the z distributions (Fig. 9), and the contribution to the soft X-ray background (Figs. 3d, 5d, 6d). Our results are summarized in Figures 7a and 7b; these show that the set of acceptable cosmogonies/cosmologies is restricted to three disjoint domains: $0.4 < \Omega_0 < 0.5$ for the standard CDM, $\Omega = 1$ for the tilted CDM, $\Omega_0 \approx 0.3$ for CDM in flat geometry. In Figure 9 we summarize the confidence levels at which the data are matched.

We next discuss in detail the issues and the results listed above.

5.1. ICP State in Evolving DM Halos

The ICP state in the hierarchically evolving gravitational wells constitutes the focus of our new approach. We propose that such state follows suit, passing through a sequence of PE that we compute semianalytically. These computations comprise the following steps: the merging histories of the DM potential wells, obtained with large statistics from Monte Carlo simulations of the hierarchical

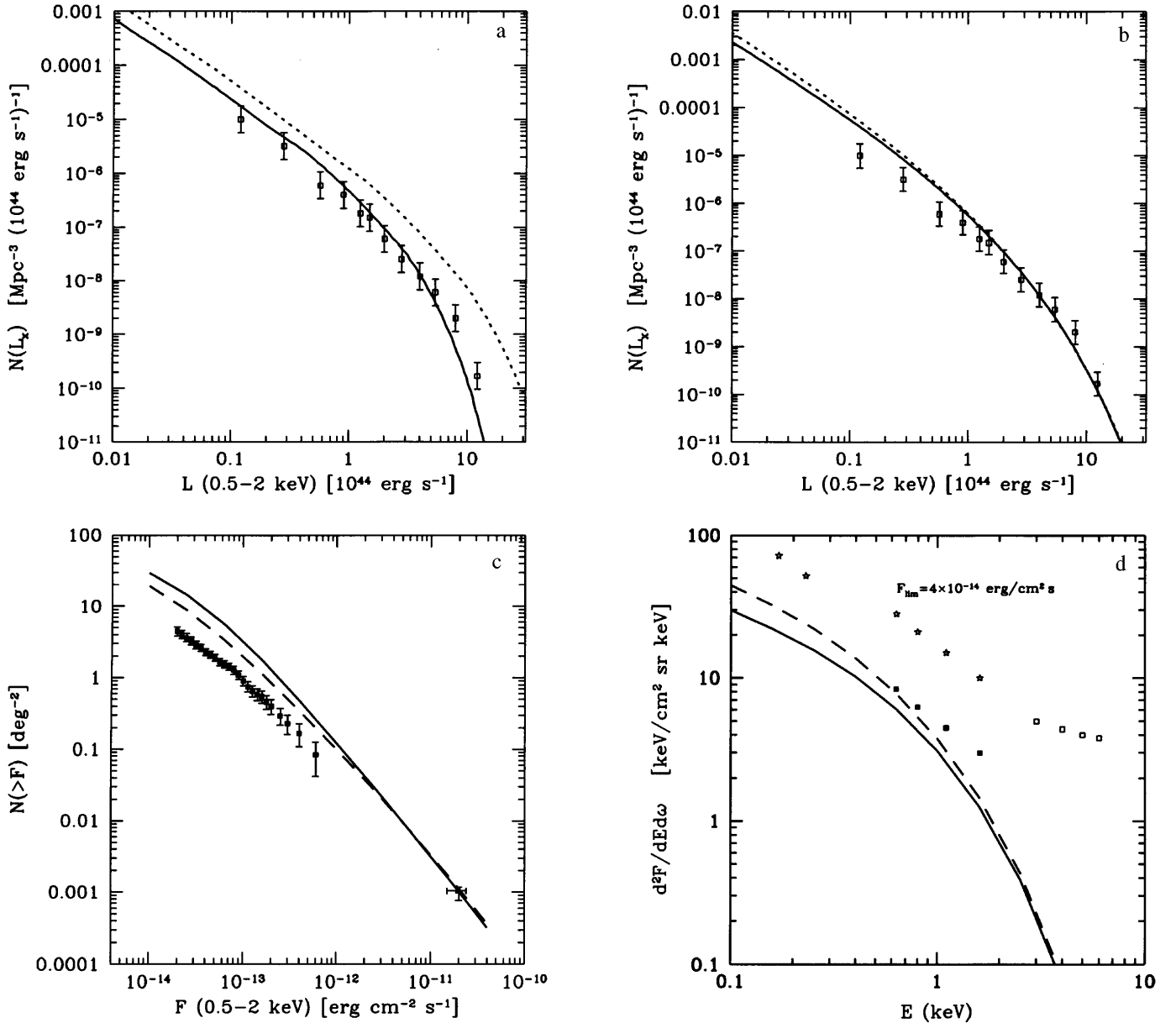


FIG. 5.—Predictions for the OCDM cosmogony with $\Omega_0 = 0.5$. (a) Luminosity functions for the shock model with the appropriate L - T relation: local (solid line) and evolved ($z = 0.7$, dashed line). (b) Same as (a) but for the adiabatic model. (c) and (d) Same as in Figs. 3c and 3d. Both the shock model (solid line) and the adiabatic model (long-dashed line) are shown.

clustering; the inner hydrostatic equilibrium disposition, updated after each merging episode; and the boundary conditions provided by strong and weak shocks, or even by a closely adiabatic compression, depending on the ratio of the infall to the thermal energy in the preheated external medium.

