INFRARED SPACE OBSERVATORY INVESTIGATES THE NATURE OF EXTREMELY RED HARD X-RAY SOURCES RESPONSIBLE FOR THE X-RAY BACKGROUND

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ABSTRACT

We analyze very deep X-ray and mid-IR surveys in common areas of the Lockman Hole and the Hubble Deep Field–North (HDF-N) to study the sources of the X-ray background (XRB) and to test the standard obscured accretion paradigm. Observations with XMM-Newton and Infrared Space Observatory (ISO) of a substantial area in Lockman are particularly important to sample luminous—but relatively uncommon—obscured active galactic nuclei (AGNs). We detect a rich population of X-ray luminous sources with red optical colors, including a fraction identified with extremely red objects (R – K > 5) and galaxies with spectral energy distributions (SEDs) typical of normal massive ellipticals or spirals at z ∼ 1. The X-ray luminosities of these objects (L0.3−10 keV ∼ 1043−1045 ergs s⁻¹) indicate that the ultimate energy source is gravitational accretion, while the X-ray–to–IR flux ratios and the X-ray spectral hardness show evidence of photoelectric absorption at low X-ray energies. An important hint on the physics comes from the mid-IR data at 6.7 and 15 μm, which are well reproduced by model spectra of completely obscured quasars under standard assumptions and line-of-sight optical depths τ0.3μm ∼ 30–40. Other predictions of the standard X-ray background (XRB) picture, such as the distributions of intrinsic bolometric luminosities and the relative fractions of type I and type II objects (1 : 3), are also consistent with our results. Obscured gravitational accretion is then confirmed as being responsible for the bulk of the X-ray background, since we detect in the IR the downgraded energy photoelectrically absorbed in X-rays: 63% of the faint 5–10 keV XMM sources are detected in the mid-IR by Fadda et al. As discussed there, however, although as much as 90% of the X-ray energy production could be converted to IR photons, no more than 20% (and possibly less) of the cosmic IR background can be attributed to X-ray–loud AGNs.

Subject headings: cosmology: observations — galaxies: active — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation — galaxies: starburst

1. INTRODUCTION

The cosmic X-ray (XRB) and cosmic infrared (CIRB) backgrounds are now well-established cosmological components, including a substantial fraction of the integrated emissions by galaxies and active galactic nuclei (AGNs) over the Hubble time. While it is common wisdom that the XRB is largely due to past activity of AGNs with spectral properties determined by a wide range of column densities for the line-of-sight absorbing gas (e.g., Setti & Wolter 1989; Madau et al. 1994; Comastri et al. 1995; Giacconi et al. 2001), the sources of the CIRB are less well understood at present (Genzel & Cesarsky 2000).

Although these two components are so far apart in photon energies, an important relationship has been suggested to hold between them. The X-ray emission that is photoelectrically absorbed in type II AGNs dominating the XRB is expected to be downgraded in energy by the dusty circumnuclear medium and to emerge thermally reprocessed in the IR between a few and a few hundred microns (Efstathiou & Rowan-Robinson 1995; Granato, Danese, & Franceschini 1997). It has even been considered that, under rather extreme assumptions about the IR emissivity of type II objects and the fraction of Compton-thick sources, half so of the CIRB itself might be due to dust-reprocessed quasar emission (Almaini, Lawrence, & Boyle 1999; Fabian & Iwasawa 1999). If this is true, then both the XRB and also partly the CIRB would be manifestations of the same phenomenon of gas accretion in strong gravitational fields.

This simple, time-honored scheme for the origin of the hard XRB turned out to be difficult to prove, however. While classical type I quasars are easily detected in optical or soft X-rays at any z, the putative type II source population has remained elusive for long time, confined by photoelectric absorption and dust extinction into poorly sampled spectral domains—the hard X-rays and the mid- and far-IR. Tests of the type II population have been attempted, in particular, by correlating deep X-ray maps and catalogs of faint millimetric sources (e.g., Fabian et al. 2000; Hornschemeier et al. 2001; Barger et al. 2001). In general, however, X-ray sources are not detected in the millimeter, probably because of the lack of cold dust in these objects (the AGN
heats the circumnuclear medium to temperatures too high to be observable at such long wavelengths, even in high-redshift sources.

