The contribution of AGNs to the X-ray background

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We report the results of a detailed analysis of the contribution of various classes of AGNs (Seyfert galaxies and quasars) to the extragalactic X-ray background (XRB). The model is based on the unification schemes of AGNs, on their related X-ray spectral properties in the light of recent observational results and on the X-ray luminosity function derived by Boyle et al. (1993). The integrated emission from AGNs, when folded with an appropriate cosmological evolution law, can provide a good fit to the XRB over a wide energy range, from several to $\sim 100$ keV, while it contributes only about 74% of the ROSAT soft XRB. The baseline model predictions have been checked against all available observational constraints from both hard and soft X-ray surveys (counts, redshift distributions and average X-ray source spectral properties).

**Key words:** X-rays: general – Cosmology: diffuse radiation – Galaxies:nuclei – quasars:general.

**Thesaurus:** 13.25.3 – 12.04.2 – 11.14.1 – 11.17.3
1 INTRODUCTION

The problem of the origin of the extragalactic X-ray background (hereafter XRB) has attracted much renewed attention in recent years following in particular the results obtained with the X-ray satellites GINGA and ROSAT (Fabian & Barcons, 1992 and Zamorani 1994 for recent reviews).

An analytical fit to the spectrum above \( \sim 3 \) keV, where most of the energy intensity resides, has been recently given by Gruber (1992) in the energy range \( \sim 3 - 60 \) keV:

\[
I(E) = 7.877 E^{-0.29} \exp(-E/41.13) \quad \text{keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1} \tag{1}
\]

and with two power laws from 60 keV to \( \sim 6 \) MeV:

\[
I(E) = 1652 E^{-2.0} + 1.754 E^{-0.7} \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}. \tag{2}
\]

It is useful to remember that in the 3-20 keV energy range the XRB spectrum is well approximated by a flat power law with spectral index \( \alpha \approx 0.4 \). Below 3 keV, in the soft X-ray band (\( \sim 0.1 - 2.0 \) keV), the XRB spectrum measured by ROSAT is significantly steeper than the extrapolation of the high energy best fit. The bulk of the emission in the softest energy range, \( \sim 0.1 - 0.5 \) keV, is of galactic origin probably due to a local bubble of gas with a temperature of about \( 10^6 \) K, while in the 0.5-2.0 keV band, where the galactic contribution should be less important, the XRB spectrum can be well approximated by a power law with an energy index \( \alpha = 1.0 \pm 0.2 \) and a normalization of \( 13.6 \pm 0.2 \) keV cm\(^{-2} \) s\(^{-1} \) sr\(^{-1} \) keV\(^{-1} \) at 1 keV (Hasinger 1992). Similar results, but affected by larger errors, have been obtained from the analysis of a shallower field (Barber & Warwick 1994). However in the \( \sim 0.5 - 0.9 \) keV passband (M band) about 40% of the flux may be due to the emission of a hot gas with a temperature of \( \sim 2.2 \times 10^6 \) K, although the origin of such component is not yet understood (Hasinger 1992; Wang & McCray 1993). The remainder of the flux in the M-band and essentially all the flux above \( \sim 0.9 \) keV are likely to be of extragalactic origin.

The absence of any deviation from a pure blackbody spectrum of the cosmic microwave background radiation as measured by the FIRAS instrument on board COBE has set a very stringent upper limit (\( \sim 10^{-4} \)) on the contribution of a diffuse hot intergalactic gas to the hard XRB (Wright et al. 1994), leaving the alternative hypothesis on the origin of the XRB as due to the sum of discrete sources the only attractive one. Among the extragalactic sources, the Active Galactic Nuclei (Quasars and Seyfert galaxies, hereafter AGN) are known to be the strongest X-
ray emitters and have been considered to be the prime candidates able to satisfy
the energy requirements of the XRB. However the fact that their X-ray spectra
in the 2-10 keV energy interval are characterized by an average slope of $\alpha \sim 0.7$
(Mushotzky 1984; Turner & Pounds 1989) much steeper than that of the XRB,
has been, for a long time, the main problem for models in which most of the XRB
is due to AGNs.

The GINGA discovery of a flattening of the hard X-ray spectra of Sy 1 galaxies
at $> 8$ keV, explained either as a partial coverage of the sources (Matsuoka et al.
1990) or as a reprocessed flux from a relatively cold plasma (Pounds et. al 1990),
has led to several new attempts to fit the overall XRB spectrum as a superposition
of AGN spectra (Morisawa et al. 1990; Fabian et al. 1990; Rogers & Field 1991;
Terasawa 1991). A key feature of most of these models is the assumption of a
strongly enhanced reflected component, much larger than observed in Sy 1 galaxies.
It has later been shown that these models do not meet the constraints imposed
by the source counts and/or source spectra in the soft X-ray band (Setti 1992,
Comastri 1992). In addition, Zdziarski et al. (1993a) have argued that these
models do not fit the position and the width of the peak of the XRB spectrum.
This conclusion has been refuted in the case of the Fabian et al. model (Reynolds
et al. 1994).

A very good fit to the XRB spectrum in the energy range $\sim 2$–100 keV has been
obtained in a subsequent paper (Zdziarski et al. 1993b). In order to be consistent
with the GINGA observations and the recent OSSE results ($\sim 50$ – 300 keV),
the mean AGN X-ray spectrum has been described by a thermal Comptonization
model with a temperature of $\sim 40$ keV and an optical thickness of a few ($\tau_T \sim 3$),
leading to a power law with $\alpha = 0.7$ in the 2-10 keV energy interval with about
half of the flux reflected by a cold surface. The fit to the XRB has been achieved
by integrating up to a redshift cutoff $z_{\max} = 4$ with the cosmological evolution law
which best fit the results of Boyle et al. (1993). This model has not been checked
for consistency with the soft X-ray source counts, but it is likely that the predicted
soft X-ray source spectra are too flat compared with those actually observed in
the ROSAT surveys.