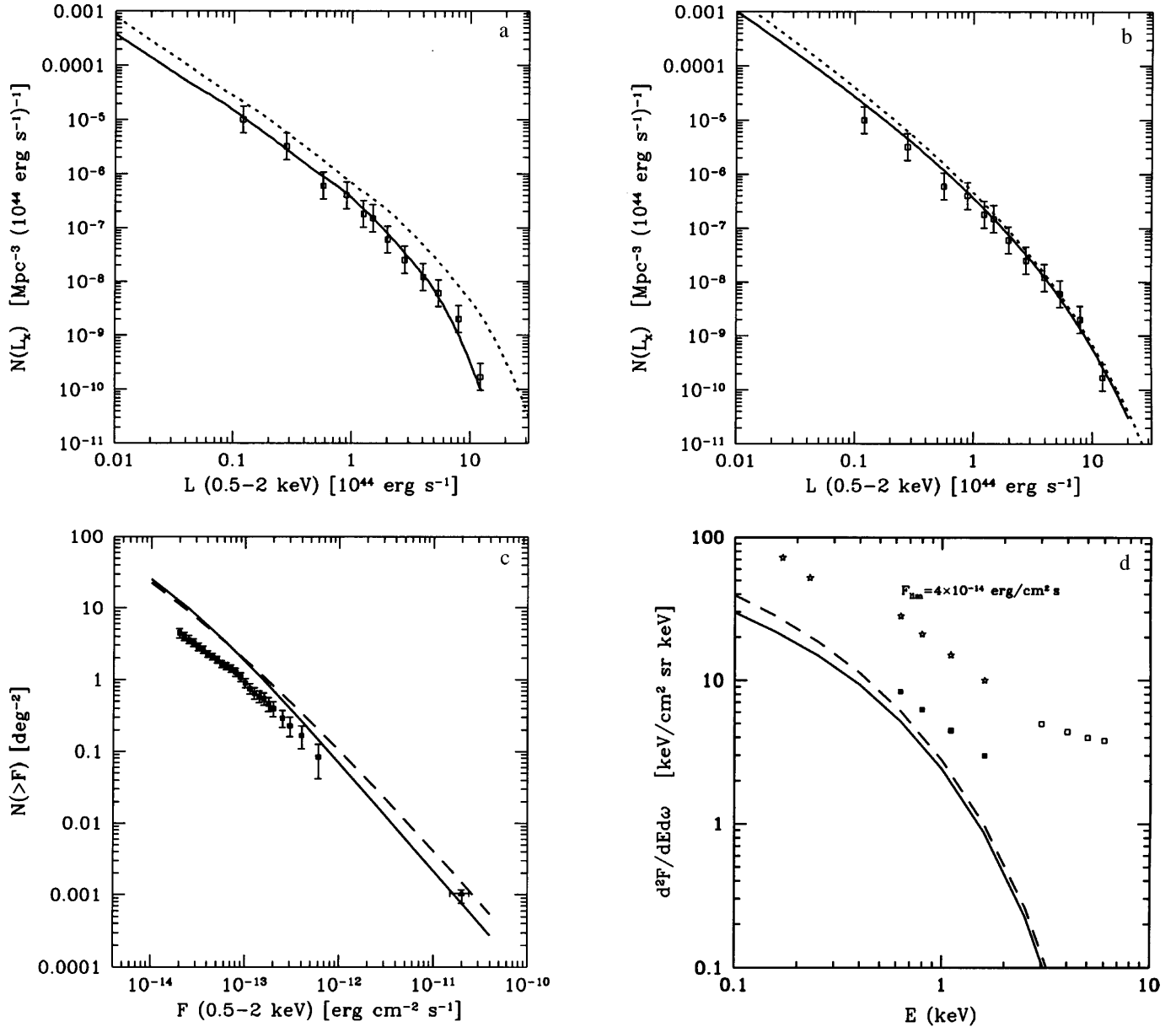
The results of our model depend on two parameters, the external temperature T_1 and density n_1 , which are *not* free. Specifically, we use for T_1 the lower bound $T_{1,\ell} = 0.5$ keV provided by the literature on stellar preheating; in the merging events the effective T_1 is the virial temperature of the incoming clumps, when this is larger than 0.5 keV. The value of n_1 for rich clusters is related to the DM density by the universal baryonic fraction $\Omega_B \approx 0.15$.

Note that our PE model does not require strict spherical symmetry, but rather that the residual internal velocities be smaller than the inflow velocity. So they can include merging episodes ranging from nearly isotropic accretion of

small clumps and diffuse gas, to anisotropic coalescence of comparable clumps along filaments of the large-scale structures.

The expression of the bolometric luminosity is proportional to g^2 , the square of the density jump at the bounding shock. The average of such factors over the merging histories is what gives to the statistical L - T correlation the curved shape shown in Figure 2. For rich clusters we obtain $L \propto T^3$. This flattens to $L \propto T^2$ for larger T , corresponding to the saturation of the shock compression factor, i.e., $g(T/T_1) \rightarrow 4$ when $T \gg T_1$. At the other end, the correlation steepens toward $L \propto T^5$ in the group range, where $T/T_1 \sim 1$ and the shocks are substantially weakened by the preheating temperature in the infalling clumps. The amplitude of the L - T correlation rises gently proportionally to $(1+z) \propto \rho_1(z)^{1/2}$, where ρ_1 is the density in the large-scale structures hosting clusters and groups.

In addition, our PE approach predicts an intrinsic

FIG. 6.—Same as Fig. 5 but for the Λ CDM cosmogony

variance of dynamical origin due to the different merging histories, and built in the factor g^2 . Such variance constitutes a lower bound, in view of additional contributions from the variance in the ambient density and the central luminosity associated with cooling flows (Fabian et al. 1994; White, Jones, & Forman 1997; Sarazin 1997).

5.2. Contact with Hydrodynamical Simulations and with Observations

The PE model includes, in a simplified semianalytical form, compression and shocks at the boundary with the surrounding environment, which is modulated in density by the large-scale structure and in temperature by the stellar preheating.

Simulations now clearly show the shocks occurring also in major merging events (Schindler & Mueller 1993; Roettiger, Stone, & Mushotzky 1998). The inclusion of the Rankine-Hugoniot conditions rises the internal temperature at the expenses of the inflow velocities. Complex

features are found, such as residual kinetic stresses and unmixed hot spots in the temperature distribution, but over times of about 2 Gyr such kinetic pressures over cluster scales reduce to less than 20% of the thermal one.

On the other hand, in the hierarchical clustering such major events are rare; our Monte Carlo simulations give a probability $\lesssim 20\%$ for very asymmetric events with mass ratios 2:1 or larger occurring within 2 Gyr from the cluster observation. In addition, in such events the ICP temperature in the infalling subcluster is comparable to the virial value in the main cluster. Such major events with their low frequency and large T_1 yield a minor contribution to the statistical $\langle (n_2/n_1)^2 \rangle$.

