THE NATURE OF LUMINOUS X-RAY SOURCES WITH MID-INFRARED COUNTERPARTS

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ABSTRACT

We investigate the luminous X-ray sources in the Lockman Hole (LH) and the extended Groth strip (EGS) detected at 24 μm using the Multiband Imaging Photometer (MIPS) and also with the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope. We assemble optical/infrared spectral energy distributions (SEDs) for 45 X-ray/24 μm sources in the EGS and LH. Only about one-quarter of the hard X-ray/24 μm sources show pure type 1 active galactic nucleus (AGN) SEDs. More than half of the X-ray/24 μm sources have stellar emission–dominated or obscured SEDs, similar to those of local type 2 AGN and spiral/starburst galaxies. One-third of the sources detected in hard X-rays do not have a 24 μm counterpart. Two such sources in the LH have SEDs resembling those of S0/elliptical galaxies.

The broad variety of SEDs in the optical-to-Spitzer bands of X-ray–selected AGNs means that AGNs selected according to the behavior in the optical/infrared will have to be supplemented by other kinds of data (e.g., X-ray) to produce unbiased samples of AGNs.

Subject headings: galaxies: active — galaxies: fundamental parameters — infrared: galaxies — X-rays: galaxies

Online material: color figure, machine-readable table

1. INTRODUCTION

The very rapid evolution of quasars from $z \sim 2$ to the present (Boyle et al. 1987) raises the question of whether any properties of these sources other than space density have changed over this interval. One way to probe changes in the active galactic nucleus (AGN) population is to compare spectral energy distributions (SEDs) over a broad frequency range as a function of redshift. The SED of an active galaxy reflects the presence of the underlying AGNs, plus the luminosity of the host galaxy stellar population, the reddening of the AGNs, and the role of star formation, all in different frequency regimes. SED determination in large samples of high-z AGNs using imaging detectors is therefore an efficient way to survey for evolutionary trends in quasars and AGNs and in their host galaxies.

A number of trends might be expected. Will we be able to confirm predictions that the relative number of obscured AGNs was higher at large look-back times than now, to fit models of the X-ray background (e.g., Gilli et al. 1999)? AGN activity may be triggered by gas inflow caused by galaxy interactions. Interactions also trigger starbursts: will we find that an elevated rate of star formation in the host galaxy is a typical characteristic of distant AGNs? Will younger AGN host galaxies have more material in their interstellar medium (ISM) than current-epoch ones, causing greater extinction of their nuclei?

To probe such questions, we have used the Infrared Array Camera (IRAC; Fazio et al. 2004), the Multiband Imaging Photometer (MIPS; Rieke et al. 2004), and ancillary data to assemble SEDs for AGNs in the Lockman Hole (LH) and extended Groth strip (EGS). We have made use of deep X-ray images to locate the AGNs. For this initial survey, we wanted an unambiguous detection of an infrared (IR) excess to make SED classification robust. We have included objects detected at 24 μm, although we briefly discuss galaxies not detected at 24 μm. We compare the results with SEDs of a sample of nearby ($z < 0.12$) hard X-ray–selected AGNs that are bright in the mid-IR and hence nominally similar to the sources identified in the deep Spitzer/X-ray fields. This comparison allows us to make tentative identifications of trends in the AGN/host galaxy behavior from the typical redshift of the AGN in the survey fields ($z \sim 0.2–1.6$) to the present.

2. SPITZER OBSERVATIONS

We have obtained 24 μm MIPS observations of two fields in the LH: primary field (area of $5' \times 5'$) at R.A. = $10^h52^m$ and decl. = $57'25''$ (J2000.0), and parallel field (area of $7' \times 6'$) at R.A. = $10^h52^m$ and decl. = $57'37''$. We also obtained MIPS
observations of the EGS overlapping with the Chandra observation (≥180 arcmin²; see next section) at R.A. = 14h17m and decl. = 52°28’. Gordon et al. (2004), Egami et al. (2004), Papovich et al. (2004), and Le Floc’h et al. (2004) describe the data reduction and photometry in detail. The astrometric uncertainties of Spitzer observations are less than 1″. The 80% completeness limits at 24 μm are 0.17 and 0.1 mJy for the LH primary and parallel fields, respectively, and 0.11 mJy for the EGS (Papovich et al. 2004).