A different approach, based on the X-ray properties of unified schemes of AGNs,
has been suggested by Setti & Woltjer (1989). In the simplest version of unified
models (Antonucci 1993, for a review) the different observed properties of various
types of AGNs (e.g. Sy 1 versus Sy 2) are entirely due to the different orienta-
tion of the assumed absorbing molecular torus with respect the line of sight.
For reasonable values of tori masses and sizes, the nuclear emission can be ab-
sorbed up to $\sim 20 - 30$ keV depending on the torus column density and geometry. The existence of the torus has now been confirmed in the most dramatic way by direct imaging with HST (Jaffe et al. 1993). With simple hypotheses on the source spectra, assumed to have the “canonical” $\alpha = 0.7$ slope, on the percentage distribution of absorption cutoffs in the observed source population and on the source cosmological evolution properties, Setti & Woltjer demonstrated that it is possible to reproduce the flat slope of the XRB spectrum below $\sim 20$ keV, thus removing the main objection to the interpretation of the hard XRB in terms of the observed properties of AGNs. The required number of absorbed sources (Sy 2) is approximately equal to that of unabsorbed ones. A more sophisticated model has been computed by Madau et al. (1993). For two different assumptions on the source spectra and evolution, and by requiring a fine tuning of the optical thickness ($\tau_T = 2 - 3$) of the molecular torus, they obtain excellent fits to the XRB spectrum up to $\sim 100$ keV. A set of good fits to the XRB spectrum have been also obtained by Matt and Fabian (1994) assuming a broken power law for the source spectra and a distribution of absorbed sources with column densities ranging from $10^{23}$ cm$^{-2}$ to $10^{25}$ cm$^{-2}$. Including the contribution of the iron absorption edge and emission line on the source spectra, some features in the XRB spectrum between 2 and 3 keV are expected.

It is clear from the results discussed above that using the most recent AGN spectral data it is possible to obtain good fits to the XRB spectrum. However, on this basis only, it is difficult, if not impossible, to discriminate between the proposed models: almost equally good fits can be obtained with significantly different assumptions on the source spectra and evolution. As pointed out by Zamorani (1994), a good fit to the XRB spectrum is not a sufficient condition to conclude that the problem of the production of the XRB is solved.

In this paper we shall discuss a self-consistent AGN model for the synthesis of the XRB in the framework of the simplest AGN unified scheme mentioned above, taking into account the observational constraints provided by the observed source number counts in the soft (ROSAT and Einstein) and hard (HEAO-1 A-2 and GINGA) X-ray energy bands, the respective redshift distributions and spectral characteristics and the relative distributions of different types of sources (i.e. Type 2 vs. Type 1) as a function of the limiting flux and energy range.

In §2 we summarize the observational constraints on the X-ray spectral and cosmological properties of AGNs provided by the various soft and hard X-ray surveys. In §3 we discuss our basic model and compare its predictions with all the available observational constraints. The main results are discussed in §4 and
summarized in §5.

Throughout this paper the adopted values for the Hubble constant and the cosmological deceleration parameter are $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0$.

2 AGN X-RAY SPECTRA, LUMINOSITY FUNCTION AND COSMOLOGICAL EVOLUTION

2.1 AGN broad band X-ray spectra

Large samples of AGNs have been observed in the soft X-ray band with the *Einstein* IPC in the energy range $\sim 0.2 - 4.0$ keV and with the ROSAT PSPC in the energy range $\sim 0.1 - 2.4$ keV. The *Einstein* IPC spectra of Sy 1 galaxies and quasars cover a wide range of power-law spectral indices with a mean $\alpha \sim 1.0$ for the radio-quiet, and a mean $\alpha \sim 0.5$ for the radio-loud objects, with a large fraction of the objects showing an upturn of the spectrum below $\sim 0.5$ keV (Wilkes & Elvis 1987; Kruper, Urry and Canizares 1990). Since the contribution of the radio-loud objects to the soft XRB at 2 keV is only a few percentage points (Della Ceca et al. 1994), for simplicity we shall not treat them as a separate population.

The analysis of two samples detected in the ROSAT all sky survey shows a gradual flattening of the mean spectral slope with increasing redshift from about $\alpha \sim 1.5$ for nearby AGNs to $\alpha \sim 0.8 - 0.9$ at redshifts $\sim 2.0 - 2.5$ (Walter & Fink 1993, Schartel 1994). The most likely interpretation of this effect is a flattening toward the medium energies of the intrinsic spectrum redshifted in the ROSAT band.

In the $\sim 0.1 - 2.0$ keV energy range a power law fit to the summed spectra of the sources detected in ROSAT deep surveys fields suggests an energy index $\alpha \sim 1.0$ (Hasinger et al. 1993, hereafter H93).

The observations from the GINGA satellite of a large sample of bright AGNs, mainly Sy 1 galaxies (Nandra 1991), have revealed several new spectral features in the energy range $\sim 2 - 20$ keV. In particular, an emission line complex near 6.5 keV along with an iron K-absorption edge around 7-8 keV and a spectral “hump” above $\sim 10$ keV are common properties of the sample. All these features are widely interpreted as the re-processing (“reflection”) of the primary X-ray radiation by relatively cold matter in the proximity of the central source, probably associated with the accretion disk (Pounds et al. 1990). The percentage of the flux which is observed in the reflected component is approximately equal to that present in the direct flux, implying that the reflecting matter is consistent with an accretion disk.
subtending about $2\pi$ sr at the X-ray source. An important result of this “reflection model” fit is that the resulting slope of the intrinsic power law spectrum ($\alpha \sim 0.9$) is significantly steeper than the observed “canonical” slope $\alpha \sim 0.7$ (Mushotzky 1984; Turner & Pounds 1989). As pointed out by Zdziarski et al. (1993b) the reflection component below 10 keV is very weak and it seems difficult to explain the flattening of the average 2-10 keV power law, by $\Delta \alpha \sim 0.2$, as only due to the contribution of the reflected flux. However, the results of a careful analysis of 61 high quality spectra of Sy 1 galaxies observed by GINGA (Nandra & Pounds 1994) indicate that the observed “canonical” slope of $\alpha \sim 0.7$ is probably due to the combined effects of reflection and warm absorber features on the underlying mean X-ray continuum with slope $\alpha \sim 0.9 - 1.0$. The signature of highly ionized material ($\text{O VII} - \text{O VIII}$) at $\sim 0.7 - 0.8$ keV, the so-called warm absorber, has been revealed in few high signal-to-noise ROSAT observations of AGNs (Nandra & Pounds 1992; Nandra et al. 1993; Turner et al. 1993a; Fiore et al. 1993).