Our semianalytical model only crudely describes these transient if conspicuous features, to focus on the lesser and more symmetric events that contribute the most to the L - T relation. At the extreme of spherical accretion of loose gas the simulations (see Takizawa & Mineshige 1998) show in detail that shocks also form and expand slowly, to leave

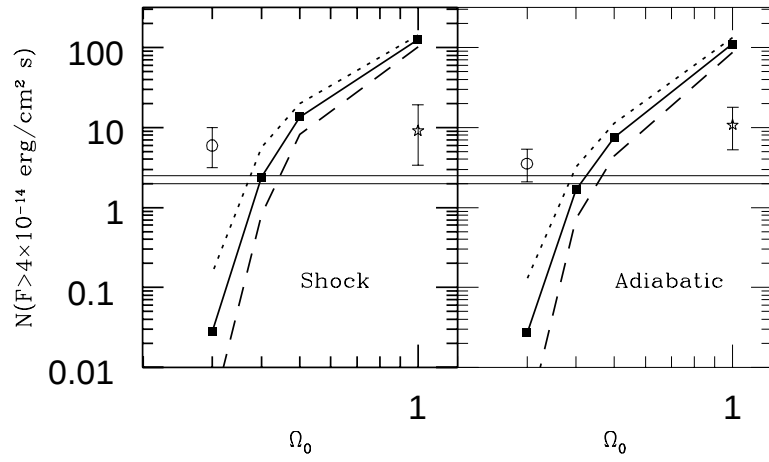


FIG. 7a

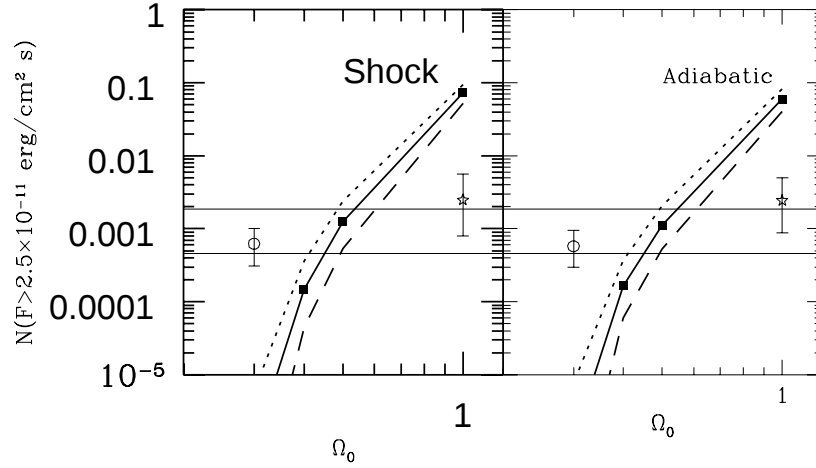


FIG. 7b

FIG. 7.—(a) Predicted faint counts at $F = 4 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2}$ are shown on logarithmic scales for the full range of Ω_0 in standard CDM cosmogony. The solid line is computed for the amplitude σ_8 of the perturbation spectrum corresponding to central values of the *COBE* normalization; the strips enclosed between the dashed and the dotted lines represent the uncertainties in σ_8 added to the intrinsic variance in L_0 . The predictions from TCDM cosmogony (*open stars*) and from Λ CDM cosmogony (*open circles*) are also shown. The horizontal lines correspond to the upper and lower error bars of the data by Rosati et al. (1998). (b) Same as (a) but for the bright counts at $F = 2.5 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$; here the horizontal lines correspond to the errors estimated by Piccinotti et al. (1982).

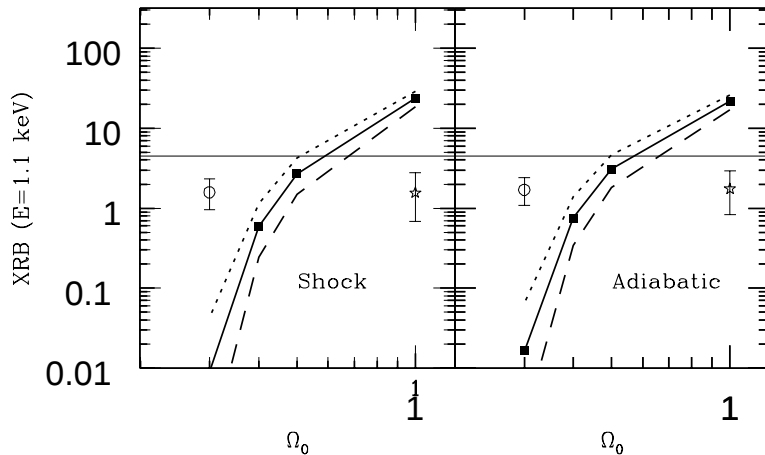


FIG. 8.—Predicted contribution to the XRB (at $E \approx 1 \text{ keV}$) of unresolved clusters and groups is shown for the whole range of Ω_0 in standard CDM cosmogony. The results for TCDM and Λ CDM cosmogonies are also shown with same symbols as in Fig. 7. The horizontal lines correspond to the data by Hasinger (1996), with the 70% contribution of resolved sources subtracted out.