New powerful instrumentation from space is ultimately providing opportunities for direct tests of the standard synthesis model of the XRB and its obscured accretion paradigm. More than 80% of the XRB in the 2–8 keV band has been resolved into sources with very long exposures by Chandra in the Hubble Deep Field–North (HDF-N; Brandt et al. 2001) and the Chandra Deep Field–South (Giacconi et al. 2001). XMM has resolved ~60% of the XRB in the harder band between 5 and 10 keV (Hasinger et al. 2001). For the first time, representative samples of the sources of XRB are available for detailed physical inspection.

On the IR side, ISO has produced deep diffraction-limited imaging between 12 and 18 µm (ISO-CAM-LW3), allowing the detection of hot dust emission by sources at large redshifts.

ISO and Chandra observations in a small field of the lensing cluster A2390 have been discussed by Wilman, Fabian, & Gandhi (2000) with two sources in common. Two other Chandra sources in the HDF-N with faint LW3 counterparts are reported in Alexander et al. (2001). These X-ray/IR objects are quite faint and red in the optical and lack spectroscopic redshifts (for one object, Cowie et al. 2001 estimate \( z = 1.47 \) from optical spectroscopy). Wilman et al. (2000) point out that the bright mid-IR flux from two of these sources might be consistent with that expected from a circumnuclear dust torus. Although they exploit the deepest IR and X-ray data available, these results are limited by the very small area of few tens square arcminutes in total.

We discuss in this paper the properties of a substantial population of extremely red galaxies as counterparts of faint hard X-ray and IR sources based on combined deep observations by ISO and XMM of a 220 arcmin\(^2\) field in the Lockman Hole by Fadda et al. (2002). We exploit, in particular, their remarkable finding that a large fraction (63%) of the faint 5–10 keV XMM sources have relatively bright counterparts at 15 µm, which already hints that the IR detects in these sources the reprocessed energy absorbed in X-rays. We also consider deeper data in a smaller area in the HDF-N observed with Chandra. Section 2 summarizes the observational data on the samples. In § 3 we discuss the main physical properties of the sources based on the available photometry and optical IR, and X-ray colors. § 4 is dedicated to a discussion and the conclusions. We adopt \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_m = 0.3, \Omega_\Lambda = 0.7 \).

2. THE SAMPLE

2.1. Infrared, Optical, and X-Ray Data

Our reference sample consists of 24 sources selected by XMM-Newton in the total band 0.5–10 keV and detected by ISO-CAM in a common region of 220 arcmin\(^2\) located in the Lockman Hole. This area has been observed in the XMM-European Photon Imaging Camera Performance Verification (EPIC PV) phase (Hasinger et al. 2001) to flux limits of \( S_{0.5-2 \text{ keV}} = 3 \times 10^{-16} \text{ ergs cm}^{-2} \text{ s}^{-1}, S_{2-10 \text{ keV}} = 1.4 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}, \) and \( S_{2-10 \text{ keV}} = 2.4 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1}. \) The high-energy XMM response allowed measuring X-ray hardness ratios with small uncertainties; we will use in the following the quantity \( HR = (H-S)/(H+S) \), where \( H = S_{2-4.5 \text{ keV}}, S = S_{0.5-2 \text{ keV}}. \)

The ISO observations of the Lockman Hole have been performed in the ISO-CAM GT Program with the LW3 filter (12–18 µm) for a total of 60 ks and with ISO-CAM-LW2 (5–8.5 µm) for 70 ks. The 4 \( \sigma \) sensitivity limits are \( S_{15\mu} \approx 0.35 \text{ mJy for the LW3 observations and } S_{15\mu} \approx 0.3 \text{ mJy for LW2}. \) The analysis of these data is reported by Fadda et al. (2002), who exploit them to evaluate the AGN contribution to the CIRB background. A total of 22 XMM sources are detected in LW3; two more are detected in LW2 only, and seven are detected in both LW2 and LW3. \( V, R, I, \) and \( K \) magnitudes are reported with X-ray and IR data in Fadda et al. (2002; their Table 3).

