STUDYING FAINT ULTRA-HARD X-RAY EMISSION FROM AGN IN GOALS LIRGS WITH SWIFT/BAT

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Received 2012 September 7; accepted 2013 January 15; published 2013 February 21

ABSTRACT

We present the first analysis of the all-sky Swift Burst Alert Telescope (BAT) ultra-hard X-ray (14–195 keV) data for a targeted list of objects. We find that the BAT data can be studied at three-times-fainter limits than in previous blind detection catalogs based on prior knowledge of source positions and using smaller energy ranges for source detection. We determine the active galactic nucleus (AGN) fraction in 134 nearby (z < 0.05) luminous infrared galaxies (LIRGs) from the GOALS sample. We find that LIRGs have a higher detection frequency than galaxies matched in stellar mass and redshift at 14–195 keV and 24–35 keV. In agreement with work at other wavelengths, the AGN detection fraction increases strongly at high IR luminosity with half of the high-luminosity LIRGs (50%, 6/12, log LIR/L⊙ > 11.8) detected. The BAT AGN classification shows 97% (37/38) agreement using Chandra and XMM-Newton AGN classification using hardness ratios or detection of an iron Kα line. This confirms our statistical analysis and supports the use of the Swift/BAT all-sky survey to study fainter populations of any category of sources in the ultra-hard X-ray band. BAT AGNs in LIRGs tend to show higher column densities with 40% ± 9% showing 14–195 keV/2–10 keV hardness flux ratios suggestive of high or Compton-thick column densities (log N_H > 24 cm^-2), compared to only 12% ± 5% of non-LIRG BAT AGNs. We also find that using specific energy ranges of the BAT detector can yield additional sources over total band detections with 24% (5/21) of detections in LIRGs at 24–35 keV detected at 14–195 keV.

Key words: galaxies: active – X-rays: galaxies

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The Swift Burst Alert Telescope (BAT) survey with over 500 active galactic nuclei (AGNs) has revolutionized our study of the ultra-hard X-ray sky (Tueller et al. 2010), but is still limited to bright (F_14-195 > 10^{-11} erg s^{-1} cm^{-2}) objects in a blind survey. However, the stability of the instrument and the Gaussian nature of the noise, along with its wide energy range, allow the detection at fainter limits for a well-defined, moderate-sized sample of objects. For the first time, we use this property to study the AGNs in luminous infrared galaxies (LIRGs; log LIR/L⊙ > 11.0).

The nature of the IR (8–1000 μm) emission and its relation to star formation in AGNs are still not well understood. Past studies of samples of LIRGs have suggested, based primarily on optical and IR AGN indicators, that the dominant power source is star formation and AGN activity is more common in luminous sources (e.g., Veilleux et al. 1995). Recent studies used a variety of mid-IR spectral diagnostics and X-ray observations (Ptak et al. 2003; Teng et al. 2005; Veilleux et al. 2009; Teng & Veilleux 2010; Petric et al. 2011) to determine the AGN contribution. However, contamination from star formation and obscuration by dust and gas are problematic. Additionally, studies of AGNs in the hard X-rays have shown the existence of a large fraction of AGNs not showing Spitzer/IRAC AGN indicators (e.g., Donley et al. 2012) and some AGNs are not optically detected (Koss et al. 2011a, 2012). Since a significant fraction of X-ray-selected AGNs are in LIRGs (Koss et al. 2011b), an ultra-hard X-ray survey of LIRGs might come to different conclusions than those derived at lower energies.

The ultra-hard X-rays (>15 keV) are much less sensitive to obscuration in the line of sight than soft X-ray or optical wavelengths and are biased only against highly Compton-thick AGNs (Burlon et al. 2011). This band is also free from contamination from star formation that is significant in the soft X-rays (<5 keV). Additionally, in Compton-thick AGNs the radiation below 10 keV is almost completely absorbed in the X-rays, whereas a broad Compton reflection hump appears in the >15 keV continuum (Reynolds 1999). Thus, ultra-hard X-ray observations are an important complement to lower energy X-ray data.

