**XMM-NEWTON OBSERVATIONS OF THREE INTERACTING LUMINOUS INFRARED GALAXIES**

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**ABSTRACT**

We investigate the X-ray properties of three interacting luminous infrared galaxy systems. In one of these systems, IRAS 18329+5950, we resolve two separate sources. A second and third source, IRAS 19354+4559 and IRAS 20550+1656, have only a single X-ray source detected. We compare the observed emission to point-spread function (PSF) profiles and determine that they are all consistent with the PSF, albeit with large uncertainties for some of our sources. We then model the spectra to determine soft (0.5–2 keV) and hard (2–10 keV) luminosities for the resolved sources and compare these to relationships found in the literature between infrared and X-ray luminosities for starburst galaxies. We obtain luminosities (0.5–10 keV) ranging from 1 to 7.3 × 10^{41} erg s^{-1} for our systems. These X-ray luminosities are consistent with predictions for star-formation-dominated sources and thus are most likely due to starbursts, but we cannot conclusively rule out active galactic nuclei.

**Key words:** galaxies: active -- galaxies: interactions -- galaxies: nuclei -- galaxies: starburst -- infrared: galaxies -- X-rays: galaxies

**Online-only material:** color figures

1. INTRODUCTION

Over the past few decades, much work has emphasized the role and importance of mergers in shaping galactic evolution (e.g., Toomre & Toomre 1972; Ellison et al. 2011; Hopkins et al. 2006). In particular, mergers have been presented as potential drivers of starbursts (SBs) and active galactic nuclei (AGNs; Bauer et al. 2004; Summers et al. 2004; Bell et al. 2012; Komossa et al. 2003; Teng et al. 2009; Piconcelli et al. 2010). Broadly, hierarchical growth simulations, such as those in Hopkins et al. (2006), paint a picture in which galactic mergers provide gas inflows to ignite SBs, which are then followed by growth of the central supermassive black holes (SMBHs) of galaxies, sometimes leading to the birth of an AGN, until some feedback mechanism, whose origin and existence is contentious, possibly stops the process. The interactions of two galaxies can also cause their central SMBHs to become active simultaneously, resulting in a dual AGN (Komossa 2006). A complication in this scenario is that some simulations suggest that most of the dual AGN activity is non-simultaneous, particularly during their highest luminosity phases when they would be easiest to detect observationally (Van Wassenhove et al. 2012). Other simulations have hinted that this merger scenario was more important in the past, when interacting systems were much more gas-rich, but that it still plays a role in the local universe for lower-luminosity AGNs (Draper & Ballantyne 2012).

Luminous infrared galaxies (LIRGs), galaxies that have infrared (IR) luminosities $L_{IR} \gtrsim 10^{11} L_\odot$ (for a review, see Sanders & Mirabel 1996 and references therein), where IR ranges span 8–1000 μm, are often found to be mergers and have distinctive morphologies (Yuan et al. 2010). The emission from such systems is prominent in the IR portion of the spectrum due to heavy dust reprocessing. The Great Observatories All-sky LIRG Survey (GOALS), which has been observing LIRGs across the electromagnetic spectrum (e.g., Armus et al. 2009 and Iwasawa et al. 2011), and other studies (e.g., Ptak et al. 2003; Braito et al. 2009; Alonso-Herrero et al. 2012; Charmandaris et al. 2010) have attempted to determine if the drivers of the high IR luminosities in these systems are central SBs or AGNs. In one such system, NGC 6240, two separate AGNs were detected by Komossa et al. (2003) at a separation of about 1.4 kpc. This discovery has fueled much discussion about the nature of dual AGNs, their prevalence, and lifetimes.

Several studies have investigated the connection between AGN activity and environment. When looking at quasars, Serber et al. (2006) found a local overdensity of galaxies of ~3 around the brightest objects and an overdensity of ~1.4 for fainter quasars compared to an average galaxy. They show that the overdensity of galaxies around quasars is the same as the overdensity around L* galaxies on scales of ~1 Mpc. At smaller radial separations, however, quasars have a larger overdensity of nearby galaxies than L* galaxies do at the same separations. Ellison et al. (2011) reported a complementary result focusing on AGNs; they found AGNs are 2.5 times more likely to be in pairs than similar but inactive galaxies. Using Swift’s Burst Alert Telescope (BAT) AGN sample, Koss et al. (2011) also found evidence that strong AGN activity is associated with...
mergers and interactions. Specifically, they report that 24% of BAT AGNs are undergoing a merger, whereas this number is closer to 1% for a sample of normal galaxies. Similarly, looking at a subsample of the Sloan Digital Sky Survey (SDSS) DR7, Liu et al. (2012) found that young stellar ages, star formation, and SMBH activity in a given galaxy correlate well with smaller separation from its nearby neighbors. These and other works (e.g., Ajello et al. 2012) suggest that a galaxy’s environment can play a non-negligible role in fueling the AGN, whether through interactions or mergers with nearby galaxies.