Recent analyses of EXOSAT and GINGA observations of high luminosity AGNs (Comastri et al. 1992; Williams et al. 1992) have shown that the distribution of the power law energy index of QSOs has a mean value $\alpha \sim 0.9$, steeper than the one observed for lower luminosity AGNs. While the Sy 1 galaxies are well described by a power law plus a disk reflection model, the higher luminosity sources do not show evidence of the reflected component.

The unified scheme scenario is supported by GINGA observations of a relatively large sample of Sy 2 galaxies (Awaki et al. 1991), where most of the detected sources (14 out of 28 observed) show evidence of intrinsic absorption with column densities in the range $10^{22} - 10^{24}$ cm$^{-2}$. The non-detection in hard X-rays of other optically selected Sy 2 may be an indication of even larger column densities, of the order of $\sim 10^{24} - 10^{25}$ cm$^{-2}$ with solar composition. It should also be noted that intrinsic absorption, with column densities in the range $N_H \sim 10^{21-23}$ cm$^{-2}$, has been observed in the X-ray spectra of Seyfert galaxies of intermediate types (Turner & Pounds 1989; Nandra & Pounds 1994), suggesting the existence of a continuous distribution in the absorption column densities in the Seyfert population.

Soft X-rays were also detected from some Sy 2 galaxies (Kriss, Canizares & Ricker 1980), but the implied X-ray luminosities are in general much smaller (two or more orders of magnitude) than those of Sy 1 galaxies of comparable optical magnitude. ROSAT X-ray spectra of Sy 2 galaxies have been recently published (Turner et al. 1993b; Mulchaey et al. 1993). They generally show substantial photoelectric absorption with a range of column densities up to several times $10^{22}$ cm$^{-2}$ in agreement with GINGA observations. In some cases the observed X-ray
fluxes are greater than expected by simple extrapolations from the high energy data plus a uniform absorber, suggesting a different origin for the soft component. The soft X-ray emission has been interpreted, in the framework of unified schemes, as electron scattered nuclear radiation. At least in the case of NGC 1068 the soft flux is known to arise from an extended starburst region (Wilson et al. 1992).

There is a growing observational evidence that, as suggested by Barthel (1989), radio-loud quasars and strong radio galaxies can also be unified in a way similar to the Seyferts. X-ray observations of strong radio galaxies tend to support this unified picture (Koyama 1992; Allen & Fabian 1992). In addition, the discovery of absorption \( N_H \sim 10^{22} \text{ cm}^{-2} \) in the ROSAT spectra of high-redshift quasars (Elvis et al. 1994) reverses the trend for the most luminous AGN to show the least X-ray absorption. It should also be borne in mind that the possible existence of an obscured population of intrinsically luminous radio-quiet quasars is still uncertain, although Sanders et al. (1989) have suggested that the IRAS ultra-luminous galaxies might be the obscured counterpart of luminous quasars.

Until recently, the spectral properties of AGNs at higher energies were essentially limited to the early balloon observations of bright nearby AGNs (i.e. 3C273; Bezler et al. 1984). The OSSE instrument on the **Compton Gamma-Ray Observatory** has now detected hard X-ray emission \( (E > 50 \text{ keV}) \) from numerous Seyfert galaxies (Johnson et al. 1994). The OSSE spectrum of NGC 4151 (Maisack et al. 1993) is very soft and can be described by a broken power law with \( \alpha = 1.1 \pm 0.3 \) below 100 keV and \( \alpha = 2.4 \pm 0.4 \) above the break energy, or by a thermal Comptonization model with a temperature of \( \sim 40 \text{ keV} \). This is consistent with earlier observations obtained by the SIGMA telescope onboard GRANAT (Jourdain et al. 1992). Somewhat different results have been obtained from the OSSE observations of the Sy 1 galaxy IC 4329A, which is likely to be more representative of the Seyfert population than NGC 4151 (Madejski et al. 1994). Joint fits of the ROSAT, GINGA and OSSE data are well modeled using an exponentially cut-off power law continuum with an e-folding energy \( 240 \lesssim E \lesssim 900 \text{ keV} \) plus reflection (Madejski et al. 1994).

The existence of a high energy cutoff is also clearly indicated by the analysis (Johnson et al. 1994) of the average OSSE spectrum from a sample of 15 Seyfert galaxies. Moreover, the non-detection of a hard X-ray selected sample of Seyfert galaxies at energies \( > 100 \text{ MeV} \) by EGRET (Lin et al. 1993) is consistent with the break in the spectrum at a few hundreds keV being a common spectral feature of the Seyfert population.

The few radio-loud quasars which have been detected by OSSE (Johnson et
al. 1994) generally show harder spectral indices than Seyfert galaxies, consistently with the EGRET detection at energies greater than 100 MeV of more than 20 core dominated radio quasars (Kurfess 1994). As pointed out by Padovani et al. (1993) and Setti & Woltjer (1994) the radio-loud objects detected by EGRET may well provide a relevant fraction of the $> 100$ MeV $\gamma$-ray background.