We use the most sensitive all-sky ultra-hard X-ray survey from the Swift/BAT instrument to search for AGN emission in LIRGs. Previous studies using the INTEGRAL satellite stacked emission from a large sample of IRAS bright galaxies and found no AGN detection (Walter & Cabral 2009). Additionally, past BAT AGN catalogs generated >4σ sources from “blind” detections (e.g., Tueller et al. 2010). To achieve higher sensitivities, we identify AGNs (see Section 2.2) based on the prior knowledge of source positions and search in energy bands where we expect the AGN emission to be brightest. We adopt a standard cosmology (Ω_m = 0.3, Ω_Λ = 0.7, H_0 = 70 km s^{-1} Mpc^{-1}) to determine distances.

2. SAMPLE SELECTION AND DERIVED QUANTITIES

2.1. Sample of LIRGs and ULIRGs

We selected a sample of nearby LIRGs (z < 0.05) in the Earth’s Northern Hemisphere (decl. > -25) from the Great Observatories All Sky LIRG Survey (GOALS; Armus et al. 2009). In this redshift range, we are sensitive to X-ray luminosities of L_{14-195 keV} > 10^{42.0} erg s^{-1}. This limit effectively detects AGNs since it is 10 times larger than the maximum known emission from a starburst galaxy (e.g., M82, log L_{14-195 keV} = 40.8 erg s^{-1}). Since single temperatures and
spectral energy distribution (SED) templates can overestimate IR luminosities (Casey 2012), we recomputed GOALS IR luminosities based on SED fitting using IRAS data and a model joining a modified, single dust temperature graybody that approximates hot-dust emission from AGN heating. We have limited our sources to be outside the Galactic plane ($b > 10^\circ$) because of source confusion in IRAS and Swift, as well difficulty measuring stellar masses because of high levels of optical extinction.

We have also limited our sample because in the low-resolution BAT detector, source confusion from nearby bright AGNs can occur. For blind source detection, Ajello et al. (2009) estimated a confusion radius of 5.5$^\circ$ at signal-to-noise ratio $S/N = 2, 3, 8$ at $S/N = 3$, and 2.8 at $S/N = 4$. We use a conservative approach and exclude all detections within 15 of BAT catalog sources. This excludes seven LIRGs from our study. NGC 232 and NGC 838 are in merging galaxy groups with a nearby (<2') bright BAT-detected AGN companion. Additionally, UGC 3608 is 5.1 from a nearby ROSAT X-ray source, 1RXS J065711.8+462731. A 1.5 ks X-Ray Telescope (XRT) observation suggests that the majority of the flux is coincident with this ROSAT source. IRAS F03217+4022 and UGC 02717 near a bright BAT AGN, IRAS 03219+4031 at 8.5$^\circ$ and 7$^\circ$ separation, respectively. Finally, NGC 2524 is near a bright BAT AGN Mrk 0622 at 10.7$^\circ$. This leaves our total LIRG sample with 134 objects.

2.2. Faint BAT Source Detection in the GOALS Sample

In Swift/BAT, the detector noise distribution is a Gaussian function centered at zero significance. Real astrophysical sources show a tail in the distribution at positive significances. Significant detections in the blind BAT detection catalogs are defined at >4.8 $S/N$ to ensure zero false sources caused by random fluctuations in a large sample ($\approx$500). Source detection is performed on a map weighted to the Crab Nebula, using a single average map of all eight energy bins between 14 and 195 keV.