Because of heavy obscuration at most wavelengths in dust-enshrouded systems, X-rays, which are less attenuated, become a useful tool to probe behind optically thick screens. From a sample of the optically luminous quasars from SDSS DR3, spanning a redshift of 1.5–4.5, the average power-law index for X-ray emission was found to be $1.9^{+0.3}_{-0.1}$ (Just et al. 2007). The spread in the 2–10 keV photon index, however, is quite large, with observed systems running the range of $\Gamma \sim 1.5–2.5$. A proposed explanation for this spectral behavior is that an accretion disk feeding the central SMBH thermally emits in the optical and UV. These photons then inverse Compton upscatter to X-rays off of a hot plasma surrounding the disk (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Haardt & Maraschi 1993). The rather large spread in the value of the photon index is thought to arise from the specific accretion rate of the SMBH regulating disk cooling; a high accretion rate increases the rate of disk emission, providing more soft (here, $0.5–2$ keV) photons and increasing the Compton cooling of the corona. This, then, reduces the abundance of hard photons. Combined with the increase of soft photons, higher accretion rates are thus associated with a steeper index (Williams et al. 2004; Shemmer et al. 2008). Much of a galaxy’s SMBH growth is believed to occur in regions heavily obscured by dust (Hopkins et al. 2006; Fabian 1999), so searching in X-rays is one of the few viable options for spotting this enshrouded phase, provided that the column density is not overly large ($\gtrapprox 10^{22}$ cm$^{-2}$).

AGN activity is not the only interesting phenomenon strongly associated with galactic interactions. Another prominent event often triggered is a marked increase in the star formation rate (SFR) of one or both component galaxies, provided neither is gas poor. If this increase is large enough, the galaxy becomes a SB. Muzzin et al. (2012) suggest that, while the gross properties of star-forming galaxies are tied to their stellar masses, their environment appears to regulate the fraction of systems that are starbursting.

Like AGNs, star-forming regions also produce specific X-ray signatures (e.g., Persic & Rephaeli 2002). The ionizing photons from supernovae and short-lived O and B stars form a thermal plasma, typically with a temperature between 0.1–1 keV. A secondary power-law component, associated with high-mass X-ray binaries (HMXBs), indicative of recent star formation (Fabbiano 2006), is often observed in SB systems as well. These are said to trace recent or ongoing star formation because they require an OB star around a neutron star (NS) or black hole (BH) and thus only have a lifetime of $10^6$–$10^7$ yr. HMXBs have been observed with a range of photon indices, typically lying within $\Gamma = 1–2$ with the steepest being greater than 2.4 (Remillard & McClintock 2006). Low-mass X-ray binaries (LMXBs), a possible contaminant, are usually described by either a power law with index $\sim 1.6$ or bremsstrahlung at 7.3 keV (Irwin et al. 2003; Fabbiano 2006; Persic & Rephaeli 2003). These LMXB spectral indices can run as steep as 2 in the highest luminosity cases. LMXBs do not trace recent star formation, however, since they are connected to lower mass companions around an NS or BH and thus have lifetimes that are 100–1000 times longer than their higher mass counterparts.

Kennicutt (1998) associated star-forming regions with IR emission due to dust reprocessing of UV and optical emission from young stars. Several studies (e.g., Ranalli et al. 2003) have proposed X-ray/IR luminosity relationships in IR bright galaxies, arguing that star formation is traced in the IR from reprocessing and in X-rays from HMXBs, provided there is no AGN present. The use of X-rays as a tracer of star formation also requires that LMXBs are a negligible contributor, which is generally a safe assumption for the high SFRs encountered in starbursting systems. One can then use these relations to predict the X-ray output of a system originating from star formation alone. It should be noted, however, that the existence of either a SB or an AGN does not discount the other (Sani et al. 2010; Santini et al. 2012). Additionally, some argue for a more complete picture taking into account escaping, non-reprocessed UV radiation when attempting to synthesize star formation data for certain luminosity regimes (e.g., Vattakunnel et al. 2012; Mineo et al. 2012).

In this paper, we use the association between AGN activity, SBs, mergers, and, by extension, large IR luminosity, to search for dual AGNs. We also investigate how well our data are fit by a starbursting population alone. In Section 2, we describe our sample selection and discuss the systems we examined in detail. Section 3 presents image and spectral analysis as well as the luminosities we find. Section 4 compares our data to existing IR/X-ray relations and discusses our prospectives on dual AGN detection. Finally, we conclude in Section 5.

We adopt a cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$, and all relationships taken from the literature assume a Salpeter initial mass function.