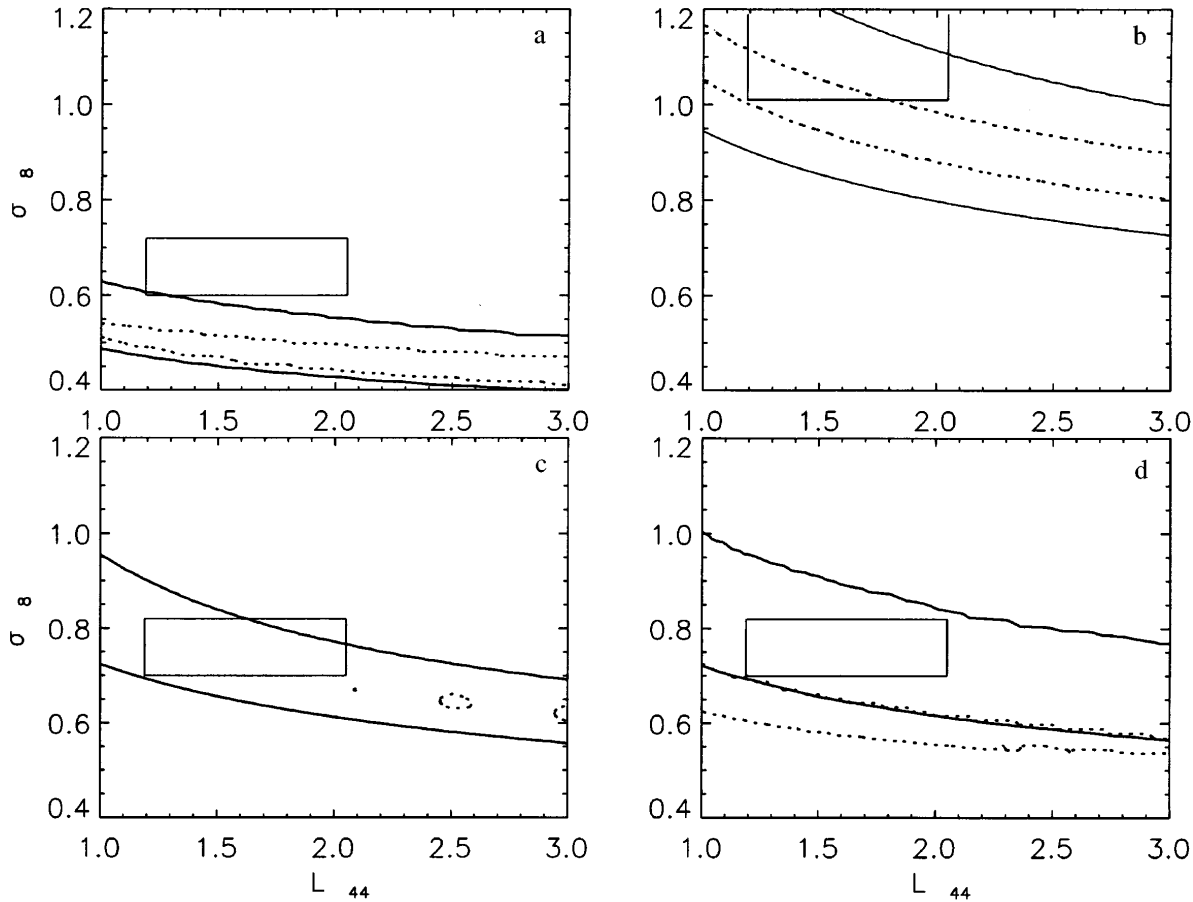


FIG. 9.—This shows the 99% confidence contours for both the computed local luminosity function (*solid lines*) and the computed number counts (*dotted lines*), in the L_{44} - σ_8 plane ($L_{44} = L_0/10^{44}$ ergs s $^{-1}$). The boxes indicate $\pm 1 \sigma$ in σ_8 (corresponding to the *COBE* uncertainty) and in L_{44} (from our Monte Carlo L - T relation). Data as in Figs. 3–6. (a) Shock model with TCDM. This cosmogony is consistent with the counts within 2σ below σ_8 . (b) Shock model with Λ CDM. This shows acceptable fits. (c) Adiabatic model with OCDM ($\Omega_0 = 0.5$). The 99% contours for the counts are outside the uncertainty box for σ_8 and L_{44} . (d) Shock model with OCDM ($\Omega_0 = 0.5$). The counts are consistent within 2σ below σ_8 .

inside a declining temperature profile and a steeper density profile.

Our PE model yields temperature profiles decreasing as shown in Figure 1. These agree with the published data (see Hughes et al. 1988; Honda et al. 1997; Markevitch et al. 1997); they agree also with the results from state-of-the-art simulations (Bryan & Norman 1998) obtained by running on supercomputers advanced three-dimensional Eulerian codes with adapting mesh and reliable shock capturing methods. While high-resolution simulations are limited (for now and for some time to come) as to rendering the no stellar preheating our model includes the effects of preheating of the outer gas over the whole range from groups to clusters.

5.3. Constraining Cosmology

With the ICP state so described, we proceeded to constrain the cosmological parameters. After the observations by Rosati et al. (1998), the main rule of the game turns out to be as follows: the dynamical evolution contained in the standard Press & Schechter (1974) formula (eq. [8]) must combine with the evolution of the L - T correlation and with cosmology to yield closely nonevolutionary $N(L, z)$.

We stress that such combinations are severely selected in our approach. In fact, strong shocks are common in the critical cosmology, where accretion and merging activity are currently ongoing, and there shocks apply in full; these

include also weak shocks for small groups with virial temperatures below 1 keV, and for those rich clusters that merge with comparable clumps. Closely adiabatic compressions, instead, prevail for all structures in very open universes with high formation redshifts and little or no strong shocks and mixing at present. This defines the domain of applicability of the two adiabatic models by Kaiser (1991) and Evrard & Henry (1991).

In detail, our results are as follows (see Fig. 7).

We confirm that standard CDM in the critical cosmology is definitely ruled out on account of its overproduction of local clusters and of their considerable positive evolution.

We also rule out open cosmologies with $\Omega_0 \leq 0.3$, the simplest way to enforce little evolution and also to provide a solution to the baryonic crisis. In fact, these cosmologies when *COBE* normalized yield a severe deficit in the local luminosity function and in the source counts.

Thus, we investigated more elaborate solutions: the critical universe with tilted CDM and a high baryon content and two cases of intermediate deceleration, comprising CDM with canonical nucleosynthesis either in mildly open universes with $\Omega_0 \approx 0.5$ or in flat geometry with $\Omega_0 = 0.3$ and $\Omega_\lambda = 0.7$.

With the first solution we obtain (marginally) acceptable results (see Figs. 3a–3c) for the local luminosity function $N(L, 0)$, for the source counts, and for the contribution to the soft XRB, within the present uncertainties of the data

and within the variance intrinsic to the theory. We note that the cosmological/cosmogonical sectors by themselves may be tested independently, based on the fast evolution with z (see Fig. 3b) of the temperature distribution in the critical case, as pointed out by many authors (see Oukbir & Blanchard 1992; Henry 1997); this constitutes an important program for the satellites *BeppoSAX* and *XMM*.

As for cosmologies with intermediate deceleration, here neither the PE nor the adiabatic models for the ICP are cogently indicated; thus we considered both, obtaining generally similar results as expected. For open cosmologies in particular, the results are inconsistent with the observations of the local luminosity function and of the counts, except for the range $\Omega_0 = 0.45\text{--}0.55$; even there the counts are excessive at more than the formal 99% confidence level (see Fig. 9), the excess being larger for the adiabatic models. The excess is a result of built-in reasons, that is, the relative large amplitude σ_8 and the relatively steep shape of the counts, as spelled out in § 4.4. Instead, in the $\Omega_0 + \Omega_\lambda = 1$ cosmology a manageable count excess is obtained.

We note that the Kaiser's (1991) variant of the adiabatic models does not yield such an excess for $\Omega_0 \approx 0.5$, due to its normalization decreasing at high z . However, the local luminosity function computed from this model overestimates the number of brightest clusters, due to the strong dependence $L \propto T^{3.5}$. Moreover, the normalization decrease at high z is hardly consistent with the data by Mushotzky & Scharf (1997). Finally, it yields a fast, negative evolution of $N(L, z)$ barely consistent with the data in the survey by Rosati et al. (1998) (the deficit is truly fatal in the critical or in the flat cosmology). As luminosities larger than some 10^{44} ergs s^{-1} are little represented in that survey, a strong test for such a negative evolution concerns any deficit at intermediate fluxes in the redshift distribution from a large-area survey. So we show in Figure 10 the redshift distribution computed also for this model.

We have conservatively chosen to focus on a limiting flux $F = 4 \times 10^{-14}$ ergs s^{-1} for which the sky coverage is nearly 100% (P. Rosati 1997, private communication), and any incompleteness is out of the question. Incompleteness due to surface brightness may be relevant at fainter fluxes, depending on the cluster and group profiles. We plan to treat such issues elsewhere, but here we point out that in our approach the impact of any such incompleteness is limited by the complementarity between counts of resolved sources and contribution to the XRB from the rest.