However, many real astrophysical sources are below 4.8 $S/N$ and can be studied based on known positions of galaxies and by studying energy range where the source population is brightest. Using the 24–35 keV energy bin for instance, we are more sensitive to the reflection component of obscured AGNs. We use the BATCELLEDTECT software, which performs a sliding cell method to locate regions of the image that are significantly different from the background. We simultaneously fit all of the 1092 previously detected BAT AGNs in the 70 month catalog along with the LIRGs in the 14–195 keV band and 24–35 keV band. Additionally, we select a comparison sample of 1000 galaxies matched in stellar mass and redshift from the NASA-Sloan Atlas (Blanton et al. 2011). To compute the stellar mass of the LIRGs and galaxy control sample, we use ugriz photometry following Koss et al. (2011b) using the software kcorrect version 4.2 and Sloan Digital Sky Survey (SDSS) imaging. For galaxies in close mergers, we follow Koss et al. (2010) and estimate the stellar mass from the largest galaxy.

We use the distribution of $S/N$ for 1000 random pointings from the SDSS survey area to measure the significance of the X-ray detections in the other samples. The significance distribution at 14–195 keV of the random pointings is well fitted by a Gaussian centered at 0.02 $\pm$ 0.11 $S/N$ with $\sigma = 1.01 \pm 0.06$, consistent with the expected values for a Gaussian distribution of pure noise. For the LIRG and matched sample, the Gaussian distribution of noise is fit from the $S/N < 0$ source distribution.

We choose a 2.7$\sigma$ cutoff $S/N$ in the 134 LIRG sample to have on average less than one “fake” noise source based on the Gaussian distribution of noise using both whole band 14–195 keV and 24–35 keV detections if we assume that the distribution is pure noise. Finally, we note that the lowest $S/N$ of any LIRG is $-2.1$ at 14–195 keV and $-2.7$ at 24–35 keV suggesting this cutoff should assure a sample of clean individual detections.

We also analyze X-ray emission using XSPEC version 12.7.1 for the new sources between 2.7$\sigma$ and 4.8$\sigma$. To calculate luminosities and upper limits, we assume an X-ray power law of $\Gamma = 1.9$ and Galactic extinction, consistent with the mean 14–195 keV power law for Seyfert 2 galaxies in the 70 month blind detection catalog (Winter et al. 2009). The BAT emission is absorbed by <10% for $N_H < 3 \times 10^{21}$ cm$^{-2}$, but sources with larger obscurations are underestimated. To determine 1$\sigma$ errors in luminosity, we include the error from assuming a fixed power-law index (14%) as well as sky and detector noise (<37%). Finally, to better understand the average properties of the sources, we fit a simple X-ray power law to the average emission in each X-ray band.

2.3. X-Ray Hardness Flux Ratios and Comparison Sample

The ultra-hard X-ray hardness flux ratio $(HR_{UX} = 14–195$ keV/(2–10 keV)) provides a measure of obscuration in heavily obscured AGNs ($N_H > 10^{23}$ cm$^{-2}$) since the transmitted hard X-ray emission is suppressed by a much larger factor than the ultra-hard X-ray emission. Long-term AGN variability can affect this ratios, but this variability is typically 20%–40% of the 2–10 keV X-rays (McHardy 2001) and smaller in the ultra-hard X-rays (Ricci et al. 2011).

To estimate absorbing columns corresponding to $HR_{UX}$, we use the MYTorus model (Murphy & Yaqoob 2009), which fully treats photoelectric absorption and relativistic Compton scattering. The intrinsic AGN emission was modeled as a power law ($\Gamma = 1.9$) and the column density assumes that the torus is seen edge-on following Burlon et al. (2011). In this model, the emission is reduced by four at $N_H = 3 \times 10^{22}$ cm$^{-2}$ and $N_H = 4 \times 10^{22}$ cm$^{-2}$ for 2–10 keV and 14–195 keV, respectively, showing that the ultra-hard X-rays can pass through an order of magnitude higher absorbing column.

Finally, as a comparison sample we measured the $HR_{UX}$ from 49 non-LIRG BAT-detected AGNs (log $L_{IR}/L_\odot < 11.0$) from Winter et al. (2009) from the same redshift range to understand whether BAT AGNs in LIRGs have higher levels of obscuration.