## 2. SAMPLE

We derived our sample from a subset of relatively local IR bright galaxies presented in Arribas et al. (2004). Our systems are nearby (redshifts of $0.03 < z < 0.07$) to ensure a high number of photon counts, and are known to be interacting with two optical nuclear regions, though there is some uncertainty about the location of the secondary nucleus in IRAS 20550+1656. All are LIRGs, and many have roughly measured nuclear separations. We selected based on interaction class using the scheme proposed in Surace (1998) and refined in Veilleux et al. (2002), restricting our sample to class IIIa and IIIb systems with nuclear separations around 10 kpc. A class IIIa system is composed of two or more galaxies with evidence of tidal interactions (tails, bridges) and with nuclear separation of greater than 10 kpc, whereas a class IIIb system has similar tidal structures but with nuclear separation less than 10 kpc. Additionally, we required that systems have angular separations that would likely be resolvable with XMM-Newton ($\sim 8''–10''$). After this, we selected the LIRGs with the highest IR fluxes, and, by association, likely the most X-ray counts barring the system being Compton thick. The IR luminosity for all of the potential targets was calculated from the IRAS Revised Bright Galaxy Sample (hereafter RBGS; Sanders et al. 2003) using the distance and IR flux defined in the RBGS as

$$F_{IR} = 1.8 \times 10^{-11} \left( 13.48 \frac{f_{12 \mu m}}{Jy} + 5.16 \frac{f_{25 \mu m}}{Jy} + 2.58 \frac{f_{60 \mu m}}{Jy} + \frac{f_{100 \mu m}}{Jy} \right) \text{erg cm}^{-2} \text{s}^{-1}.$$  

(1)
Figure 1. Top: smoothed, false-color XMM-Newton images of the three objects in our sample with the spectral extraction region, described in Section 3, overplotted as black circles. All images are scaled logarithmically over the range 0.5–10 keV and smoothed using a Gaussian with a kernel size of three pixels. The units on the scale at the bottom of each image are counts, and the physical scale on each image is as labeled. Left: IRAS 18329+5950. Middle: IRAS 19354+4559. Right: IRAS 20550+1656. Bottom: optical images of the galaxies presented in the top row. IRAS 18329+5950 (left) and IRAS 20550+1656 (right) were taken from archival Hubble Space Telescope (HST) images and show 814W–435W filters. There is no image for IRAS 19354+4559 (middle) in the Hubble archive, so this optical image was taken from the Digitized Sky Survey (DSS). Note here that the units on the scales are count rates rather than counts for the HST images. For a better look at the tidal features of this system in particular, we refer the reader to Arribas et al. (2004).

(A color version of this figure is available in the online journal.)

Table 1: Observational Data

| IRAS Name     | Observation ID (XMM) | Date       | Exposure (ks) | Distance (Mpc) | Separation (kpc) | Separation Hardness Ratio | Source Counts (0.5–10 keV) |
|---------------|---------------------|------------|---------------|----------------|-------------------|---------------------------|---------------------------|
| 18329+5950E   | 0670140301          | 2011 May 4 | 5.3           | 129            | 28"               | -0.80±0.17                | 99 ± 13                   |
| 18329+5950W   | 0670140301          | 2011 May 4 | 5.3           | 129            | 28"               | -0.83±0.17                | 106 ± 14                  |
| 19354+4559    | 0670140501          | 2011 May 10| 15.2          | 289            | 8.5               | -0.87±0.13                | 46 ± 12                   |
| 20550+1656    | 0670140101          | 2011 Oct 28| 60.5          | 161            | 12"               | -0.46±0.02                | 3461 ± 62                 |

Notes. Separation refers to the projected nuclear separation between the interacting galaxies; the first is angular separation while the second is physical separation. The hardness ratio represents the overall contribution of hard (2–10 keV) X-ray emission compared to soft (0.5–2 keV) emission. Note that exposure times are good time intervals, explained in the text, and that the source counts and hardness ratios are taken from background-subtracted data.

Three systems met our criteria: IRAS 18329+5950, IRAS 19354+4559, and IRAS 20550+1656. We observed these with XMM-Newton and restricted all analyses to 0.5–10 keV so as to stay in range of the detector’s optimal sensitivity. Table 1 summarizes our data, including the observation ID, exposure times, nuclear separations, and counts for each of our sources.