### 2.2 AGN X-ray luminosity function and evolution

Our knowledge of the AGN X-ray luminosity function and evolution in the soft X-ray band has been greatly expanded with the almost complete optical identifications of the Extended Medium Sensitivity Survey (EMSS) made in the 0.3-3.5 keV passband (Gioia et al. 1990, Stocke et al. 1991) and the ROSAT quasar survey in the 0.5-2.0 keV energy range (Shanks et al. 1991). Models for the AGN X-ray luminosity function (XLF) have been constructed from the EMSS AGNs (about 450 objects) by Maccacaro et al. (1991, M91) and from a combination of the EMSS AGNs with 42 new QSOs from two deep ROSAT pointings by Boyle et al. (1993; B93). In the framework of a pure luminosity evolution model the best XLF (cfr. B93) is represented by two power laws of the form:

\[
\rho(L, z = 0) = K_1 L_{44}^{-\gamma_1} \quad \text{for} \quad L_X < L_B
\]

\[
\rho(L, z = 0) = K_2 L_{44}^{-\gamma_2} \quad \text{for} \quad L_X > L_B
\]

where $L_{44}$ is the 0.3-3.5 keV X-ray luminosity expressed in units of $10^{44}$ ergs s$^{-1}$.

The evolution of the XLF is parameterised as a power law in $(1 + z)$:

\[
L_X(z) = L_X(0) \times (1 + z)^\beta
\]

Assuming $q_0 = 0$ and an X-ray spectral index $\alpha = 1$ an acceptable fit to the combined EMSS/ROSAT data has been obtained with the following parameter values for the XLF: $\gamma_1 = 1.7 \pm 0.2$, $\gamma_2 = 3.4 \pm 0.1$, $K_1 = K_2 L_B^{\gamma_1-\gamma_2} = 5.7 \times 10^{-7} \text{Mpc}^{-3} \ (10^{44} \text{ergs s}^{-1})^{\gamma_1-1}$, log $L_B = 43.84 \pm 0.1$ and $\beta = 2.75 \pm 0.1$. These parameters have been obtained over the full luminosity-redshift range $10^{42} < L_X < 10^{48}$ ergs s$^{-1}$ and $0 < z < 3$. The inclusion of a redshift cutoff above which the evolution stops ($z_{\text{cut}} \sim 2$), although not required by the data for $q_0 = 0$, improves the acceptability of the model.

Because of the soft X-ray selection the parameters of the XLF and evolution derived from the *Einstein* and ROSAT data can be considered to adequately represent the population of unabsorbed AGNs.
3 A SELF-CONSISTENT APPROACH TO THE SYNTHESIS OF THE XRB

This section is devoted to a detailed discussion of an AGN model for the XRB in the framework of the X-ray unified scheme.

The underlying assumption is that the shape of the XLF and evolution of absorbed objects is the same as that of the unabsorbed ones which entails that the \( N_H \) distribution is independent from the source luminosity. The luminosity range chosen for the integration is \( 10^{42} < L_X(0) < 10^{47} \) ergs s\(^{-1}\). We have further assumed \( L_B \) (i.e. the break luminosity in the XLF at redshift zero) as the dividing luminosity between the low luminosity unabsorbed objects (i.e. Sy 1 with the spectrum of Eqs. 6,8) and the high luminosity unabsorbed objects (i.e. quasars with the spectrum of Eqs. 6,7). We have also assumed that the gaseous matter responsible for the absorption has solar chemical composition independent of the object redshift. Finally, it should be noted that we did not try to reproduce the full intensity and spectrum of the soft (below a few keV) XRB. In fact it is already known that in the soft X-ray band other classes of sources (e.g. galaxies and clusters of galaxies) provide a non–negligible contribution to the XRB. Also, due to the large number of free parameters involved in the calculations we did not try a global best fit of the whole set of observational constraints, but we have followed the approach described below.

3.1 The baseline model and the fit to the XRB

In this model the parameters for the broad band X-ray spectrum and cosmological evolution of different types of AGNs have been chosen in order to obtain a good fit to the overall set of observational constraints. All the assumed parameters are consistent, within the errors, with those suggested by the present available observations. The adopted spectral shape of the different types of AGNs (cfr. §2) can be written as follows:

\[
F(\text{Quasars, Sy } 1) \propto E^{-\alpha_s} \quad \text{for } E < 1.5 \text{ keV} \tag{6}
\]

\[
F(\text{Quasars}) \propto E^{-\alpha_h} \exp \left( -\frac{E}{E_c} \right) \quad \text{for } E > 1.5 \text{ keV} \tag{7}
\]

\[
F(\text{Sy } 1) \propto E^{-\alpha_h} \exp \left( -\frac{E}{E_c} \right) \left[ 1 + f_r A(E) \right] \quad \text{for } E > 1.5 \text{ keV} \tag{8}
\]
\[ F(\text{Type 2}) = F(\text{Type 1}) \times e^{-\alpha E N_H} \]  