3. RESULTS

3.1. The Fraction of AGNs in U/LIRGs

We compare the BAT detection significance at 14–195 keV and 24–35 keV of the LIRGs and a sample of galaxies matched in stellar mass and redshift (Figure 1). There is an excess of LIRGs at $S/N > 3$ for 14–195 keV and $S/N > 2$ at 24–35 keV, based on the distributions from random pointings. There is an excess of LIRG detections over the matched galaxies at $S/N > 4$ at 14–195 keV and at $S/N > 2$ at 24–35 keV. The fraction in the LIRG sample above 2.7$\sigma$ at 14–195 keV is 11% $\pm$ 2% (16/134) and at 24–35 keV 14% $\pm$ 2% (19/134), while the matched galaxy sample is only 2% $\pm$ 1% (21/1000) at 14–195 keV and 1% $\pm$ 1% (5/1000) at 24–35 keV. This suggests that LIRGs are more likely to be detected as ultra-hard X-ray AGNs than galaxies of a similar stellar mass and redshift consistent with previous results (e.g., Koss et al. 2011b). Although
we cannot reliably identify individual sources below 2.7 S/N, analysis of Gaussian fits to the negative S/N distribution representative of noise shows a total LIRG sample detection fraction of 33% ± 8% at 14–195 keV and 36% ± 7% at 24–35 keV compared to the matched galaxy sample detection fraction of only 9% ± 2% at 14–195 keV and 4% ± 1% at 24–35 keV.

We also analyze the average emission in each BAT energy band (Figure 2). We find that there is a significant excess among stacked sources at >1 S/N, between energies of 14 and 150 keV (Figure 2, left). For the >4.8 S/N sources, we find they are fit by a power law with index $\Gamma = 2.18 \pm 0.30$ and for the sources above the cutoff ($2.7 < S/N < 4.8$), we find a harder spectrum of $\Gamma = 1.51 \pm 0.22$ (Figure 2, right).

We also look for additional sources detected in the 24–35 keV band where the reflection component of Compton-thick AGN is expected to contribute significantly that are not detected in the 14–195 keV band. Of the 12 new S/N = 2.7–4.8 detections, 5 are detected in the 14–195 keV band with a stronger significance than the 24–35 keV, and the remaining 7 are detected with stronger significances in the 24–35 keV band. More than half (12/21, 57%) of detected LIRGs are at $S/N = 2.7–4.8$ and thus not detected in previous BAT catalogs.

The BAT detection fraction of LIRGs at 24–35 and 14–195 keV is shown in Figure 3. The AGN detection fraction increases strongly at high IR luminosity ($\log L_{\text{IR}}/L_\odot > 11.8$) with half 50% (6/12) detected above 2.7 S/N.
3.2. Comparison with 2–10 keV Classification

We compare the AGN classification using *Chandra* and *XMM-Newton* of previous LIRG samples based on hardness ratios of the X-ray spectra (HR > −0.3) or the detection of an Fe Kα line with the BAT classification. The C-GOALS *Chandra* survey (Iwasawa et al. 2011) classified luminous LIRGs (*L_{IR} > 11.73*). The BAT and *Chandra* classifications agree for 18/19 galaxies common in both samples. VV 340a, a Compton-thick AGN, is detected in C-GOALS, but not in BAT (*S/N = 0.57*). More nearby studies of less luminous LIRGs were performed by Lehmer et al. (2010) and Pereira-Santaella et al. (2011) using *Chandra* and *XMM-Newton*. We find agreement with BAT in 20/20 cases in these samples. Overall we find agreement in 38/39 cases or 97% based on hardness ratios or the detection of an Fe Kα line. There are other cases where a lower luminosity AGN is detected using the ratio of the galaxy nucleus to total galaxy emission in the 2–8 keV band (NGC 4194, NGC 7771; Lehmer et al. 2010) that are not detected as AGNs in BAT.