IRAS 18329+5950 is a class IIIa system composed of two merging galaxies with estimated nuclear separations of 28" (Arribas et al. 2004). The offset in declination (5.70) of the two galaxies in this system is much smaller than the offset in right ascension (27.5). In projection, it appears that the nucleus of the eastern component (18329E) is close to the plane of the disc of the western component (18329W), as can be seen in the bottom row of Figure 1. The system is classified as a LIRG in the RBGS. Using the RBGS fluxes, we calculate an IR luminosity of \( \log(L_{IR}/L_\odot) = 11.60 \) based on the redshift of \( z = 0.029 \), which corresponds to a distance of \( \sim 129 \) Mpc (Armus et al. 2009). Optical line ratios, discussed further in Section 4.3, suggest that this system is a SB or SB/AGN composite.
IRAS 19354+4559 is a class IIIb merger system with nuclear separation of approximately 8′′5 (Arribas et al. 2004). In this case, the offsets in right ascension and declination are comparable, being 6′′7 and 5′′3, respectively. Both galaxies have significant tidal features in the optical, suggestive of mutual interaction. They appear as mostly edge-on disks, although the eastern component has several foreground stars contaminating the optical images, partially confusing the orientation, which can be seen in Figure 1 of Arribas et al. (2004). Using fluxes from the RBGS, we calculate an upper limit IR luminosity of log($L_{\text{IR}}/L_{\odot}$) = 11.85 based on the redshift of $z = 0.067$, which corresponds to a distance of ~289 Mpc (Lawrence et al. 1999). We did not find any IR or optical line diagnostics for this system.

Similarly, IRAS 20550+1656 is also a class IIIb merger system. The separation between the optical nuclei is uncertain but believed to be about 11′′7 (Arribas et al. 2004). From the RBGS fluxes, we calculate the IR luminosity to be log($L_{\text{IR}}/L_{\odot}$) = 11.94 for a redshift of $z = 0.036$, corresponding to a distance of ~161 Mpc (Armus et al. 2009). Optical (Baan et al. 1998) and IR (Inami et al. 2010) spectroscopy and ratio line diagnostics indicate that this system is a SB. The Spitzer data in particular (Inami et al. 2010) suggests that 80% of the IR luminosity comes from a region outside the nuclei of the two interacting galaxies in this merger.

### 3. XMM-NEWTON OBSERVATIONS

#### 3.1. Image Analysis

All data were taken with the EPIC instruments on board XMM-Newton and reduced using XMM SAS Version 12.0.1. As is typical in X-ray image analysis, we filtered the event files to discard any time interval with $\geq 0.5$ counts s$^{-1}$ in order to minimize contamination from cosmic rays and other short, time-variant noise sources. As the EPIC MOS cameras have a smaller pixel scale than the EPIC PN by nearly a factor of four, we first tried creating images and radial profiles using EPIC MOS. Unfortunately, there were not enough counts in the MOS images to robustly determine the radial profiles, so we proceeded to use the much more abundant data from the PN detector for our analysis. Processed EPIC PN images in the entire 0.5–10 keV band for the three sources in our sample are shown in Figure 1. The top-left panel of Figure 1 demonstrates that the nuclear regions of the two separate galaxies in IRAS 18329+5950 are resolved in X-rays. Additionally, the top-middle and top-right panels of Figure 1 show that for both IRAS 19354+4559 and IRAS 20550+1656, the nuclei from the individual component galaxies are not distinctly separable. Thus, only a single area could be analyzed for each of these sources.

As hinted at above, one avenue for discerning the probable X-ray source type is to compare the radial profile of the observed flux to the point-spread function (PSF) of the detector. A lone AGN, being a point-like source, would have a profile that approximately matched the PSF’s, whereas a SB or a blend of SB with an AGN would be more extended from diffuse emission. We used the XMM/SAS task radial to calculate the sources’ radial profile distributions at an energy of 2–8 keV. We chose this energy range because an AGN which is not heavily obscured would likely provide a greater fractional contribution to the hard band flux than the soft band as compared to a SB region. The radial task returned the emission profile in concentric circular radii of each source. It also created a model of the PSF, using the built-in ELLBETA model type, at that same location on the CCD chip at 5 keV, the midpoint of our hard energy range. The ELLBETA model is based around an elliptical King profile, with an added Gaussian to account for spokes. The normalization of the PSF was set by using weights inversely proportional to errors on the extracted radial profile of the data. The background was fit using a region of the same area as the extraction region on the same CCD chip in order to avoid nearby sources and avoid any inter-chip variance. Figure 2 shows the background-subtracted radial profiles. Our systems appear to be either consistent with or marginally extended with respect to the PSF over our energy range. We find the profiles of both galaxies in IRAS 18329+5950 and the single source of IRAS 20550+1656 are fully consistent with the PSF, while IRAS 19354+4559 may potentially be extended. However, it is still consistent with a point source within the errors.

#### 3.2. Spectral Analysis

For spectral analysis, we used the entire 0.5–10 keV band. The 90% encircled energy radius of the EPIC PN PSF above 2 keV is over an arcminute, so we tried to use a spectral extraction region as large as possible. In IRAS 20550+1656, we have only one source detected and used a spectral extraction radius of 3′′, which is out to the CCD chip boundary. In IRAS 19354+4559, again we have a single source detected. We used a 20′′ spectral extraction radius for this system, as there are a couple of nearby sources in this field which prevented us from using a larger region. For IRAS 18329+5950, we detected both galaxies of the system individually, which are separated by 28′′, as stated in Section 2. For these sources, a spectral extraction region had to be defined carefully to avoid contamination between the two galaxies. As such, we used a 32′′5 radius circle instead, shown in Figure 1 around 18329W. From this region, we excised 18329E with a rectangular region centered at its coordinates, which is also shown in Figure 1. A similar procedure was followed to create an extraction region for 18329E that had 18329W excised. The background region was subtracted, as described in Section 3.1. We then corrected our final luminosities based on the XMM on-axis PSF encircled energy fraction at the region size for each extracted source.