The LH primary field and the EGS were observed by IRAC at 3.6, 4.5, 5.8, and 8 μm. The data reduction is discussed in Huang et al. (2004) for the LH and in P. Barmby et al. (2004, in preparation) for the EGS. Counterparts of all MIPS and X-ray sources were nearly pointlike, and the photometry used circular apertures and the standard point-source calibration (see Huang et al. 2004).

3. X-RAY OBSERVATIONS

The *XMM-Newton* images of the LH were formed from seven data sets taken in 2000 and 2001 to a total integration time of 150 ks. The data cover entirely both the primary and parallel 24 μm MIPS fields. We produced images in the energy bands 0.2–0.5, 0.5–2, 2–5, and 5–10 keV and searched for sources simultaneously in an iterative process to optimize the background model and thereby the sensitivity. In the LH we have detected 35 *XMM-Newton* sources with X-ray fluxes down to *f* 0.5–10 keV ≃ 10⁻¹⁵ erg cm⁻² s⁻¹. The astrometric uncertainties are better than 1″ for bright sources and less than 3″ for the faintest sources.

For the EGS, three *Chandra* ACIS data sets were taken from the CXC archive with an exposure time of 131 ks. We searched for sources separately in four bands (0.5–8, 0.5–2, 2–8, and 4–8 keV) using *waredetect*. In the overlapping area between the *Chandra* and MIPS fields we have detected 77 sources in the full band with fluxes down to *f* 0.5–8 keV ≃ 10⁻¹⁵ erg cm⁻² s⁻¹. Of these, 40 are detected in the 2–8 keV band. Astrometric uncertainties are 1″–2″, where the high value is for sources at large off-axis angles.

4. CROSS-CORRELATION OF X-RAY AND 24 μM SOURCES

Taking into account the astrometric uncertainties, we used radii of 2″ and 3″ for matching 24 μm sources to *Chandra* and *XMM-Newton* sources, respectively. Within the LH approximately 57% of the *XMM-Newton* sources are detected at 24 μm. Furthermore, 75% of LH X-ray sources with *f* 0.5–10 keV > 10⁻¹⁵ ergs cm⁻² s⁻¹ have 24 μm counterparts. In the EGS approximately 50% of *Chandra* sources have a 24 μm counterpart, and this fraction is ≥60% for sources detected in the hard (2–8 keV) band. Taking into account the surface density of 24 μm sources (80% completeness limit), the probability of a chance match with an X-ray source is 2%–3% for both the LH and EGS.

5. ACTIVITY CLASSIFICATION

Hard X-ray–to–mid-IR flux ratios are known to be different for AGN-dominated galaxies and starbursts in the local universe and can be used to assess if the AGN emission is dominant in the mid-IR. Figure 1 shows the 24 μm fluxes versus 2–10 keV X-ray fluxes for our sample. As a comparison we plot the extrapolation to fainter fluxes of the region occupied by hard X-ray–selected AGNs from Piccinotti et al. (1982) with detected mid-IR emission and z < 0.12. This sample should be nominally similar to the sources studied here. The effect of increasing redshift on the observed ratio of hard X-ray to mid-IR fluxes is small for AGNs with low X-ray column densities, but it will make this ratio increase for Compton thick AGNs at higher z (Alexander et al. 2001). For starbursts at z < 1, Alexander et al. (2001) predict just a slight decrease of the ratio of hard X-ray to mid-IR emission for increasing z. The majority of sources in this study appear to derive their X-ray emission from powerful AGNs because they lie in the region of Figure 1 populated by local hard X-ray–selected AGNs extrapolated to fainter fluxes (Fadda et al. 2002; Franceschini et al. 2002; Alexander et al. 2001) and because for our sample the z-dependent effects (see next section) in this figure are small.

Also shown in Figure 1 are sources in the Chandra Deep Field–South (CDF-S) from Rigby et al. (2004). The greater sensitivity of the CDF-S X-ray data (compared with the EGS and LH) results in detection of relatively weaker X-ray sources that either have a greater portion of their luminosity generated from star formation or are obscured in the X-rays (compare to Fig. 1 in Alexander et al. 2002). Indeed, spectroscopic observations of faint sources detected in the deepest X-ray surveys to date indicate that these are starbursts and low-redshift normal galaxies (Barger et al. 2003).

All X-ray sources in the LH not detected at 24 μm appear to be consistent with being type 1 AGNs or S0/elliptical galaxies (see next section). Alexander et al. (2002) found that most X-ray–emitting galaxies in the Hubble Deep Field–North (HDF-N) with no mid-IR emission are classified...
spectroscopically as S0/elliptical galaxies; that is, they showed no emission-line evidence for activity.