We also exploit a sample of 24 very faint Chandra and ISO-CAM sources in a small area of 25 arcmin\(^2\) centered in the HDF-N and detected by Brandt et al. (2001) and Aussel et al. (1999) with sensitivity limits of \( S_{2-10 \text{ keV}} = 1.4 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \) and \( S_{15\mu} \approx 0.05 \text{ mJy}. \) The cross-correlation of the two Chandra and ISO catalogs is discussed in Fadda et al. (2002; their Table 4).

2.2. Redshift Measurements

Spectroscopic redshifts are available for all 24 HDF-N sources but two, while only 11 of the Lockman objects have spectroscopic measurements (mostly type I quasars; we operatively define a type I object as having either blue optical colors or broad-line emission in optical spectra; type II objects are the complementary population). For the remaining objects, we estimated photometric redshifts with a tool based on the PEGASE spectral synthesis code (Fioc & Rocca-Volmerange 1997). This allowed a large database of galaxy spectra to be synthesized, including the effects of dust extinction. The tool has been trained on samples of ISO galaxies in the HDF-S with excellent results (Franceschini et al., in preparation). For the typical SEDs of our sample objects, these estimates turned out to be rather insensitive to the amount of extinction. A comparison of our photometric estimates with Keck spectra obtained for three Lockman galaxies (see Lehmann et al. 2002; I. Lehmann et al. 2001, private communication) revealed the reliability of the procedure (errors \( \Delta z \approx 0.1 \), consistent with what is found in the HDF-S).

Photometric redshifts for 11 Lockman and 1 HDF-N sources have been obtained in this way. Data on four type II galaxies and best-fit solutions (thin solid lines) are reported in Figure 1.

3. PROPERTIES OF THE X-RAY/IR COMBINED SAMPLE

Figure 2 is a plot of the X-ray luminosities versus \( V-K \) colors in the broad 0.5–10 keV band for the combined HDF-N and Lockman samples. Evidently, the two cover different domains of the parameter space: the much fainter HDF-N data allow detection of low-luminosity emissions in moderate-redshift galaxies, part of which (those with \( L_{0.5-10 \text{ keV}} \leq 10^{41} \text{ ergs s}^{-1} \)) should be attributed to stellar processes. Only in Lockman is the survey area large enough to include a sizeable number of high-luminosity sources.

The \( V-K \) colors for the combined sample are very widely spread between \( V-K \approx 1 \) and 7. Objects classified as type I QSOs based on existing optical spectra (open squares) have blue colors (\( V-K \leq 4 \)) and high luminosities. Instead, the bulk of the newly discovered XMM sources (previously
undetected in the ultra deep ROSAT image of the field) have very red optical SEDs ($V-K > 4$, filled squares; Fig. 2). Several of these would be classified as extremely red objects (EROs, $R-K > 5$ in Fig. 3) by optical selection schemes (e.g., Daddi, Cimatti, & Renzini 2000).

Figure 3 shows a clear relationship between optical $R-K$ colors and the X-ray hardness ratios (HRs): while the blue type I objects have HR values consistent with standard X-ray photon indices $\Gamma \sim 2$ (HR $\sim -0.7$); the red sources display a wide range of HR values, including very hard X-ray spectra. Other Chandra deep surveys have found similarly red, optically normal galaxies hosting hard X-ray sources (Mushotzky et al. 2000; Fiore et al. 2000; Hornschemeier et al. 2001; Barger et al. 2001; see also Lehmann et al. 2001).