Following extraction, we performed our analysis using XSPEC version 12.7.0. We modeled each system with multiple components in combination to account for AGNs, possibly obscured, and SBs in an attempt to recover the observed count and energy distributions. We were, however, limited in the complexity of our models due to low source number counts, as can be seen in Table 1. Our fewest counts came from IRAS 19354+4559 with 46. Both sources in IRAS 18329+5950 had around 100 counts, and IRAS 20550+1656 had over an order of magnitude greater at ~3500.

For IRAS 18329+5950, due to the low number counts in both sources, we decided not to bin the data and used Cash statistics rather than fit based on the more commonly used reduced $\chi^2$ value (Cash 1979). We took into account Galactic absorption using the “tbabs” model (Wilms et al. 2000). We first tried to fit the data for 18329E, shown in Figure 3, with solely an absorbed power law ($C = 98.31$; degrees of freedom = 115) followed by an absorbed power law and MEKAL (Mewe et al. 1985, 1986; Liedahl et al. 1995) thermal plasma component ($C = 94.60$; degrees of freedom = 110), with their respective fit parameters highlighted in Table 3. We adopt the latter model, which has a spectral index $\Gamma = 1.8 \pm 0.5$ and temperature of 0.57$^{+0.46}_{-0.30}$ keV. The component luminosities are presented in Table 2; we note...
Figure 2. Radial profile plots for our sources at 2–8 keV, as well as the models of the detector’s PSF at 5 keV at the same locations. Top: IRAS 18329+5950 West (18329W, left) and IRAS 18329+5950 East (18329E, right). Bottom: IRAS 19354+4559 (left) and IRAS 20550+1656 (right). A harder bandpass was chosen for this analysis as an AGN would be expected to be less contaminated by emission related to star formation at these energies.

(A color version of this figure is available in the online journal.)

Figure 3. Best-fit spectrum of the eastern source in IRAS 18329+5950 (18329E, left) and western source (18329W, right), both composed of a power law and thermal plasma component with Galactic absorption, taken from Dickey & Lockman (1990). The data is rebinned for illustration purposes. For comparison, the bottom panel presents the residuals between the fit and the data in units of sigma.

that this source is dominated in the hard band by the power-law component.

The system 18329W, shown in the right panel of Figure 3, was also fit by an absorbed power law ($C = 98.93$; degrees of freedom = 114) and then by an absorbed power-law model and one with an additional MEKAL plasma ($C = 95.70$; degrees of freedom = 111), and once again, a comparison between the two models is shown in Table 3. Here, the best-fit value for the
with a spectral index of 2. The best-fit model is a power law, index 2.7, with Galactic absorption.

Table 2: Final Model Component Luminosities

| IRAS Name      | Component | $L_{\text{w},0.5-2\text{keV}}$ (10^{40} \text{ erg s}^{-1}) | $L_{\text{hard,2-10keV}}$ (10^{40} \text{ erg s}^{-1}) |
|----------------|-----------|-------------------------------------------------------------|-------------------------------------------------------------|
| 18329+5950E    | Full model| 11.6^{+7.2}_{-6.3}                                         | 14.2^{+5.8}_{-3.5}                                         |
|                | Power law | 8.2^{+3.3}_{-3.2}                                          | 14.1^{+5.7}_{-5.5}                                         |
|                | MEKAL plasma | 3.4^{+4.2}_{-2.9}                                          | 0.07^{+0.09}_{-0.06}                                        |
| 18329+5950W    | Full model| 9.0^{+9.1}_{-4.8}                                          | 8.7^{+3.3}_{-3.2}                                          |
|                | Power law | 6.4^{+2.5}_{-2.4}                                          | 8.6^{+3.4}_{-3.3}                                          |
|                | MEKAL plasma | 2.7^{+6.7}_{-2.4}                                          | 0.04^{+0.11}_{-0.04}                                        |
| 19354+4559     | Power law | 9.9^{+3.1}_{-2.9}                                          | 6.6^{+2.1}_{-2.0}                                          |
| 20550+1656     | Full model| 23.9^{+3.3}_{-3.2}                                         | 49.0^{+7.2}_{-6.9}                                         |
|                | Power law | 12.4^{+1.8}_{-1.8}                                         | 48.3^{+7.1}_{-6.9}                                         |
|                | VMEKAL plasma | 11.5^{+1.4}_{-1.4}                                         | 0.70^{+0.09}_{-0.09}                                        |

Notes: Comparison of X-ray luminosities of model components. Luminosities are reported in 10^{40} \text{ erg s}^{-1}. Errors are calculated from the errors on the normalizations of each model component.