(9)

where \( \alpha_s = 1.3 \) is the energy index in the soft band, \( \alpha_h = 0.9 \) is the index above 1.5 keV and \( E_c = 320 \) keV is the e-folding energy of the exponential spectrum. The here adopted \( E_c \) value has been taken from the results of the combined ROSAT-Ginga-OSSE fit to IC 4329A (model D in Madejski et al. 1994). It should be noted that this falls within the range of \( E_c \) values obtained by fitting our power law plus reflection spectrum to the OSSE data points of the average Seyfert spectrum in Johnson et al. (1994). For the angular dependence of the X-ray radiation reprocessed by the accretion disc, \( f_r(\theta) \), we have adopted the analytical approximation given by Ghisellini et al. (1994). \( A(E) \) is the reflectivity of the cold gas (White, Lightman & Zdziarski 1988; Lightman & White 1988) and \( \sigma_E \) the photoelectric absorption cross section assuming solar composition (Morrison & McCammon 1983). As required by the unified scheme, the intrinsic X-ray spectrum of type 2 AGNs has been assumed to be the same as the spectrum of type 1 objects, modified by absorption effects, with \( N_H \) the column density of the molecular torus in units of atoms cm\(^{-2}\). Assuming \( \theta_0 = 45^\circ \) for the torus half-opening angle (Barthel 1989; Awaki et al. 1991; Goodrich et al. 1994) the average value of \( f_r \), weighted over the solid angle, for the unabsorbed \((0 < \theta < \theta_0)\) type 1 objects is 1.29, while it is 0.88 for type 2 objects \((\theta_0 < \theta < 90^\circ)\).

The adopted XLF and evolution are those described in §2.2 with one minor modification. The best fit evolutionary parameter \( \beta = 2.75 \pm 0.1 \) has been obtained by B93 under the assumption of a single population of unabsorbed objects. The possible presence in the sample of a fraction of absorbed objects, which in the soft band are more easily detected at high redshift, makes the derived luminosity evolution higher than the real one. For this reason we have adopted \( \beta = 2.6 \) in our baseline model. Moreover, since a lower evolution implies a higher normalization of the local XLF, the \( K_1 \) value given by B93 is increased by 20%. As a compromise between the B93 suggestion \((z_{\text{cut}} \sim 2)\) and the most recent results on optically selected high redshift quasars which suggest a higher redshift cutoff (Warren et al. 1994), we have introduced a redshift cutoff \( z_{\text{cut}} = 2.25 \). For \( z > z_{\text{cut}} \) the XLF has been assumed to be constant up to \( z_{\text{max}} = 4.0 \). An additional important parameter of the model is the distribution of absorbed objects as a function of \( N_H \). Such a distribution, normalized to the number of unabsorbed AGNs \((N_H < 10^{21})\), has been estimated by requiring acceptable fits to all the observational constraints described in the following sub-section.

The solid curve in Fig. 1a shows the fit to the XRB resulting from our model,
while the dotted and dot-dashed curves show the contribution of the various classes of AGNs as a function of intrinsic $N_H$. For simplicity the absorbed objects ($N_H > 10^{21} \text{ cm}^{-2}$) have been divided into four subclasses, one decade in $N_H$ wide, up to $N_H = 10^{25} \text{ cm}^{-2}$. The number density of objects in the four $N_H$ classes, normalized to the number of unabsorbed AGNs is 0.35,1.10,2.30,1.65. The data for $E > 3$ keV are a compilation of best results from various instruments, while the soft data are from ROSAT (Hasinger 1992; solid lines). Figure 1b shows the fractional difference between our model results and the analytical approximation of the XRB in the energy range 3-100 keV (Eqs. 1 and 2). To help in judging the goodness of the fit, we show in this figure a few typical measurement errors at various energies. It is seen that, while for $E \gtrsim 5$ keV the computed intensity is within two sigma from all the available data points, at $E \lesssim 5$ keV it falls significantly below the observed data. This has been done purposely in order to accomodate minor additional contribution from other extragalactic sources such as clusters of galaxies, normal and starburst galaxies (Setti 1990 and references therein).

3.2 Other Soft and Hard X-ray constraints

The number of sources per steradian with flux $> S_{lim}$ in the energy range $E_1 - E_2$ can be computed, for a given luminosity function $\rho(L, z)$, as:

$$N(> S_{lim}) = \left( \frac{c}{H_0} \right) \int_0^{z_{max}} \int_{\max[L_{min}(S_{lim}),L_{min}]}^{(1+z)^{\beta}L_{max}(0)} \frac{D_L^2(z)}{(1+z)^3} \rho(L, z) dL dz$$

(10)

where: $L_{min}(S_{lim}) = 4\pi D_L^2_{\max}(E_1, E_2)/K(z, E_1, E_2)$, $L_{min} = (1+z)^{\beta} \times 10^{42}$ ergs s$^{-1}$, $D_L = \frac{c}{H_0} z(1+z/2)$ is the luminosity distance and $K(z, E_1, E_2)$ is the K-correction term.

The expected counts for each class of sources of the “baseline model” (in the 0.5-2.0 keV passband) are presented in Fig. 2. One can see that the total counts are in good agreement with the observed EMSS AGN Log N - Log S (Della Ceca et al. 1992) converted from the 0.3-3.5 keV IPC to the ROSAT 0.5-2.0 keV band assuming a spectral slope $\alpha = 1$. The predicted surface density at the limiting flux $S_{lim} \sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ is in good agreement with the available optical identifications of a number of deep ROSAT observations, where the AGN content has been estimated to be in the range 60-85%, while at the faintest flux limit $\sim 2.5 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ it is close to the observed one ($\sim 400$ objects per square degree). The predicted AGN counts are also fully consistent with the fluctuation analysis at even fainter fluxes.

The redshift distribution in the energy range 0.3-3.5 keV has been computed
taking into account the sky coverage of the EMSS (M91) as a function of the limiting flux, which in turns depends on the source spectral shape. The flux limits quoted in M91 apply to the unabsorbed AGNs, while they should be increased by about a factor 2 for sources with log $N_{H} = 21.5$ (Zamorani et al. 1988), the only relevant contributors to the EMSS counts among the absorbed AGNs (Fig. 2). As a consequence the derived distribution is largely dominated by the unabsorbed AGNs ($\sim 97\%$). The results (Fig. 3) are in good agreement with the EMSS AGN redshift distribution. The overprediction at low redshift ($z < 0.5$), which is statistically not significant, is likely to be due to the adopted slope for the faint end of the XLF ($\gamma_1 = 1.7$) steeper, but consistent within the errors, with the EMSS slope ($\gamma_1 \sim 1.4$, Della Ceca et al. 1992).

