ORIGIN OF THE X-RAY BACKGROUND AND AGN UNIFICATION: NEW PERSPECTIVES

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ABSTRACT
We critically review the basic assumptions of the standard model for the synthesis of the XRB in the light of new data from ultradeep surveys by Chandra and XMM, resolving major parts of it. Important constraints come in particular from the observed redshift distributions of faint hard X-ray sources – showing large excesses at redshifts (z ~ 0.8) much lower than expected by the synthesis models – and from their X/optical/IR SEDs combined with the IR counts of type-II AGN. We find that hard X-rays and the mid-IR appear to detect the same population of buried AGNs with peak emissivity around z ~ 1. This analysis, although supporting the general scheme which interprets the XRB as due to absorbed AGNs with broad N_H distributions, requires major revision of the other postulate of the XRB synthesis models: the AGN unification. We argue that the unification scheme based on a simple orientation effect fails at high redshifts, where galaxy activity is induced by strong interactions and mergers among gas-rich systems. This helps explaining the observational evidence that type-I and II AGNs follow different evolutionary patterns, with type-I quasars providing a very biased trace of this activity. Combined deep X-ray and IR surveys consistently find that the universe has experienced a violent phase of galaxy activity around z ~ 1, probably related with the assembly of massive galaxies. This has involved both star formation (primarily sampled in the IR) and obscured AGN fueling (as detected in hard X-rays and mostly responsible for the XRB): our analysis implies that roughly 10 to 20% of this activity has involved substantial AGN emission, this fraction likely reflecting the AGN/starburst duty cycle during the activation phase.

Key words: Active galaxies:infrared, active galaxies:X-ray, AGN:surveys, galaxies:evolution, galaxies:active

1 INTRODUCTION
The X-ray Background (XRB) has been interpreted since long time as the integrated contribution of photo-electrically absorbed AGNs with a broad N_H distribution and spread over a large redshift interval (Setti & Woltjer 1989). A variety of observational tests, including X-ray spectral analyses and optical follow-up of very faint hard X-ray sources detected by Chandra and XMM, have confirmed this assumption (Fiore et al. 2000; Hasinger et al. 2001; Barger et al. 2001; Alexander et al. 2001; Brandt et al. 2001).

A very natural complement to this model was to postulate that the distributions of type I and II fractions and of the corresponding N_H values are ruled by the AGN unification scheme (Madau, Ghisellini & Fabian 1994; Comastri et al. 1995). The ratio of obscured to unobscured objects was then taken to be ~ 4 : 1, as indicated by the statistics on local objects and consistent with the average covering factor of AGN tori (e.g. Maiolino & Rieke 1995). Further assumption by these early XRB models is that these population distributions remain unchanged in the past, with the X-ray luminosity functions evolving back in time following the evolution laws observed for the type-I category (e.g. Miyaji et al. 2000): a strong increase of the X-ray emissivities from z=0 to z~ 2 and a flattening thereof.

With these assumptions, the predictive power of the synthesis models was remarkable, as was the possibility to prove or disprove them. A first indication that some revisions of the above scheme should be considered has come from the very low fractions of luminous absorbed (type-II) quasars identified in faint X-ray samples (otherwise expected to be
more numerous than the classical quasars). An attempt to adapt the XRB models to this new evidence was done by Gilli et al. (2001), by increasing the evolution rate of the type-II population above that of type-I.

However, more radical revision of the synthesis models seems now required by recent results of spectroscopic identifications of faint hard X-ray sources by Chandra and XMM. At such faint limits substantial fractions of the XRB are resolved into sources. Rosati et al. (2002) and Hasinger (2002) show that the z−distribution for the absorbed AGNs are very different from the model predictions. The statistics reported by Hasinger (2002) are rich (∼300 redshifts) and complete (60%) and come from the deepest hard X-ray surveys ever achieved: the majority of the sources are found at z<1, contrary to the expectations.

We discuss in this Letter these unexpected results, also in the light of recent deep observations in the mid-IR revealing interesting properties of these faint X-ray sources found at moderate redshifts (Section 2). Section 3 compares the statistics of absorbed AGNs detected in hard X-rays and in the IR. Implications for the origin of the XRB and for the AGN unification are discussed in Section 4.