The spectral index was slightly steeper and the temperature of the plasma slightly lower than 18329E, though they are consistent within their errors. Like with 18329E, Table 2 indicates that 18329W derives the vast majority of its model’s hard band luminosity from the power law and comparable amounts from both the plasma and power law in the soft band.

After correcting for the encircled energy at 32\arcsec, both systems have a final soft band luminosity of $\sim$10^{36} \text{ erg s}^{-1} and hard band luminosities of 9 \times 10^{40} and 1.4 \times 10^{41} \text{ erg s}^{-1} for 18329W and 18329E, respectively. It should be noted that in both 18329E and 18329W, the thermal plasma models were fixed at solar metallicity via the prescription in Anders & Grevesse (1989), which is adopted by default in XSPEC.

The data for IRAS 19354+4559, which can be found in Figure 4, were also fit without binning and using Cash statistics rather than $\chi^2$. Even so, multicomponent models were not well constrained due to the paucity of counts. As such, we tried modeling the system with a plasma, blackbody, and power-law component separately, each with Galactic absorption. The best fit (C = 72.05; degrees of freedom = 89) is the power law with a spectral index of 2.7^{+0.6}_{-0.6}. After correcting for the smaller extraction region, this system is roughly 10^{41} \text{ erg s}^{-1} in the soft band and 7 \times 10^{40} \text{ erg s}^{-1} in the hard band, as can be seen in Table 2.

For the spectrum of IRAS 20550+1656, presented in Figure 5, we were able to bin the raw spectrum such that each bin contained a minimum of 20 counts, permitting us to use reduced $\chi^2$ fitting for this system. As with all of the systems, we began by fitting solely with an absorbed power law ($\chi^2 = 360.0$; degrees of freedom = 148). Next, we tested an absorbed power law and MEKAL thermal plasma model ($\chi^2 = 145.3$; degrees of freedom = 145). Comparing this to the original model, one can see this model is strongly favored with a reduced $\chi^2$ close to unity. We were concerned about the bump-like features around 2 and 4.5 keV (Figure 5), however, and tested to see if non-solar abundances could reproduce this data. Assessing each element individually, we found that the bump around 2 keV could be due to a super-solar silicon abundance.

Figure 4. Similar to Figure 3, but for IRAS 19354+4559. Here, the best-fit model is a power law, index 2.7, with Galactic absorption.

Figure 5. Similar to Figure 3, but for IRAS 20550+1656. The best-fit model has a metal-variant MEKAL plasma of temperature $kT \sim 0.63$ keV, with the strong bump feature just below 2 keV in the spectrum fit by adopting a super-solar alpha abundance tied to silicon ([Si] = 0.5). The index of the power law is $\Gamma = 1.4$.

To investigate whether this silicon enhancement was part of a larger alpha element enrichment, we next fit the system with a model where all of the alpha elements were tied to the silicon value ($\chi^2 = 132.5$; degrees of freedom = 144). It should be noted that we also fit with both alpha elements independent from one another as well as all metals as free parameters. Our data are unable to provide firm constraining power in either of these instances. This fit, with the alpha elements fixed to the silicon value, has an abundance log(Si/Si) = [Si] = 0.5^{+0.1}_{-0.2} and is compared to the single power law and power law with a solar abundance plasma in Table 3.

We are still left with the prevalent bumps between 4 and 5 keV, as well as smaller ones around 1 keV. Fitting the larger feature as a Gaussian emission line, the line has a central value of $E = 4.3 \pm 0.5$ keV and line width of $\sigma = 0.7^{+0.6}_{-0.5}$ keV. If this feature is an emission line from the source, it is most likely Ca XX at 3.0185A, or $\sim$4.1 keV. We found no reports of this line in emission in the literature, though it may have been seen in absorption in a few systems (Tombesi et al. 2010). However, due to the tenuous detection of this line and the marginal improvement to our fit after its addition, we report the model without this component as our best fit. The final parameters of the fit are summarized in Table 3. From Table 2, we note that this source is dominated in the hard band by the power-law component, whereas the two components are comparable.
observations is that IRAS 20550+1656 is intrinsically variable, the differences in luminosity between the source over the range 2–8 keV. One possible explanation for these sum to about 50% of the luminosity we find for our single source. In a recent study, Nardini et al. (2013) found an elevated $\alpha$/Fe ratio for the merging galaxy NGC 6240, known to host a dual AGN. They argue that the heightened presence of alpha elements in NGC 6240 is consistent with Type II supernovae and can pollute the region with alpha elements. In a recent study, Nardini et al. (2013) found an elevated $\alpha$/Fe ratio for the merging galaxy NGC 6240, known to host a dual AGN. They argue that the heightened presence of alpha elements in NGC 6240 is consistent with Type II supernovae yields from Nomoto et al. (2006). In the Antennae Galaxies, another well-known merger, high spatial resolution revealed that the metallicity of the gas is quite variable, sub-solar in some regions and as high as 20–30 solar in others, also arguing in favor of supernova enrichment (Baldi et al. 2006a, 2006b). Additionally, Araya Salvo et al. (2012) report several super-solar alpha elements in their discovery spectra for an AGN in the bulgeless galaxy, NGC 4561.