The predicted redshift distribution in the 0.5-2.0 keV energy range has been computed, for the unabsorbed sources, down to the flux of $\sim 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$, corresponding to the limiting flux of the already optically identified sources in a number of ROSAT deep fields. In analogy with the procedure described above, the flux limits for the absorbed population has been computed adopting the appropriate conversion factors for the ROSAT 0.5-2.0 keV band. The results (Fig. 4) are consistent with the redshift distribution of the AGNs so far identified in five deep ROSAT fields: Lockman hole, Marano field, NEP, QSF1 and QSF3 (Hasinger 1994). Given the present size of the sample and its incomplete identification, the excess of predicted sources above $z \sim 2$ is statistically not significant. If such an excess remains when a larger complete sample becomes available, it may be necessary to lower the adopted value for $z_{cut}$.

The average soft (0.5-2.0 keV) X-ray spectrum has been computed for different flux limits ranging from $10^{-13}$ to $3 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (see Table 1). The mean slope shows a gradual flattening from $\alpha \sim 1.0$ at the bright flux limit, consistent with the average AGN spectrum of the *Einstein* EMSS sources (Maccacaro et al. 1988), to $\alpha \sim 0.84$ at the faint end. As shown in the last entry of the Table the average spectrum becomes significantly harder at fluxes even fainter that the current ROSAT limit. This trend is consistent with what has been observed by H93 (see their Fig. 3). The average spectrum of the ROSAT deep survey sources in the Lockman hole ($< \alpha > = 0.96 \pm 0.11$; H93) has been computed by summing the counts of all the sources fainter than $4 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ in the $\sim 0.1-2.0$ keV energy range. The mean spectrum of the sources in our model, computed with the same prescription of H93, is $\alpha = 0.99$, being thus in excellent agreement with the observed one. The gradual steepening of the mean soft X-ray spectrum toward lower energies is also shown, for various limiting fluxes, in Table 1.
In the hard (2-10 keV) X-ray band the HEAO-1 A-2 all-sky survey (Piccinotti et al. 1982) provides an important constraint. Thirty AGNs, mostly Sy 1 galaxies, constitute a complete sample at the flux limit of $2.74 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ over 8.2 steradians of the sky. The predicted number of sources is lower than but consistent (within 1σ) with the Piccinotti et al. (1982) AGN surface density (Fig. 5). Moreover it should be noted that the AGN counts in the HEAO-1 A-2 survey are likely to be somewhat overestimated because of the excess of sources in the local supercluster. In fact, nine of the twelve sources with $z < 0.01$ are located toward the central region of the local supercluster, while only three are in the anticenter direction. Moreover all but one have supergalactic latitude less than $|\theta| < 30^\circ$. The excess of sources in the Piccinotti et al. sample is thus estimated to be of the order of 20%.

Adding the contribution of clusters of galaxies, the predicted counts are also consistent with the region allowed by the GINGA (Hayashida 1990) and HEAO-1 A-2 (Shafer 1983) fluctuation analysis in the flux range $\sim 10^{-13} - 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$. It should be noted that the fluctuation analysis includes the contribution of all emitting X-ray sources (galactic and extragalactic). The galactic contribution at $\sim 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ is estimated to be of the order of 10% (Hayashida 1990).

Also, the derived redshift (Fig. 6) and absorption (Fig. 7) distributions of the AGNs at the flux limit of the Piccinotti sample show a good agreement with those observed. The X-ray spectra and absorbing column densities for all the objects in this sample have been measured by EXOSAT (Turner & Pounds 1989) in the $\sim 0.1 - 10$ keV band and by ROSAT (Schartel 1994) in the $\sim 0.1 - 2.4$ keV energy range. The mean ratio between the hard (2-10 keV) and soft (0.5-4.5 keV) X-ray fluxes $< S_H/S_S > = 2.05$ is consistent with the value $(1.95^{+0.40}_{-0.33})$ obtained by Franceschini et al. (1993). The local X-ray volume emissivity of the baseline model in the 2-10 keV band is $3.8 \times 10^{38}$ ergs s$^{-1}$ Mpc$^{-3}$, fully consistent with that derived by Miyaji et al. (1994) from a cross-correlation analysis of the HEAO-1 A-2 all sky XRB maps and the galaxies from the IRAS 2 Jy redshift survey sample and the 0.7 Jy projected sample.

4 DISCUSSION

The baseline model described in the previous section not only provides an excellent fit to the XRB from a several keV up to $\sim 100$ keV, but it is also consistent with essentially all the available observational constraints in the soft and hard X–ray bands. In order to test the sensitivity of the results to the various parameters
defining the model, we have run a number of different models by modifying a few of the input parameters. In essentially all the cases we have been able to reproduce acceptable fits to the XRB, but worsening one or more of the additional consistency checks described in Section 3.2. For example, we have varied by 0.2 the slope of the faint end of the XLF (within the 1σ error quoted by B93). Using a steeper slope ($\gamma_1 = 1.9$), the increased number of low luminosity objects allows a better fit of the 2-10 keV AGN surface density (Piccinotti et al. 1982), but the predicted number of low redshift ($z < 0.3$) sources in the soft energy range increases significantly and becomes inconsistent with the observed EMSS data. Qualitatively the same effects are obtained if one extrapolates the assumed XLF down to $L_X = 10^{41}$ ergs s$^{-1}$. Viceversa, using a flatter slope ($\gamma_1 = 1.5$) allows an even better fit to the low redshift distribution of EMSS AGNs, but underestimates significantly the surface density of bright 2-10 keV AGNs. We have also considered a different description of the X-ray spectral properties, moving below 1.5 keV the low energy steepening of the average spectrum. In particular, assuming a mean spectrum described by a single power law ($\alpha = 0.9$) above 0.5 keV, we find that the mean ROSAT source spectrum is significantly flatter, by $\Delta \alpha \sim 0.3 - 0.4$, than the observed one.