X-ray hardness ratios can be used to distinguish between low-obscuration (soft) and high-obscuration (hard) AGNs (e.g., Hasinger et al. 2001; Mainieri et al. 2002; Szokoly et al. 2003). This X-ray classification agrees with the spectroscopic classification of type 1 (broad lines) and type 2 (narrow lines) AGNs, respectively. Based on their hard-to-soft flux ratios, there are approximately equal numbers of type 1 and type 2 AGNs among the hard X-ray–selected sources in the LH and EGS with and without mid-IR emission. This finding is in contrast with the local sample of hard X-ray–selected AGNs of Piccinotti et al. (1982), where most of the sources are classified as type 1 AGNs (70%–80% for AGNs at z < 0.12).

6. SPECTRAL ENERGY DISTRIBUTIONS

We have collected optical and near-IR data for all the X-ray/24 \( \mu \)m sources in the EGS and LH (Cristóbal-Hornillos et al. 2003; Wilson 2003). The observations have been band merged with the Spitzer data as described by Le Floc’h et al. (2004). We used spectroscopic and photometric redshifts for five X-ray sources in the LH (Lehmann et al. 2001; Mainieri et al. 2002) and nine sources in the EGS (from the Deep Extra-galactic Evolutionary Probe and Miyaji et al. 2004). For the remaining sources, we estimated photometric redshifts where possible from the stellar spectral peak at \( \lambda_{\text{rest}} = 1.6 \) \( \mu \)m (see Le Floc’h et al. 2004).

We then classified the X-ray/24 \( \mu \)m sources according to the shape of their SEDs. Sources that are relatively flat in \( f_{\nu} \) from the optical through the mid-IR, resembling the median QSO SED of Elvis et al. (1994), are termed type 1 AGNs (Fig. 2). Sources that are relatively flat in \( f_{\nu} \) at the IRAC and MIPS wavelengths but whose spectra drop toward the blue are consistent with being obscured AGNs. Although the redshifts cannot be estimated well for these two types of objects, the SEDs are distinctive and the classification unambiguous. Galaxies with decreasing \( f_{\nu} \) in the range \( \lambda_{\text{obs}} = 3.6–8 \) \( \mu \)m and a significant stellar contribution in the optical and near-IR resemble type 2 AGNs or spiral/starburst galaxies, and their SEDs appear intermediate between that of Circinus and that of M82 (Fig. 2). The majority of these sources have spectroscopic/photometric redshifts in the range \( z = 0.2–1.6 \). A few galaxies have increasing \( f_{\nu} \) for \( \lambda_{\text{obs}} \geq 3.6 \) \( \mu \)m and look similar to local ultraluminous infrared galaxies (ULIRGs; Fig. 2). Table 1 lists the X-ray properties and SED types for those EGS sources with well-determined SEDs (Fig. 2).

For the 45 X-ray/24 \( \mu \)m sources in our sample with SED type, we find that 10 can be classified as pure type 1 AGN SED, 27 as obscured AGN, type 2 AGN, or spiral/M82-like SED, and eight as ULIRG-like SED. In the absence of quality X-ray data, the optical–to–mid-IR SED does not unambiguously identify AGN activity. This will complicate efforts to identify complete samples of AGNs via optical and Spitzer photometry.

Figure 3 shows the hard-to-soft X-ray flux ratio distributions for the three different types of SEDs. All galaxies with type 1 AGN-like SEDs show a range of hard-to-soft flux ratios consistent with those of spectroscopically classified type 1 AGNs (that is, broad-line AGNs). Galaxies with obscured AGNs, type 2 AGNs, and spiral/M82-like SEDs include a fraction of sources that would be classified as type 1 AGNs based on their X-ray properties. ULIRG SED objects appear to have a tendency toward softer X-ray flux ratios characteristic of type 1 AGNs.