The combination of very deep imaging in the IR and X-rays and the exploitation of the global constraints set by the X-ray and IR backgrounds offer for the first time the opportunity to strongly constrain the whole phenomenon of hidden gravitational accretion. If the hard X-ray surveys sample the transmitted primary nuclear emissions, mid-IR surveys detect the re-radiated energy by the dusty circum-nuclear medium. A prediction of X-ray AGN counts based on the IR statistics is particularly useful if we consider that the population responsible for the XRB between 10 and 60 keV (where the bulk of the energy resides) cannot be presently observed in X-rays. We assume $H_0 = 50 \, \text{Km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$.

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**Figure 1.** Broad-band spectrum of the source ISO J105306+5728.2 at z=0.9 detected by ISO and XMM in the Lockman Hole (source #113 in Fadda et al. 2002). The XMM data are from Hasinger et al. (2001), analysed by Mucciarelli (2002). This source has the average z and spectrum ($N_H \simeq 2.5 \times 10^{23} \, \text{cm}^{-2}$) of those in common ISO and XMM surveys, and is typical of type-II AGNs in general (Norman et al. 2002; Franceschini et al. 2000). The fitting curve corresponds to our adopted SED for type-II AGNs, redshifted to z=0.9 and normalized to the 15 $\mu$m flux.

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**Figure 2.** Top panel: ratios of the X-ray (2-10 keV) to 15 $\mu$m luminosities as a function of the X-ray luminosity for ISO, XMM and Chandra sources in the Lockman Hole (filled) and HDFN (open squares), where $L_x = (5 \, \text{keV}) L_{5\text{keV}} \, \text{[erg/s/keV]}$; $L_{15\mu} = (15 \, \mu\text{m}) L_{15\mu} \, \text{[erg/s/} \mu\text{m]}$. $L_{5\text{keV}}$ is computed assuming a standard power-law spectrum. Bottom panel: same as top, vs. $L_{15\mu}$.

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### 2 RESULTS FROM RECENT COMBINED DEEP X-RAY AND IR SURVEYS

Surveys in the mid-IR even at moderately deep flux limits have revealed remarkable capabilities to detect the IR counterparts of very faint hard X-ray sources. Hornschemeier et al. (2001) have correlated Chandra and ISO 15 $\mu$m images by Aussel et al. (1999) in the HDF-North and found that in the inner top-sensitivity region 6 out of the 8 Chandra sources with $S_{2-10 \text{keV}} \geq 0.7 \times 10^{-15} \, \text{erg/s/cm}^2$ are detected above $S_{15\mu} = 100 \, \mu\text{Jy}$. Combined XMM and ISO surveys in the Lockman Hole area have been published by Hasinger et al. (2001) and Fadda et al. (2002): here 63% of the faint 5-10 keV sources are detected at 15 $\mu$m above 0.35 mJy. The large majority of these are clearly AGNs at 0.5<z<1.5, as suggested by their high luminosities ($L_{0.5-10\text{keV}} \simeq 10^{32} - 10^{45} \, \text{erg/s}$). Their optical colours and X-ray hardness ratios were used by Franceschini et al. (2002) to classify them as type-II or type-I AGNs: the observed relative fractions (∼3:1) and bolometric luminosities were found consistent with the unified model, although this result may not be significant due to the poor statistics and the complex and uncertain selection biases.

The optical-IR SEDs of type-II AGNs detected in the Lockman surveys and in the lensing cluster A2390 (Wilman et al. 2000; Franceschini et al. 2002) are consistent with these being completely buried AGNs (see one example in Fig. 1): the optical spectra reveal very red colours (often extremely red, R-K>4) which can be fit only as the redshifted emission by the host galaxy and show no scattered light from the AGN. The unification model, which assumes that the AGN sequence is due to different line-of-sight inclinations of the torus axis in a randomly oriented sample, does not seem to apply to this population.

Fadda et al. (2002) used these combined IR and X-ray survey data to quantify the relationship between the AGN emissions at the two wavelengths. The top panel in Fig. 2 plots the ratios $L_x/L_{15\mu}$ of the 5 keV to 15 $\mu$m luminosities as a function of $L_x$ for sources in common in the HDFN and Lockman, and reveals a clear correlation: the...
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A similar AGN fraction around 10% was also found among high-z sub-mm SCUBA sources observed in X-rays (Fabian et al. 2000; Hornschemeier et al. 2001; Barger et al. 2001).

If the AGN fraction keeps so stable, this means that the AGN activity originating by gravitational accretion and the starburst activity of stellar origin should be tightly related with each other.