The fit to the XRB does not depend critically on the precise form of the mean source spectrum above 3 keV. For instance, good fits have been obtained by assuming somewhat harder power laws ($\alpha \sim 0.7 - 0.8$) and no “reflection” component. As originally argued by Setti & Woltjer (1989), a dominant factor in this fit is represented by the distribution of absorbed sources. This is why we have not attempted a more detailed modeling of the source spectral characteristics: if on the one hand it is true that not all Sy 1 galaxies present a “reflection” component, on the other hand we have not considered the additional contribution of the “warm absorber” component (cfr. § 2.1) to our mean source spectrum. Similarly, we have not considered possible modifications to the observed spectra induced by Compton-thick tori. These effects are important for the objects with the highest density ($N_H > 10^{24}$ cm$^{-2}$; Ghisellini, Haardt & Matt 1994) and their inclusion would not modify substantially any of our conclusions.

Likewise, above several tens keV the fit to the XRB spectrum is not strongly dependent on the precise shape of the high energy spectrum as long as an exponential cut-off or a break to a steeper slope is present. In fact good fits have been also obtained by adopting a broken power law model for the mean AGN spectrum with a steep slope ($\alpha \sim 1.6$) above a break energy of 75 keV, which provides a reasonable representation of the OSSE data points for the average Seyfert spectrum (Johnson et al. 1994). The main conclusions reached in this paper remain
unchanged. Due to the paucity of the spectral data above \( \sim 50 - 100 \) keV both the average slope and the break energy are still very uncertain.

A detailed model for the XRB above \( \sim 100 \) keV is beyond the purposes of this paper and will be discussed elsewhere.

Obviously, given the large number of parameters which define the model, we have not attempted a full exploration of the entire allowable parameter space and therefore we can not exclude that more complex modifications of the baseline model could provide even better fits than those described in the previous Section. However it is useful to discuss some of the implications and testable predictions deriving from the baseline model.

The fit to the XRB is within 6% of the observed data from 6 keV up to 100 keV. In the range 3 to 6 keV the model prediction is below the data by (5–10)%. In this energy range the contribution of clusters of galaxies to the XRB has been estimated to be \( \sim 5\% \) (Piccinotti et al. 1982) and can therefore be easily accommodated in our model. On the contrary, a dominant contribution from star-forming galaxies, as proposed by Griffiths & Padovani (1990), would be inconsistent with our model.

Below 2 keV a careful fit to the XRB spectrum has not been attempted because other classes of extragalactic sources may contribute significantly. In this band the XRB is not totally accounted for by the AGN model discussed here. At the flux limit of \( 3 \times 10^{-15} \) ergs cm\(^{-2}\) s\(^{-1}\) about 59% of the 1-2 keV XRB is already resolved into sources (this fraction rises to at least 75% on the basis of a P(D) analysis (H93)), to be compared with about 50% resulting from integration, at the same flux limit, of our log N - log S relation for AGNs. An extrapolation of our model to zero fluxes accounts for \( \sim 74\% \) of the 1-2 keV background.

Preliminary results of ASCA observations of the 1-10 keV XRB spectrum (Gendreau et al. 1994) indicate that the high energy power law \( (\alpha \sim 0.4) \) can be extrapolated down to \( \sim 1 \) keV with no evidence for a steepening around 2-3 keV, at variance with the ROSAT observations. If these results will be confirmed by future observations, the predicted AGN contribution to the soft XRB of our model could be higher.

The AGN number counts predicted by B93 at the faintest ROSAT limit by integrating their XLF is lower by a factor \( \sim 1.8 \) than the total observed number of sources. The reason for this difference is that at faint fluxes the relative contribution of absorbed sources \( (10^{21} \leq N_H \leq 10^{23} \text{ cm}^{-2}) \), not considered by B93, becomes increasingly more important in our model (Fig. 2). We expect that the faint sources with relatively hard X-ray spectra observed in the Lockman Hole deep survey (see Fig. 3 of H93) will be identified with absorbed AGNs at intermediate
to high redshifts.

For four ROSAT deep fields a relevant fraction (∼ 76%) of sources have been already spectroscopically identified above a flux of ∼ 10^{-14} ergs cm^{-2} s^{-1}. The results indicate that the stellar fraction in the deep ROSAT surveys is at most 10% and that, among the extragalactic sources, unabsorbed type 1 AGN are the dominant population (∼ 60%), followed by galaxies, clusters of galaxies, and BL Lac objects (Shanks et al. 1991; B93; Zamorani 1994; Hasinger 1994). The number of clusters identified in these surveys is still very low, also because their optical identification, requiring spectroscopy on very faint galaxies, is difficult. As a consequence, their contribution to the soft XRB is uncertain, depending also on their still ill defined cosmological evolution. The integrated emission of a diffuse relatively cool intergalactic medium in clusters of galaxies, not precluded by the COBE results, could in principle complement the AGN contribution so as to saturate the soft XRB (Burg, Cavaliere & Menci 1993).

The percentage of galaxies in the ROSAT deep surveys at the limiting flux of ∼ 10^{-14} ergs cm^{-2} s^{-1} is relatively small (5–10%). On the basis of preliminary and still incomplete optical identifications it has been suggested (Griffiths et al. 1994) that early type and Narrow-Emission-Line galaxies may become at least as numerous as the AGNs at even fainter fluxes (5 × 10^{-15} < S_x < 10^{-14} ergs cm^{-2} s^{-1}). This result, if confirmed by more complete optical identifications, can still be accommodated in our model. In fact, it is seen from Fig. 2 that some room is left for fluxes around 10^{-15} ergs cm^{-2} s^{-1}. This is even more true if, as pointed out by Griffiths et al. (1994), the presence of Sy 2 nuclei among their Narrow-Line galaxies cannot be ruled out.