Our summary is that many combinations of standard

cosmogonies/cosmologies with ICP models are ruled out. A relatively small set of disjoint cosmologies/cosmogonies survive, as shown by Figure 7: $\Omega = 1$ with tilted CDM and high baryonic abundance combined with the punctuated equilibria, which is marginally consistent with the data; CDM in open cosmology with $0.5 < \Omega_0 < 0.55$, which is barely consistent using the PE, and even less so using the adiabatic models; CDM with $\Omega_0 = 0.3$ and $\Omega_\lambda = 0.7$, which is consistent using either the PE and the adiabatic models.

So cosmological parameters can be constrained on the basis of X-ray clusters, but only *up to a point*; for example, the residual uncertainty in the density parameter is $\Delta\Omega_0/\Omega_0 > 20\%$.

5.4. What Next

To what extent enlarging the database on X-ray clusters will help in further constraining cosmology? Here we argue that the variance intrinsic to the hierarchical clustering, and amplified by the ICP emissivity, sets an effective limitation. In fact, Figure 7 shows that the present Poissonian error bars in the observed faint counts are already smaller than the (minimum) intrinsic variance in the predicted ones. Decreasing the former with richer, faint surveys will hardly provide a sharper insight into cosmology unless one reduces both the uncertainty concerning σ_8 and the larger one concerning L_0 ; in fact, the two enter with comparable weights equation (8), since it is seen that $\Delta\sigma_8/\sigma_8$ acts roughly as $(n_e + 3)\Delta L_0/6L_0 \approx 0.2\Delta L_0/L_0$.

To what point are these reductions feasible? On the theoretical side, the minimum $\Delta L_0/L_0$ of dynamical origin may be sharpened by Monte Carlo simulations so extensive as to provide the full scatter distribution. But then one must tackle also the enhanced emissivity produced or signaled by cooling flows, correlated with higher ambient densities; this we shall treat elsewhere (Cavaliere, Menci, & Tozzi 1998).

On the observational side, one needs large statistics for the distributions of L and T ; this will help in deriving narrower L - T correlations for subsamples categorized in terms of mass deposition rates from cooling flows, see White et al. (1997). Such aim calls for spectroscopic measurements of T , which are obviously harder than the bolometric L , and require *BeppoSAX* or even *XMM*. However, we stress that such efforts will find soon a more proper aim than constraining Ω_0 .

This is because soon *MAP* (Bennett 1997), and subsequently *PLANCK* (Bersanelli et al. 1996), will accurately measure on very large and still linear scales not only the

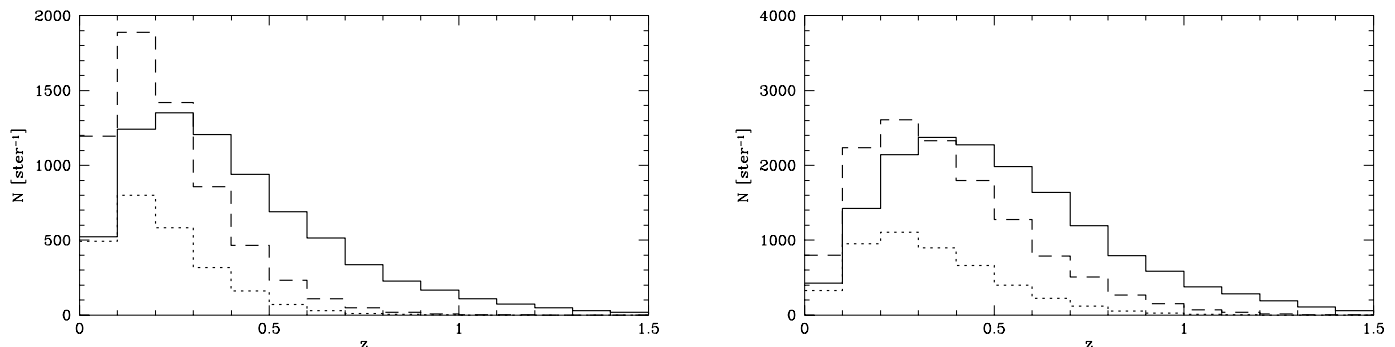


FIG. 10.—*Left*: Redshift distribution per steradian computed in the OCDM ($\Omega_0 = 0.5$) for bright fluxes $F \geq 10^{-13}$ ergs $cm^{-2} s^{-1}$ (the corresponding luminosity functions are given in Figs. 3, 5, and 6). *Solid line*, shock model; *dashed line*, for the adiabatic model of Evrard & Henry (1991); *dotted line*, adiabatic model in the Kaiser (1991) version. *Right*: Redshift distribution per steradian computed in Λ CDM for fluxes $F \geq 4 \times 10^{-14}$ ergs $cm^{-2} s^{-1}$. Lines as in the left panel.

perturbation power spectrum (from which σ_8 is derived), but also directly Ω_0 to better than 10%; this will supersede constraints set at cluster scales gone nonlinear.

Once the cosmological framework has been fixed, the study of groups and clusters in X-rays will resume what we submit to be its proper course; that is, the physics of systems of intermediate complexity, which is comprised of the DM and of the ICP component.

With the latter fully understood and the scatter in the L - T relation assessed, cluster X-raying will finally expose the underlying process of nonlinear condensation of DM on scales 1–10 Mpc. Then any mismatch concerning the number counts or $N(L, z)$ will be telling of failures either in the CDM spectra or in the current representation of cosmogony in terms of the Press & Schechter (1974) formula.

As a relevant example, we recall from § 4.4 that even the acceptable models we computed tend to exceed the observed faint counts and can be brought to consistency only at the lower end of the current uncertainty concerning σ_8 . On the other hand, the corrections to the Press & Schechter (1974) formula currently discussed yield a larger

number of clusters. For example, Jain & Bertschinger (1995) and Gardner, Tozzi, & Governato (1998) find that the threshold δ_c must be lowered from the canonical value 1.69 to 1.5, at least at $z \geq 1$ if not already at $z = 0$; a similar trend obtains considering that the formation redshift is always greater than the observation's redshift as discussed in § 4.4. If *MAP* will provide definite values of n_p , σ_8 , and Ω_0 such as to enhance the excess in the faint counts, then the Press & Schechter (1974) rendition of the nonlinear cosmogony will have to be reconsidered.

Preliminary computations of the source counts and the contribution to the soft X-ray background have been performed by F. Lupini in his thesis. We are indebted with P. Rosati for communicating his data prior to publication and for much information. We thank S. De Grandi, C. Gheller, M. Girardi, S. Molendi, L. Moscardini, O. Pantano, and D. Trevese for helpful discussions. We also thank our referee M. Henriksen for several helpful comments and for stimulating us to better focus our exposition. Partial grants are acknowledged from MURST and ASI.