IRAS 20550+1656 was also the subject of an extensive multiwavelength campaign, including an X-ray analysis with Chandra as part of the GOALS project (Inami et al. 2010), that we can compare to our data from XMM-Newton. They were able to distinguish two distinct objects in X-rays (see their Figure 5, sources labeled as “A” and “C+D”) with Chandra’s spatial resolution, whereas we see only a single source with XMM-Newton. One of their two X-ray sources was reported as extended, covering two distinct IR bright regions seen with Spitzer. Using Spitzer data on the individual sources, they concluded that source A is most likely a SB, obeying the Ranalli et al. (2003) relations relating IR luminosity (a proxy for star formation) to X-ray luminosity (a proxy for X-ray binaries). For C+D, they find that Ranalli et al. (2003) overpredicts the X-ray values for its IR luminosity, though it should be noted that these relations were calibrated for less intense star-forming systems.

Looking once again to this system’s data from Inami et al. (2010), they report soft X-ray luminosities of $L_{A,0.5–2\text{keV}} = 6.6 \times 10^{40} \text{erg s}^{-1}$ and $L_{C+D,0.5–2\text{keV}} = 1.8 \times 10^{40} \text{erg s}^{-1}$. Their hard X-ray (2–7 keV) luminosities for the two sources were both $L_{2–7\text{keV}} = 10^{41} \text{erg s}^{-1}$. Over the entire range 0.5–7 keV, then, these sum to about 50% of the luminosity we find for our single source over the range 2–8 keV. One possible explanation for the differences in luminosity between the Chandra and XMM observations is that IRAS 20550+1656 is intrinsically variable, which could be suggestive of an AGN in either source A, source C+D, variations in the extended emission from HMXBs, or combinations thereof. Unfortunately, with the lower spatial resolution of our observation, we are unable to determine which of their reported sources, if only one, is responsible for our larger X-ray luminosity.

4. DISCUSSION

With models in hand, we further investigate the likelihood of the SB and/or AGN nature of our sources.

4.1. Determining Star Formation Rates

With known X-ray and IR luminosities, we now discuss the SFRs in these systems. There are many available prescriptions in the literature, and we start with the often-used Kennicutt (1998) IR SB relation. For an IR luminosity given in erg s$^{-1}$,

$$\text{SFR} = 4.5 \times 10^{-44} L_{\text{IR}} M_\odot \text{ yr}^{-1}. \quad (2)$$

From Equation (2), we find SFRs in the range of $75–150 M_\odot \text{ yr}^{-1}$ for our three systems, with IRAS 20550+1656 being the strongest. We have listed the star formation and IR luminosities for each individual system in Table 4. As is typically expected of mergers and LIRGs, in general, these are relatively large SFRs, implying that at least one of the galaxies in each pair is likely in a SB phase. The underlying assumption in this and other relations is that all of the UV emission from O and B stars, whose presence is indicative of recent star formation, is absorbed by dust surrounding the star-forming region and re-radiated into the IR. Not all of this UV radiation is absorbed, however. For example, Miralles-Caballero (2012) observed some star clusters with as much as 15% unobscured UV radiation. As such, we decided to also try a more recent SFR relationship that takes both IR and UV radiation into account (Iglesias-Páramo et al. 2004, 2006; Hirashita et al. 2003; Bell 2003):

$$SFR_{\text{Tot}} = SFR_{\text{NUV}}^0 + (1 - \eta)SFR_{\text{IR}}.$$ \quad (3)

where

$$SFR_{\text{IR}} = 4.6 \times 10^{-44} L_{\text{IR}} M_\odot \text{ yr}^{-1}, \quad (4)$$

$$SFR_{\text{NUV}} = 1.2 \times 10^{-43} L_{\text{NUV,obs}} M_\odot \text{ yr}^{-1}, \quad (5)$$

and all luminosities here are taken in erg s$^{-1}$.