More than half of the bright X-ray/24 \( \mu \)m sources in our sample have SEDs dominated by stellar emission or show a significant level of obscuration. This is consistent with the finding that 40%–60% of the Chandra-selected galaxies have optical spectra with no signs of nuclear AGN activity (e.g., Barger et al. 2001; Hornschemeier et al. 2001). Many of these galaxies have colors of old stellar populations (Barger et al. 2003). It is possible that their AGN emission lines are overwhelmed by stellar light (see Moran et al. 2002). Others appear highly absorbed in X-rays (Barger et al. 2001; see also Fig. 3); if a similar level of absorption applies to their emission lines, these lines will be undetectable. In agreement with the finding that spectroscopic type 1 (broad lines) AGN behavior is relatively
### TABLE 1

**Chandra Positions and Fluxes and SED Types for X-Ray Galaxies in the EGS with Well-determined SED Types**

| R.A. (deg) | Decl. (deg) | $f$(0.5–8 keV) (ergs cm$^{-2}$ s$^{-1}$) | Error (ergs cm$^{-2}$ s$^{-1}$) | $d$ | $f$(0.5–2 keV) (ergs cm$^{-2}$ s$^{-1}$) | Error (ergs cm$^{-2}$ s$^{-1}$) | $d$ | $f$(2–8 keV) (ergs cm$^{-2}$ s$^{-1}$) | Error (ergs cm$^{-2}$ s$^{-1}$) | SED Type |
|------------|------------|---------------------------------|-------------------------------|---|---------------------------------|-------------------------------|---|---------------------------------|-------------------------------|-----------|
| 214.189607... | 52.485142  | 1 0.244E−13 0.237E−14 | 1 0.425E−14 0.514E−15 | 0 0.232E−13 | ... | ULIRG |
| 214.333361... | 52.416680  | 1 0.573E−14 0.114E−14 | 1 0.713E−15 0.219E−15 | 1 0.471E−14 0.146E−14 | ... | ULIRG |
| 214.486947... | 52.523481  | 1 0.809E−14 0.129E−14 | 1 0.131E−14 0.296E−15 | 1 0.522E−14 0.162E−14 | ... | ULIRG |
| 214.355623... | 52.595469  | 1 0.535E−14 0.133E−14 | 1 0.107E−14 0.287E−15 | 0 0.770E−14 | ... | Type 1 AGN |
| 214.222970... | 52.352189  | 1 0.196E−13 0.299E−14 | 0 0.565E−14 | ... | 0 0.225E−13 | ... | Type 1 AGN |

**NOTES.**—In this table we list those EGS galaxies with well-determined SED types and with an estimate of the redshift, that is, galaxies plotted in Fig. 2. Col. (1): *Chandra* R.A. (J2000.0). Col. (2): *Chandra* decl. (J2000.0). Col. (3): Detection in the full (0.5–8 keV) band (1 = detection; 0 = 3 $\sigma$ upper limit). Col. (4): Flux in the full (0.5–8 keV) band. Col. (5): Error of flux in the full (0.5–8 keV) band. Col. (6): Detection in the soft (0.5–2 keV) band (1 = detection; 0 = 3 $\sigma$ upper limit). Col. (7): Flux in the soft (0.5–2 keV) band. Col. (8): Error of flux in the soft (0.5–2 keV) band. Col. (9): Detection in the hard (2–8 keV) band (1 = detection; 0 = 3 $\sigma$ upper limit). Col. (10): Flux in the hard (2–8 keV) band. Col. (11): Error of flux in the hard (2–8 keV) band. Col. (12): SED type (see Fig. 2 and text). Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.
rare (e.g., Hornschemeier et al. 2001), the fraction of type 1 AGN SED–dominated X-ray sources in our sample is small. About one-third of the sources with emission in hard X-rays are not detected at 24 μm. Figure 4 shows two such X-ray sources in the LH whose SEDs are consistent with being S0 or elliptical galaxies, with no evidence for the presence of hot dust. Based on findings by Alexander et al. (2002) for the HDF-N, a significant fraction of X-ray sources detected by IRAC but not by MIPS at 24 μm are likely to have SEDs like elliptical and S0 galaxies.

To put these trends on a more quantitative basis, we have used local hard X-ray–selected AGNs from Piccinotti et al. (1982) and Kuraszkiewicz et al. (2003) to construct a comparison sample consisting of all galaxies with z < 0.12 and a mid-IR 25 μm flux density greater than 100 mJy. In this local sample, 19 of 32 galaxies, more than half the sample, would be classified by us as type 1 AGNs based on their SEDs. From the hard X-ray/24 μm detections in the EGS and LH, we classify seven of 29 as having SEDs resembling those of type 1 AGNs. Since only two-thirds of sources with hard X-ray emission were detected at 24 μm, some caution is needed in interpreting this result. However, since a significant fraction of the X-ray sources without 24 μm detections are likely to have S0/elliptical-type SEDs, it is possible that there is a trend away from pure type 1 AGN behavior with increasing redshift. This possibility will be probed by further Spitzer observations of deep X-ray fields that are currently under analysis.

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