We also compare the AGN classification for 12 new *S/N = 2.7–4.8* detections. Five of these sources are detected in the 14–195 keV band with a stronger significance than the 24–35 keV band, and seven are detected with stronger significances in the 24–35 keV band. NGC 7674, UGC 5101, NGC 6926, UGC 08696 (Mrk 273), UGC 08058 (Mrk 231), and NGC 3690 are Compton thick (Severgnini et al. 2012). IRAS F17207−0014 shows the presence of strong (at 2σ), high-ionization Fe K line on a hard continuum (Iwasawa et al. 2011). UGC 2608 is also listed as a heavily obscured Compton-thick AGN (*N_H > 10^{24} cm^{-2}*) (Guainazzi et al. 2005). A *Chandra* observation of NGC 1961 has a hardness ratio indicative of an AGN (HR = −0.2). Mrk 331 has a hardness flux ratio indicative of star formation (HR = −0.5), no significant Fe K line, and weak 2–10 keV emission (log *L_{2–10 keV} = 40.7*); however, it does have a compact radio source suggesting an AGN (Parra et al. 2010). IRAS F02437+2122 has no high-quality X-ray data, but is a LINER AGN (Veilleux et al. 1995). UGC 3094 has a Ne v detection suggesting the presence of an AGN (Petric et al. 2011). Finally, NGC 0877 has no high-quality observation to test for the presence of an AGN.

3.3. Comparison with Spitzer AGN Classification

The Ne v lines at 14.3 and 24.3 μm imply the presence of an AGN since this line requires 97 eV and is too large to be produced even by O stars. There are 29 LIRGS with Ne v detections overlapping in our sample with the Petric et al. (2011) *Spitzer* study (Table 1), with 14/29 (48%) detected in BAT. Conversely, 14/21 (67%) of BAT-detected LIRGs have Ne v. The 33% non-detection in Ne v for BAT-detected LIRGs is lower than the 10% found by Weaver et al. (2010) for all BAT AGNs. However, this study uses a deeper exposure map that is more sensitive to fainter sources (70 versus 9 months), as well as fainter detection limits (2.7 < *S/N < 4.8*), and is exclusively of LIRGs which may be more likely to have optically thick, dusty gas close to the AGNs (e.g., Armus et al. 2007). We note that five out of six of the sources without Ne v detections have X-ray, optical, or radio observations confirming the presence of AGNs (see Section 3.2).

3.4. Properties of AGNs in LIRGs Compared to non-LIRGs

Previous hard X-ray observations have found some LIRGs to be heavily obscured Compton-thick AGNs (NGC 6240, NGC 3690, UGC 5101; Komossa 2003; della Ceca et al. 2002; Imanishi et al. 2003). We measure HR_{UX} to test whether LIRGs are more obscured than non-LIRG BAT AGNs (Figure 4, right). The median HR_{UX} = 15 among LIRGs corresponds to a *N_H ≈ 4 × 10^{23} cm^{-2}* compared to a median HR_{UX} = 3.8 or *N_H ≈ 7 × 10^{22} cm^{-2}* for non-LIRG BAT AGNs. A Kolmogorov–Smirnov (K-S) test indicates a (<1%) chance that the HR_{UX} from the samples are from the same distribution indicating that LIRGS show systematically higher column densities.

4. SUMMARY AND DISCUSSION

We search for nuclear activity in nearby LIRGs based on the detection of ultra-high X-ray emission from *Swift/BAT*. We find the following.

1. A lower cutoff (*S/N > 2.7*) than previous “blind” catalogs (*S/N > 4.8*) can be used for a moderate sample size (∼100). Using this cutoff at 14–195 keV and 24–35 keV, we find agreement in AGN classification for 38/39 cases (97%) from *Chandra* and *XMM-Newton* based on hardness ratios or the detection of a Fe Kα line.

2. We find that using specific energy ranges of the BAT detector can yield additional sources over single band detections with 24% (5/21) of detections in LIRGs at 24–35 keV not detected at 14–195 keV. Of the 12 new *S/N = 2.7–4.8* detections, 7 are detected with stronger significances in the 24–35 keV band than the 14–195 keV band.