APPENDIX A

STANDARD HIERARCHICAL CLUSTERING

We recall that the variance of the perturbation field at a scale $R = 2\pi/k$ (associated to the mass scale $M = \bar{\rho}4\pi R^3/3$ in terms of the average density $\bar{\rho}$) is defined by

$$\sigma^2(R) = \frac{1}{V} \int d^3k |\delta_k|^2 W(kR), \quad (\text{A1})$$

where $W(kR)$ is a top-hat filter (see Bond et al. 1991; Lacey & Cole 1993). This is given in terms of the power spectrum $|\delta_k|^2 = k^{n_p} T^2(k)$, which depends on the physics of the early universe (see Peebles 1993; Lucchin, Matarrese, & Mollerach 1992) and by the subsequent microphysics.

Results from the *COBE*/DMR experiment give $n_p \approx 1 \pm 0.2$ and provide the normalization on large-angle scales (see Bunn & White 1996 and references therein). The transfer function $T(k)$ depends on the nature of DM, which is the main constituent of the perturbations; for CDM, and given values of the parameters Ω_0 , h , and Ω_B , standard formulae are given, e.g., by Sugiyama (1995); White et al. (1996). These can be recast into the form $\sigma(m) = \sigma_8 m^{-a}$, where $a \equiv (n_e + 3)/6$, with n_e being the effective, scale-dependent index in the full power spectrum $\langle |\delta_k|^2 \rangle$. The values of the amplitude at $8 h^{-1}$ Mpc are given, e.g., by Bennett et al. (1996) for different cosmologies.

The scale $8 h^{-1}$ Mpc also defines a characteristic mass

$$M_0 = \frac{4\pi}{3} \rho_0 (8 h^{-1} \text{ Mpc})^3 = 0.6 \times 10^{15} \Omega_0 h^{-1} M_\odot, \quad (\text{A2})$$

which we shall use as our unit mass. At any given mass scale, the time evolution is derived from the linear growth of the perturbations $D(t)$ (see Peebles 1993), which depends both on the density parameter Ω_0 and on the parameter $\Omega_\lambda = \Lambda/3H_0^2$ associated to the cosmological constant Λ . An expression valid in all cases with $\Omega_0 + \Omega_\lambda = 1$ (as predicted by most inflationary models) is given by Lupini (1996) in terms of the epoch t and writes

$$D(t) = \left[\frac{1 + 3(\Omega_\lambda/\Omega_0)\alpha^2}{(t_0^2/t^2) + 3(\Omega_\lambda/\Omega_0)\alpha^2} \right]^{1/3}, \quad (\text{A3})$$

where t_0 is the present epoch, and $\alpha \equiv 2\Omega_0^{1/2}/\pi H_0 t_0$. For $\Omega = 1$ the one obtains $D(z) = (1 + z)^{-1}$.

The mass distribution $N(M, z)$ of the condensations given in equation (8) has been derived by Press & Schechter (1974), and is discussed by Bond et al. (1991). Here we stress that it contains only the linear mass variance $\sigma(m)$ and the threshold for nonlinear collapse δ_c for which the canonical value 1.69 is taken.

APPENDIX B

POSTSHOCK CONDITIONS AND POLYTROPIC EQUILIBRIUM

The jump conditions at the shocks are based on the Rankine-Hugoniot conservations and may be obtained from the implicit expressions given, e.g., by Landau & Lifshitz (1959). We work out the explicit expression of the postshock tem-

perature T_2 for 3 degrees of freedom and for a nearly static postshock condition with $v_2 \ll v_1$, in the form

$$kT_2 = \frac{\mu m_H v_1^2}{3} \left[\frac{(1 + \sqrt{1 + \epsilon})^2}{4} + \frac{7}{10} \epsilon - \frac{3}{20} \frac{\epsilon^2}{(1 + \sqrt{1 + \epsilon})^2} \right], \quad (\text{B1})$$

where $\epsilon \equiv 15kT_1/4\mu m_H v_1^2$. In a “cold inflow” with $\epsilon \ll 1$ the shock is strong, and the expression simplifies to $kT_2 \simeq \mu m_H v_1^2/3 + 3kT_1/2$. The flow velocity v_1 is set by the potential drop across the region of nearly free fall, to read $v_1^2 \simeq -1.4\phi_2/m_H$ where ϕ_2 is the potential at $r = R$ (see CMT97). Since $1.4\mu \approx 1$, the above equation may be effectively approximated by $kT_2 \simeq -\phi/3 + 3kT_1/2$.¹ Instead, for $\epsilon \gg 1$ the shock is weak and $T_2 \simeq T_1$ is recovered as expected.

When the temperature profile is polytropic with $T(r) \propto n(r)^{\gamma-1}$, equation (2) is modified to

$$L \propto T^2 \rho^{1/2} \left(\frac{T_2}{T} \right)^{1/2} \frac{1}{[n(r)/n_2]^{2+(\gamma-1)/2}} \quad (\text{B2})$$

The ratio $n(r)/n_2$ is obtained starting from the hydrostatic equilibrium $dP/ndr = -d\phi/dr$ with the polytropic pressure $P(r) = kT_2 n_2 [n(r)/n_2]^\gamma / \mu$. This yields (see Cavaliere & Fusco-Femiano 1978; Sarazin 1988) the profiles

$$\frac{T(r)}{T_2} = \left[\frac{n(r)}{n_2} \right]^{\gamma-1} = 1 + \frac{\gamma-1}{\gamma} \beta [\tilde{\phi}_2 - \tilde{\phi}(r)], \quad (\text{B3})$$

where $\tilde{\phi} \equiv \phi/\mu m_H \sigma^2$ is the normalized potential; we use for $\phi(r)$ and $\sigma(r)$ the forms given by Navarro et al. (1996).

Equation (B2) reduces to equation (2) of the text in the isothermal limit when $\gamma \rightarrow 1$ and $T = T_2$. The volume-averaged factor in equation (B2) differs from that for the isothermal case by less than 20% in the full range $1 < \gamma \leq 5/3$.

APPENDIX C

LUMINOSITY FUNCTIONS AND THEIR INTEGRALS

The X-ray emission of clusters of galaxies is due to optically thin, thermal bremsstrahlung of the hot ($T \sim 10^7$ – 10^8 K) ICP in equilibrium with the cluster potential wells (Cavaliere, Gurski, & Tucker 1971; see Sarazin 1988 for a review).