The important point illustrated by Figure 2 is that all the red ISO/XMM sources detected in Lockman have X-ray luminosities ($L_{0.5-10\,\text{keV}} > 10^{42}\,\text{ergs s}^{-1}$) high enough to be classified as AGNs or quasars rather than starbursts. For
comparison, none of the classical local starbursts (from M82 to Arp 220) approach these luminosity regimes; all those exceeding it host an AGN (Fadda et al. 2002).

Assuming that an AGN dominates the X-ray production, Mushotsky et al. (2000) and Fiore et al. (2000) propose the following three different interpretations for the red population: (a) AGNs hosting optically silent advection- or convection-dominated accretion flows (Ball, Narayan, & Quataert 2001; Di Matteo et al. 2000); (b) a kind of red BL Lac objects; and (c) heavily obscured AGNs. The last hypothesis in particular constitutes the basic assumption of standard models of the XRB (see §1). Our combined X-ray/optical/mid-IR survey in Lockman offers a way to test these various hypotheses.

In particular, we detect with ISO mid-IR emissions from a substantial fraction (33%) of all Lockman XMM sources (Fadda et al. 2002). This fraction increases to 63% of the X-ray sources selected at very hard energy bands (5–10 keV). X-ray objects undetected in the IR are consistent with also belonging to the same population but fainter than the ISO-CAM limits. For the few sources for which we have both 6.7 and 15 μm flux detections (two are reported in Fig. 1), the LW3/LW2 flux ratios are inconsistent with being due to a starburst and require an AGN-like power source.

We have compared in Figure 1 predicted SEDs for dusty quasars (dashed lines) with our observed optical/near-IR/mid-IR data. We have used radiative transfer models taken from Granato et al. (1997) and Andreani, Franceschini, & Granato (1999), assuming a central pointlike source surrounded by a dust distribution. The radius of the innermost dust shell is defined by the grain sublimation condition (T ~ 1000), which sets the short-wavelength limit of dust emission, while the outermost radius is a free parameter affecting the spectrum at the longest wavelengths. Following Andreani et al. (1999), we have represented a toroidal dust distribution as a “flared” disk with a fixed covering factor f = 0.7 and a variable equatorial optical depth τ0.3μν. Our observed SEDs for type I QSO spectra are fit by solutions assuming pole-on (Θ = 0°) or intermediate viewing inclinations.

Dashed lines in Figure 1 are solutions with Θ = 90° (edge-on view) and equatorial optical depths of typically τ0.3μν ≈ 30–40, providing good fits to the observed 6.7 and 15 μm fluxes for type II QSOs. An important result of these fits is that, given the very red optical spectra of these sources, the contribution by scattered light from the primary continuum should be minimal or absent (the parameter Θ in our model has to be 90°; see also Wilman et al. 2000). Unfortunately, we lack sensitive submillimeter observations in the Lockman area to constrain the long-wavelength tail of the spectra for the X-ray/IR AGN population; consequently, the maximum radius of the dust distribution and the dust masses are presently essentially unmeasurable. On the other hand, data at 6.7 and 15 μm (in addition to those in optical/NIR for type I objects) provide a robust constraint on the bolometric source luminosity (the assumption of a central illuminating source implies in particular that the bulk of the energy is emitted between 5 and 40 μm for type II QSOs). We report in Figure 4 as a function of z our estimated bolometric luminosities between 0.1 and 1000 μm (the X-ray flux would add only a minor contribution; see Fig. 5 below) for type I and type II AGNs in Lockman (open and filled squares, respectively). This plot indicates that there is no systematic difference between the bolometric emissions of the two classes at the various redshifts. This is in agreement with the standard unification paradigm.