From the previous discussion on our model it is possible to obtain some estimate on the number ratio between Sy 2 and Sy 1 galaxies. It should be stressed that the computed ratios between the absorbed and unabsorbed populations can not be directly associated with the number ratio between Sy 2 and Sy 1. In fact it is known that there is a non negligible number of galaxies classified as Sy 1 which show substantial intrinsic absorption, with column densities up to several times 10^{22} cm^{-2} (Turner & Pounds 1989, Nandra & Pounds 1994). On the other hand, a number of galaxies classified as Sy 2 show a column density smaller than 10^{22} cm^{-2}. For this reason it is not easy to identify the N_H value which best separates the two classes of Seyfert galaxies. However, if we tentatively consider as Sy 1 the unabsorbed objects and those with relatively low intrinsic column densities (N_H < 10^{22.0} – 10^{22.5} cm^{-2}), the resulting ratio between Sy 2 and Sy 1 is in the range 2.4–3.7 in reasonable agreement with the value of 2.3±0.7 found by Huchra
& Burg (1992) for a complete sample of optically selected Seyfert galaxies. From a finer subdivision, Osterbrock & Martel (1993) find that the ratio between Sy 1.8-1.9-2 and Sy 1-1.5 is 3.5-4.0.

One of the main results of our analysis is that, contrary to the suggestion discussed by Franceschini et al. (1993), there is no need for two distinct populations (soft and hard X-ray selected) of AGNs with different spectral and evolutionary properties. This can in principle be tested when deeper samples of hard X-ray selected AGNs may become available: hard X-ray selected sources should have the same evolutionary properties as the soft X-ray selected ones.

One important assumption of the model, which needs to be tested by future observations, is the existence of highly absorbed high luminosity objects. Almost nothing is known about the distribution of $N_H$ column density for high luminosity radio quiet quasars. If such distribution turns out to be different from that of lower luminosity objects, some modifications to our baseline model would be required. In addition, one hopes that future observations will permit to extend our knowledge of the $z = 0$ XLF below $10^{42}$ ergs s$^{-1}$.

5 CONCLUSIONS

The main results of our paper can be summarized as follows:

a) In the framework of the AGN unified schemes it is possible to construct a baseline model which reproduces with good accuracy the XRB spectrum over the broad energy range $\sim 5 - 100$ keV and meets essentially all presently known X-ray constraints on the source population and spectral characteristics. The predicted AGN contribution to the ROSAT XRB in the 1-2 keV band is about 74%.

b) The key feature of the model is the existence of an AGN population with absorbed X-ray spectra characterized by a distribution of intrinsic column densities in the range $N_H = 10^{21} - 10^{25}$ cm$^{-2}$. From such a distribution we derive an estimate of the ratio between Sy 2 and Sy 1 galaxies which is consistent with the observed ratio in nearby optically selected complete samples.

c) The spatial distribution and cosmological evolution of both absorbed and unabsorbed AGNs can be essentially described by the XLF parameters derived by B93, provided that the strong power law evolution shows a significant decline or cut-off at a redshift $z = 2.0 - 2.5$.

d) The model calculations do not strongly depend on the details of the spectral slope, and acceptable fits to all the observational data can be obtained as long as an exponential cut-off or a break to a steeper slope is present in the average AGN
spectra above $\sim 70$ keV.

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FIGURE CAPTIONS

**Fig. 1a.** The XRB spectrum compared with our baseline model. The 0.5-2.0 keV data are from ROSAT (solid line: Hasinger 1992), while the high energy data are a compilation of best results from various experiments (Gruber 1992). The solid line represents our best fit, the dotted line represents the contribution of unabsorbed sources, while the absorbed sources are indicated by dot-dashed lines. The labels are the logarithms of the corresponding hydrogen column densities.

**Fig. 1b.** Percentage deviations from the best fit analytical approximation (Gruber 1992). The error bars represent typical one sigma measurement errors at various energies.

**Fig. 2.** The computed predicted counts (solid line) in the soft (0.5-2.0 keV) band compared with the EMSS AGN counts (dashed lines, Della Ceca et al. 1992) the ROSAT counts (H93) and ROSAT fluctuation analysis (dashed area, H93). The predicted contribution of the unabsorbed sources is shown with a dotted line, while the absorbed sources are represented by dot-dashed lines (the labels are the logarithms of the corresponding hydrogen column densities).

**Fig. 3.** The EMSS AGNs redshift distribution (solid histogram) compared with the model prediction (dotted histogram).

**Fig. 4.** The ROSAT redshift distribution of the so far identified AGNs in five deep ROSAT fields with $S(0.5–2.0 \text{ keV}) \gtrsim 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (solid histogram) compared with the model predicted distribution (dotted line).

**Fig. 5.** The computed predicted counts in the hard (2-10 keV) energy range (solid line) compared with the GINGA fluctuation analysis results (dashed area) and with the HEA-1 A-2 AGNs surface density at $\sim 3 \cdot 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The predicted contribution of the unabsorbed sources is shown with a dotted line, while the contribution of absorbed sources is represented by dot-dashed lines (the labels are the logarithms of the corresponding column densities). The upper dashed line represents the summed contribution of AGNs and Clusters of Galaxies.

**Fig. 6.** The HEAO-1 A-2 (Piccinotti et al. 1982) AGN redshift distribution (solid histogram) compared with the model prediction (dotted line).

**Fig. 7.** The model predicted absorption distribution at the HEAO-1 A-2 flux limit (dotted line) compared with the observed absorption distribution of the AGNs in the Piccinotti et al. sample (solid line, from Turner & Pounds 1989).