The modellistic analysis of the IR counts by Franceschini et al. (2001) identified three different evolutionary components: (a) non-evolving quiescent galaxies dominating the IR counts at the bright fluxes, (b) evolving type-I AGNs as apparent in the UV-optical and soft X-ray quasar surveys, (c) and a population of strongly evolving active galaxies including starbursts and type-II absorbed AGNs (these latter making up ~ 15% of the evolving population). The contributions of these various components to the integral 15 μm counts are reported in the left panel of Fig. 3.

The model for the strongly evolving component, needed to reproduce the IR data (multi-wavelength counts, the IR background, LLFs), was based on the IRAS LLF and assumed a strong increase with z of the IR emissivity up to z ≃ 0.8 and a flattening thereof (we defer for all details on this model to Franceschini et al. 2001).

Starting from this, assuming that a fraction \( f_{\text{AGN}} = 15\% \) of these active galaxies host optically buried but X-ray loud AGNs and adopting for these the broad-band SED as the fitting line in Fig. 6, it is straightforward to estimate the contributions of these sources to the X-ray counts at various energies (the X-ray K-corrections are also computed using this same hard X-ray spectrum in the figure). The 2-10 keV X-ray counts for type-II AGNs computed in such a way are reported in the right panel of Fig. 3. While Fig. 4 shows the predicted counts at harder energies (5-10 keV). These model counts are consistent with the (large) observed fractions (> 50%) of X-ray sources with 15 μm counterparts reported by Hornschemeier et al. (2001) and Fadda et al. (2002). Note that our procedure does not account in detail for the observed spread in the X/IR flux ratio (Fig. 3), but we expect this would just moderately flatten the predicted counts.

As apparent in Figs. 3b and 4, our expectation is that IR-selected type-II AGNs provide increasingly important contributions to the X-ray counts at increasing energies (also confirmed by the larger fraction at the harder energies of identifications with faint IR sources, see Fadda et al. 2002). This implies that the counts are expected to become steeper at higher energies, in agreement with what observed by Rosati et al. (2002), while synthesis models have difficulties in reproducing this observed trend.

Our predicted contribution of type-II AGNs to the redshift distribution is reported in Fig. 3 (continuous line), providing a remarkably good fit to the data at \( z < 2 \). Type-I quasars, not included in our analysis, dominate the AGN population at \( z > 2 \), as well as the counts at \( S_{2-10} > 5 \times 10^{-15} \text{ erg/s/cm}^2 \). The excess of observed sources at \( z < 0.4 \) above the model prediction is due to the contribution of low-luminosity X-ray emissions by starburst galaxies, which are detectable at low redshifts.

The contribution of type-II AGNs to the XRB spectrum is reported in Fig. 4. This population provides < 50% of the XRB below 5 keV, but dominates it above. The lower average redshift of these sources compared with those dom-
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Figure 4. Integral counts of X-ray sources selected in the 5-10 keV band (Rosati et al. 2002) compared with our predicted contribution by type-II AGNs.

Figure 5. Redshift distributions from Hasinger (2002) of X-ray selected AGNs in deep Chandra and XMM surveys with flux limits between $S_{2-10} \sim 5 \times 10^{-16}$ and $\sim 1.5 \times 10^{-15}$ erg/s/cm$^2$, respectively. This is a representative sample of the X-ray population at the faint flux limits. The dotted line is a prediction based on the XRB synthesis model by Gilli et al. (2001) fitting the data only at $z > 1.5$. The continuous curve is our predicted contribution of type-II AGNs assuming a flux limit of $S_{2-10} = 8 \times 10^{-16}$ erg/s/cm$^2$, and provides a remarkable description of the data at $z < 2$, where the bulk of the XRB is produced.

4 DISCUSSION AND CONCLUSIONS

Not unexpectedly, the operations of a new generation of space observatories – Chandra, XMM-Newton and ISO – are dramatically improving our knowledge of the sources of the XRB. The current most popular view interprets the XRB and the X-ray source counts with evolutionary populations of absorbed and unabsorbed AGNs (the population synthesis models), assuming that the relationship between the two is ruled by the AGN unification scheme and is constant with cosmic time. We have discussed in this Letter evidence that this improved knowledge of the XRB sources requires major revision of some of the population synthesis assumptions.

On one side, the new observations have confirmed the model’s basic postulate of the XRB at high energies as due to absorbed AGNs: these sources are indeed detected in hard X-rays and the hot dust emission associated with their absorbing medium in the mid-IR (Wilman et al. 2000; Franceschini et al. 2002).