The virial theorem provides $T \propto M/R$. The virial radius R can be expressed in terms of the cluster mass M and the density ρ to read $R \propto (M/\rho)^{1/3}$, which yields $T \propto M^{2/3} \rho^{1/3}$. According to the standard hierarchical clustering, the DM density inside clusters is proportional to the background's density, so that $\rho \approx 200\bar{\rho} \propto (1+z)^3$; then one obtains

$$T \propto M^{2/3}(1+z), \quad (\text{C1})$$

corresponding to equation (6) in the text. The proportionality factors in equation (C1) are given, e.g., by Hjorth, Oukbir, & van Kampen (1998) to imply $T = 4.5$ keV for a cluster with $M = M_\odot$.

The bremsstrahlung spectrum $\ell(\nu)$ at the frequency ν (in the frame of the source) is given by

$$\ell(\nu) \propto \int_V d^3r n^2(r) \frac{e^{-h\nu/kT}}{\sqrt{kT}} G_f\left(\frac{h\nu}{kT}\right), \quad (\text{C2})$$

where n is the ICP density, V is the volume of the emission region, and G_f is the Gaunt factor, which may be effectively approximated with the function $(h\nu/kT)^{-0.4}$. From equations (C1) and (C2) one obtains in terms of the observed frequency $\nu_0 = \nu/(1+z)$

$$\ell(\nu_0) = \frac{L}{4\pi\Gamma(0.6)} \left(\frac{h\nu_0}{kT_{\text{co}} m^{2/3}} \right)^{-0.4} e^{-h\nu_0/(kT_{\text{co}} m^{2/3})} \frac{h}{kT_{\text{co}} m^{2/3}}. \quad (\text{C3})$$

Here L is the bolometric luminosity

$$L = L_0 \overline{[n(r)/n_1]^2} m^{4/3} (1+z)^{7/2}, \quad (\text{C4})$$

where $\overline{[n(r)/n_1]^2} \equiv \int_0^R d^3r [n(r)/n_1]^2 / R^3$ and $L_0 = 1.6 \times 10^{44} h^{-2} \text{ ergs s}^{-1}$ corresponds to 4.5 keV calibrated to the local L - T correlation. For comparison to *ROSAT* data, equation (C3) is to be integrated over the local range $\Delta E = 0.5$ – 2 keV. The resulting luminosity in the band ΔE reads $L_{\Delta E}(m, z) = w(\Delta E, m, z) L(m, z)$, where the correction factor is

$$w(\Delta E, m, z) = \int_{E_1(1+z)}^{E_2(1+z)} dE e^{-E/kT(m, z)} G_f[E/kT(m, z)]. \quad (\text{C5})$$

The integral number counts are given by

$$N(>F) = \int dz dV(z) \int_{m_1}^{\infty} dm N(m, z), \quad (\text{C6})$$

¹ We correct here a numerical error in eq. (3) of CMT97, where $7/8$ appeared instead of $3/2$.

where $dV = R_H d\omega d\ell(z) D_L^2(z)/(1+z)^4$ is the cosmological volume subtended by the solid angle $d\omega$, $D_L(z)$ is the luminosity distance, and $R_H d\ell(z)$ is the line-of-sight element depending on Ω_0 and Ω_λ . The lower mass m_1 is that corresponding (after eqs. [C4] and [C5]) to the lowest luminosity L_{AE} detectable, at any z , by a survey with the limiting flux F .

The complementary contribution to the soft XRB of the sources with $F' < F$ is given by the expression

$$\frac{dF}{dv_0} = \int dV(z) \int_{m_0}^{m_1} dm\ell(v_0) \frac{N(m, z)}{4\pi D_L^2(z)}. \quad (C7)$$

With the use of equation (C3) this yields the equation (10) of the text, where the limits m_0 and m_1 are discussed.