The X-ray flux has, on the contrary, a sensitive dependence on the column density of the obscuring medium. Figure 5 reports the fraction of radiation emitted in the various X-ray bands over the bolometric emission and shows that type II QSOs are systematically fainter emitters than type I in soft X-rays; the difference is reduced in the harder bands. Figures 3 and 5 require column densities of the X-ray–absorbing gas for type II objects in the range
$N_H \approx 10^{22} - 10^{23} \, \text{cm}^{-2}$, which is not inconsistent with the extinction of $\tau_{3.4 \mu m} \approx 30-40$ inferred from the fits to the IR spectra. At the same time, Figure 5 implies that the contribution of the X-ray energy to the bolometric luminosity cannot be dominant; the bulk of the QSO primary energy is produced in the UV-optical, which is consistent with the average type I spectrum by Elvis et al. (1994).

Finally, the completeness and large mid-IR identification fraction of our XMM/ISO sample in Lockman also allow a statistical test of XRB models. Again in rough agreement with the unification scheme (e.g., Lawrence 1991), the ratio of the number of type II to type I QSOs appearing in Figure 4 is $\approx 3$ within the redshift interval $0.5 < z < 1.5$ of maximal sensitivity for our combined X-ray/IR survey.

4. CONCLUSIONS

We have exploited very deep X-ray and mid-IR survey data obtained for the first time by ISO, XMM-Newton, and Chandra in common areas of the Lockman Hole and HDF-N to test standard models for the origin of the XRB and the supposed dust-obscured accretion phenomenon. The large surveyed area in Lockman was essential to detect significant numbers of luminous obscured AGNs too rare to be appropriately sampled in the small HDF-N field.

This combined X-ray/IR survey detects normal type I quasars with standard optical, IR, and X-ray properties (blue colors, power-law X-ray, and IR spectra). In addition, a rich population of X-ray luminous sources with red optical colors is identified, roughly half of which would be classified as extremely red objects ($R-K > 5$) in the optical. Their optical SEDs are those typical of normal massive elliptical or spiral galaxies at the appropriate $z$. X-ray sources with similarly red counterparts have also been occasionally reported (Fiore et al. 2000; Mushotzky et al. 2000; Barger et al. 2001; Lehmann et al. 2001; Cowie et al. 2001).

While the ultimate nuclear energy source in these objects has to be quasar-like gravitational accretion, given the large X-ray luminosities ($L_{0.5-10 \text{ keV}} \approx 10^{43} - 10^{44} \, \text{ergs s}^{-1}$), an important hint on the physics comes from the mid-IR data at 6.7 and 15 $\mu$m. These data are well reproduced by model spectra of obscured quasars under standard assumptions and line-of-sight optical depths of typically $\tau_{3.4 \mu m} = 30-40$. A detailed spectral analysis, including radiative transfer in the IR and Comptonization effects in the X-rays, is in progress (G. L. Granato et al. 2002, in preparation).

Altogether, we find that various predictions of the standard XRB picture (e.g., Madau et al. 1994; Comastri et al. 1995) are met by our analysis within the uncertainties implied by the small number of sources. In particular, the bolometric luminosity distributions do not appear to be systematically different between type I and type II objects, and their observed relative fractions are consistently close to the canonically assumed value of 1 : 3. Also, the X-ray luminosities and hardness ratios of type II objects show evidence of photoelectric absorption at low X-ray energies.

We believe that these results provide important new evidence that obscured gravitational accretion in massive normal-looking galaxies is responsible for the bulk of the X-ray background: the energy that is absorbed in X-rays (that could be as much as 80%-90% when averaged over the whole population producing the XRB; see Fabian & Iwasawa 1999) we find to be downgraded in photon energy and re-emitted in the IR, as expected. In spite of this, and following the correlation analysis of deep X-ray and IR images by Fadda et al. (2002), probably no more than 20% (and possibly much less; see Elbaz et al. 2002) of the cosmic IR background can be attributed to X-ray–loud AGNs.

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