3. LIRGs have a higher BAT-detection frequency at 14–195 keV and 24–35 keV compared to galaxies matched in stellar mass. Additionally, the BAT-detection fraction increases strongly at high IR luminosities with half of high luminosity LIRGs detected (50%, 6/12, log *L_{IR}/L_{⊙} > 11.8*).

4. BAT-detected AGNs in LIRGs have higher column densities with 40% ± 9% (6/15) having HR_{UX} suggestive of high column densities (log *N_H > 24 cm^{-2}*) compared to only 12% ± 5% (6/49) of non-LIRG BAT AGNs. Additionally,
eight out of nine of the new $S/N = 2.7–4.8$ BAT sources with high-quality X-ray data are Compton thick based on past observations. We also find the stack spectra of these new sources show an excess at 24–35 keV consistent with a reflection component in a Compton-thick AGN.

We note that there are several LIRGs in warm infrared sources detected in the ultra-hard X-rays (i.e., UGC 07064, MCG +08-11-011, NGC 5995, Mrk 520, NGC 1142, Mrk 463) that are not included in the GOALS sample because of the 60 μm cutoff; therefore, this study underestimates the total fraction of AGNs.
in all LIRGs based on the ultra-hard X-rays. These sources are predominantly unobscured Seyfert 1 galaxies where the AGN contributes significantly to the total IR emission and will be discussed in a forthcoming paper.

These results show the potential of using the *Swift/BAT* all-sky survey to study $\approx 3 \times$ fainter populations of ultra-hard X-ray sources than the past catalogs based on source positions and by using certain energy ranges where the sources are expected to be brightest. A different survey could study faint BAT detection in obscured AGNs, star-forming galaxies, radio-loud AGNs, or galactic sources. Additionally, since lower energy all-sky surveys such as ROSAT show little or no correlation in count rates with *Swift* because of the effects of obscuration (Markwardt et al. 2005), this remains an important all-sky resource to utilize with small field-of-view X-ray missions. For instance, this technique could be used to identify promising candidates to study with higher sensitivity and resolution small field-of-view missions such as NuSTAR and Astro-H.

The success of *Swift* in identifying similar numbers of AGNs in nearby LIRGs ($z < 0.05$) to *Chandra* and *XMM-Newton* suggests that higher sensitivity missions such as NuSTAR and Astro-H hold great promise to study even more distant, obscured AGNs ($z > 0.05$, $N_H > 10^{24}$ cm$^{-2}$) since they can reach these all-sky sensitivities in only 15 minutes.

We acknowledge the *Swift/BAT* team and are grateful to Ezequiel Treister and Marco Ajello for discussion and suggestions.

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**Figure 4.** Left: ultra-hard X-ray hardness flux ratio (HR$_{UX} = 14-195$ keV/2–10 keV) for an AGN with a power-law spectrum index of 1.9, as a function of the column density of the torus as seen edge-on. This measure provides a measure of obscuration since the transmitted hard X-ray emission is suppressed by a much larger factor than the ultra-hard X-ray emission. Right: approximate column density from HR$_{UX}$ as a function of IR luminosity. BAT-selected AGNs in LIRGs tend to show higher column densities than non-LIRG AGNs.

A different survey could study faint BAT detection using certain energy ranges where the sources are expected to be brightest. A different survey could study faint BAT detection in obscured AGNs, star-forming galaxies, radio-loud AGNs, or galactic sources. Additionally, since lower energy all-sky surveys such as ROSAT show little or no correlation in count rates with *Swift* because of the effects of obscuration (Markwardt et al. 2005), this remains an important all-sky resource to utilize with small field-of-view X-ray missions. For instance, this technique could be used to identify promising candidates to study with higher sensitivity and resolution small field-of-view missions such as NuSTAR and Astro-H.