REFERENCES

- Bennet, C. L. 1997, *MAP* experiment home page, URL <http://map.gsfc.nasa.gov>
- Bennett, C. L., et al. 1996, *ApJ*, 494, L1
- Bersanelli, M., et al. 1996, COBRAS/SAMBA Report on the Phase A Study, ESA D/SCI(96)3
- Blanchard, A., Valls-Gabaud, D., & Mamon, G. 1992, *A&A*, 264, 365
- Bond, J. R., Cole, S., Efstathiou, G., & Kaiser, N. 1991, *ApJ*, 379, 440
- Borgani, S., Rosati, P., Tozzi, P., & Norman, C. 1998, *ApJ*, submitted
- Bower, R. 1997, *MNRAS*, 288, 355
- Bryan, G. L., & Norman, M. L. 1998, *ApJ*, 495, 80
- Bunn, E. F., & White, M. 1996, *ApJ*, 480, 6
- Cavaliere, A., & Colafrancesco, S. 1988, *ApJ*, 331, 660
- Cavaliere, A., Colafrancesco, S., & Menci, N. 1993, *ApJ*, 415, 50
- Cavaliere, A., & Fusco-Femiano, R. 1976, *A&A*, 49, 137
- . 1978, *A&A*, 70, 677
- Cavaliere, A., Gurski, H., & Tucker, W. H. 1971, *Nature*, 231, 437
- Cavaliere, A., & Menci, N. 1997, *ApJ*, 480, 132
- Cavaliere, A., Menci, N., & Tozzi, P. 1997, *ApJ*, 484, L1 (CMT97)
- . 1998, in preparation
- Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1991, *ApJ*, 376, 380
- Collins, C. A., Burke, D. J., Romer, A. K., Sharples, R. M., & Nichol, R. C. 1997, *ApJ*, 479, L117
- David, L. P., Jones, C., & Forman, W. 1995, *ApJ*, 445, 578
- David, L. P., Slyz, A., Jones, C., Forman, W., Vrtilik, S. D., & Arnaud, K. A. 1993, *ApJ*, 412, 479
- De Grandi, S. 1996, in MPE report 263, *Röntgenstrahlung from the Universe*, ed. H. U. Zimmermann, J. Trümper, & H. Yorke, 577
- Ebeling, H., Edge, A. C., Fabian, A. C., Allen, S. W., Crawford, C. S., & Böhringer, H. 1997, *ApJ*, 479, L101
- Edge, A. C., & Stewart, G. C. 1991, *MNRAS*, 252, 428
- Evrard, A. E., & Henry, J. P. 1991, *ApJ*, 383, 95
- Fabbiano, G. 1996, *A&AS*, 188, 3103
- Fabian, A. C., Crawford, C. S., Edge, A. C., & Mushotzky, R. F. 1994, *MNRAS*, 267, 779
- Gardner, J., Tozzi, P., & Governato, F. 1998, in preparation
- Górski, K. M., Ratra, B., Stompor, R., Sugiyama, N., & Banday, A. J. 1998, *ApJ*, 114, 1
- Hasinger, G. 1996, *A&AS*, 120, 607
- Henriksen, M. J., & Markevitch, M. L. 1996, *ApJ*, 472, 17
- Henriksen, M. J., & White, R. E., III. 1996, *ApJ*, 465, 515
- Henry, J. P. 1997, *ApJ*, 489, L1
- Henry, J. P., & Arnaud, K. A. 1991, *ApJ*, 372, 410
- Henry, J. P., Gioia, I. M., Maccacaro, T. M., Morris, S. L., Stocke, J. T., & Wolter, A. 1992, *ApJ*, 386, 408
- Hjorth, J., Oukbir, J., & van Kampen, E. 1998, (astro-ph/9802293), preprint
- Honda, H., Hirayama, M., Watanabe, M., Yamashita, K., & Ohashi, T. 1997, in *X-Ray Imaging and Spectroscopy of Cosmic Hot Plasmas* (Tokyo: Univ. Acad. Press), 111
- Hughes, J. P., Gorenstein, P., & Fabricant, D. 1988, *ApJ*, 239, 82
- Jain, B., & Bertschinger, E. 1995, *ApJ*, 431, 495
- Jones, C., David, L., Forman, W., Churazov, E., & Gilfanov, M. 1997, in *Galactic and Cluster Cooling Flows*, ed. N. Soker (San Francisco: ASP)
- Kaiser, N. 1986, *MNRAS*, 222, 323
- . 1991, *ApJ*, 383, 104
- Kitayama, T., & Suto, Y. 1997, *ApJ*, 490, 557 (astro-ph/9792017)
- Klypin, A., Primack, J. R., & Holtzman, J. 1996, *ApJ*, 466, 13
- Lacey, C., & Cole, S. 1993, *MNRAS*, 262, 627
- Landau, L. D., & Lifshitz, E. M. 1959, *Fluid Mechanics* (London: Pergamon Press), 329, 331
- Liddle, A. R., Lyth, D. H., Roberts, D., & Viana, P. T. P. 1996, *MNRAS*, 278, 644
- Lucchin, F., Matarrese, S., & Mollerach, S. 1992, *ApJ*, 401, L49
- Lupini, F. 1996, Ph.D. thesis, Univ. Rome
- Markevitch, M., Mushotzky, R., Inoue, H., Yamashita, K., Furuzawa, A., & Tawara, Y. 1996, *ApJ*, 456, 437
- Markevitch, M., Sarazin, C. L., & Henriksen, M. J. 1997, in *X-Ray Imaging and Spectroscopy of Cosmic Hot Plasmas* (Tokyo: Univ. Acad. Press), 91
- Mason, K. O., Bignami, G., Brinkman, A. C., & Peacock, A. 1995, *Advances in Space Research*, 16, 41
- Mathiesen, B., & Evrard, A. E. 1998, *MNRAS*, 295, 769
- Mohr, J. J., Evrard, A. E., Fabricant, D. G., & Geller, M. J. 1995, *ApJ*, 447, 8
- Mushotzky, R. F. 1994, in *Clusters of Galaxies*, ed. F. Durret, A. Mazure, & J. Tran Tah Van (Gif-sur-Yvette: Editions Frontières), 177
- Mushotzky, R. F., & Scharf, C. A. 1997, *ApJ*, 482, 13
- Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563
- Nichol, R. C., Holden, B. P., Romer, A. K., Ulmer, M. P., Burke, D. J., & Collins, C. A. 1997, *ApJ*, 481, 644
- Ostriker, J. P., & Steinhardt, P. J. 1995, *Nature*, 377, 600
- Oukbir, J., Bartlett, J. G., & Blanchard, A. 1997, *A&A*, 320, 365
- Oukbir, J., & Blanchard, A. 1992, *A&A*, 252, L21
- Peebles, P. J. E. 1993, *Principles of Physical Cosmology* (Princeton: Princeton Univ. Press)
- Perrenod, S. C. 1980, *ApJ*, 236, 373
- Piccinotti, G., Mushotzky, R. F., Boldt, E. A., Holt, S. S., Marshall, F. E., Serlemitsos, P. J., & Shafer, R. A. 1982, *ApJ*, 253, 485
- Piro, L., et al. 1995, *Proc. SPIE*, 2517, 169
- Ponman, T. J., Bourner, P. D. J., Ebeling, H., & Böhringer, H. 1996, *MNRAS*, 283, 690
- Press, W. H., & Schechter, P. 1974, *ApJ*, 187, 425
- Ramella, M., Geller, M. J., & Huchra, J. P. 1992, *ApJ*, 384, 396
- Renzini, A. 1997, *ApJ*, 488, 35
- Roettiger, K., Stone, J. M., & Mushotzky, R. F. 1998, *ApJ*, 493, 62
- Rosati, P., Della Ceca, R., Norman, C., & Giacconi, R. 1998, *ApJ*, 492, L21
- Sarazin, C. L. 1988, *X-Ray Emission from Clusters of Galaxies* (Cambridge: Cambridge Univ. Press)
- . 1997, in *Galactic and Cluster Cooling Flows*, ed. N. Soker (San Francisco: PASP)
- Schindler, S., & Mueller, E. 1993, *A&A*, 272, 137
- Songaila, A., Wampler, E. J., & Cowie, L. L. 1997, *Nature*, 385, 137
- Sugiyama, N. 1995, *ApJS*, 100, 281
- Takizawa, M., & Mineshige, S. 1998, *ApJ*, in press
- Tormen, G. 1997, *MNRAS*, 290, 411
- Tsuru, T., et al. 1996, in *The 11th Int. Coll. on UV and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas*, ed. T. Watanabe & K. Yamashita, preprint (astro-ph/9711353)
- Tytler, D., Fan, X.-M., & Burles, S. 1996, *Nature*, 381, 207
- Walker, T., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H. S. 1991, *ApJ*, 376, 51
- West, M. J., Jones, C., & Forman, W. 1995, *ApJ*, 451, L5
- White, D. A., Jones, C., & Forman, W. 1997, *MNRAS*, 292, 419
- White, S. D. M., & Fabian, A. C. 1995, *MNRAS*, 273, 72
- White, S. D. M., Navarro, J. F., Frenk, C. S., & Evrard, A. E. 1993, *Nature*, 366, 429
- White, S. D. M., & Rees, M. 1978, *MNRAS*, 183, 341
- White, M., Viana, P. T. P., Liddle, A. R., & Scott, D. 1996, *MNRAS*, 283, 107
- Zabludoff, H. I., & Zaritsky, D. 1995, *ApJ*, 447, L21