On the other end, a revision of the model is required by the evidence that the evolutionary histories of type-I and type-II AGNs are very different. A critical observable in this sense are the redshift distributions of faint Chandra and XMM X-ray sources, recently reported by Hasinger (2002). Although in these surveys the average identification fraction is $\sim 60\%$, the observed $z$-distributions do not appear to vary appreciably with the X-ray flux or the optical magnitude limits. Hasinger’s (2002) conclusion was that the distribution reported in Fig. 5 is representative of the whole population of faint X-ray sources responsible for the XRB. As illustrated in Fig. 5 and 7, the outcome of these identifications is inconsistent with predictions of population synthesis models.

Other hints of a possible difficulty for the latter come from the shapes of the counts at various X-ray energies, showing evidence for steeper slopes at increasing energies, not completely reproduced by the synthesis models (e.g. Rosati et al. 2002). Finally, the XRB spectral shape tends to appear harder than the population synthesis predictions.

To explore new routes for the interpretation of the XRB and the X-ray AGN statistics, we have first relaxed the link between the type-I and type-II objects by assuming that the former evolve as found in optical and soft X-ray surveys, while the latter follow an independent evolutionary history. We have then modelled the type-II AGNs starting from the evolutionary model of active galaxies needed to reproduce multwavelength IR counts (Franceschini et al. 2001) and exploiting the evidence (Fadda et al. 2002; Fabian et al. 2000; Barger et al. 2001) that a constant fraction $f_{AGN} \sim 15\%$ of this active population contains buried AGNs. We have combined this information with the observed flux ratios between the 15 µm and X-ray fluxes, and with a typical hard
faint X-ray fluxes, particularly at the high energies (Fig. 4).

The X-ray spectrum as found in the deep XMM surveys (Fig. 1) for K-correction computations.

With these assumptions, the expected integral counts of such hidden AGN population should continue steeply at high energies (Fig. 4). Correspondingly, these sources should dominate the XRB at > 10 keV, while contributing a decreasing fraction at lower energies (Fig. 4). Due to the fast rise of the IR emissivity to \( z \approx 0.8 \) and quick convergence thereof, the \( z \)-distributions of the faint hard X-ray sources are expected to have a maximum at this redshift of peak emissivity, hence explaining the outcomes of the spectroscopic surveys.

We emphasize that these predictions rest on our only assumption that the type-II AGN fraction \( (f_{\text{AGN}} \approx 15\%) \), observed down to \( S_{15\mu} = 0.1 \text{ mJy} \), does not drop immediately below. As a consequence, they should be quite robust.

In conclusion, combined deep X-ray and IR observations consistently find that the universe has experienced a violent phase of galaxy activity around \( z \approx 1 \), probably related with the assembly of massive galaxies. This activity generates massive stars (whose flux is mostly re-radiated in the IR) and fuels nuclear BH’s. Our analysis implies that roughly 10 to 20% of this activity involves substantial AGN emission mostly detectable as a faint hard X-ray flux. This fraction likely represents the duration of the AGN phase compared with that of the starburst during the activation process. While their IR re-radiated part can only contribute a minor fraction (~ 10%) of the cosmic IR background, their hard X-ray emission is largely responsible for the XRB.

Type-I quasars turn out to be very biased tracers of this activity, their epoch of maximal emissivity being quite displaced to \( z \geq 2 \). Absorbed and unabsorbed AGNs appear to form cosmologically distinct populations, as anticipated in Franceschini et al. (1993).

Consequently, the simple and attractive scheme trying to explain the XRB in the framework of the AGN unification scenario is ruled out by the present observations. The unification concept itself based on a simple orientation effect – which works locally in the presence of modest amounts of ISM in regular rotationally-supported flows perturbed by weak galaxy interactions – fails at higher redshifts. Galaxy activity during these past epochs is induced by strong interactions and mergers among gas-rich systems, which channel large amounts of absorbing gas around the nuclear source, completely covering it.

The different evolutionary patterns observed for type-I and II AGNs require an explanation. There may be an effect induced by luminosity, favouring the optically-thin quasar phase in relation with the highest-mass nuclear BH’s, quickly expelling the surrounding gas by radiation pressure. Then the two AGN categories may trace environments with different cosmic densities: type-I AGNs tracing the highest density peaks which evolve on faster cosmological timescales, and type-II AGNs, present in lower density concentrations, showing protracted activity down to much lower redshifts. Once again, significant complication of previous schemes and new imagination are required by new observational facts.

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