| IRAS Name        | Model                        | $\Gamma$  | $T$ (keV) | Fit Statistic | DoF |
|------------------|------------------------------|-----------|-----------|---------------|-----|
| 18329+5950 Easta | PL                           | 2.0$^{+0.4}_{-0.3}$ | ...       | 98.31         | 113 |
|                  | PL + Thermal plasma          | 1.8$^{+0.5}_{-0.5}$ | 0.57$^{+0.36}_{-0.30}$ | 94.60         | 110 |
| 18329+5950 Weesta | PL                           | 2.1$^{+0.4}_{-0.3}$ | ...       | 98.93         | 114 |
|                  | PL + Thermal plasma          | 2.0$^{+0.5}_{-0.5}$ | 0.53$^{+0.36}_{-0.28}$ | 95.70         | 111 |
| 19354+4559a      | PL                           | 2.7$^{+0.6}_{-0.6}$ | ...       | 72.05         | 89  |
| 20550+1656b      | PL                           | 1.9        | ...       | 360.00        | 148 |
|                  | PL + Thermal plasma          | 1.5$^{+0.1}_{-0.1}$ | 0.64$^{+0.04}_{-0.04}$ | 145.3         | 145 |
|                  | PL + Super-solar plasma      | 1.4$^{+0.1}_{-0.1}$ | 0.63$^{+0.04}_{-0.03}$ | 132.5         | 144 |

Notes. Comparison of spectral fitting parameters for the two components of IRAS 18329+5950 and the single sources in IRAS 19354+4559 and IRAS 20550+1656. Note that “DoF” here stands for degrees of freedom.

a Fit statistic is the Cash statistic.

b Fit statistic is chi squared.
The $\eta$ factor in Equation (3) is a correction factor (between zero and unity) for the fraction of IR emission that is cirrus in nature rather than directly related to recent star formation. The value of $\eta$ for a specific galaxy is difficult to ascertain. Bell (2003) find that $\eta \sim 0.09$ for galaxies with $\log(L_{\text{IR}}/L_{\odot}) > 11$, whereas galaxies below this threshold have $\eta \sim 0.3$. As all of our systems are in the former regime, we adopt a value of 0.09 in all of our analyses when necessary. For the NUV luminosities, we used Galaxy Evolution Explorer (GALEX) data presented in Howell et al. (2010) for two of our systems. The NUV term in Equation (3), however, has less than a 1% effect on the total SFR for IRAS 18329+5950 and IRAS 20550+1656, so we proceed using only the IR SFR. Equation (4) modified by $\eta$, for our systems. We caution that IRAS 19354+4559 has the lowest IR luminosity and thus may have a larger relative UV contribution than the other systems for which GALEX data was available. Overall, the SF rates obtained in this way are slightly below those from the Kennicutt (1998) formalism, ranging from 72 to $140 \, M_{\odot} \, \text{yr}^{-1}$. These are also listed in Table 4 for the individual systems in our sample for comparison.

Inami et al. (2010) find an SFR of 120 $M_{\odot} \, \text{yr}^{-1}$ for the non-nuclear IR source (labeled “D” in their paper) in IRAS 20550+1656. Comparing to our value for the system as a whole, this would imply that most of the star formation in the system is happening in this non-nuclear region.

4.2. X-Ray Origins

Our next objective was to determine the major contributor to our systems’ X-ray luminosities. Are they related to star formation, AGN activity, or both?

To accomplish this, we compare our luminosities to literature predictions for X-rays associated with star formation. For this task, we employ the relationship of Mineo et al. (2014):

$$L_{0.5–8 \, \text{keV}}(\text{erg s}^{-1}) = (3.5 \pm 0.4) \times 10^{39} \, \text{SFR}(M_{\odot} \, \text{yr}^{-1}). \quad (6)$$

For consistency, we use SFRs from Iglesias-Páramo et al. (2006), here simplified to Equation (4) for our IR luminous systems, rather than Kennicutt (1998), as these were the rates used to calibrate Equation (6). Using the latter, however, results in a 6% increase in the predictions.

Since these relationships pertain directly to SBs via their diffuse emission and integrated X-ray binary luminosity, if they are similar to the luminosities we find from our observations, we may infer that our systems, at least in the X-ray range, are most likely dominated by star formation rather than AGNs. If a strong, unabsorbed AGN is present, however, we would expect a notable excess in X-ray luminosity compared to these predictions.

For consistency, we use SFRs from Iglesias-Páramo et al. (2006), reproduced in text as Equations (2) and (4), respectively. The predicted X-ray luminosities from SFR alone are found using SFR$_{\text{IP}}$ values and Equation (6), taken from Mineo et al. (2014). Our X-ray values are from our best-fit spectral models described in the text.

| IRAS Name     | $L_{\text{IR}}$ ($10^{44} \, \text{erg s}^{-1}$) | SFR$_K$ ($M_{\odot} \, \text{yr}^{-1}$) | SFR$_{\text{IP}}$ ($M_{\odot} \, \text{yr}^{-1}$) | $L_{0.5–8 \, \text{keV}}(\text{Pred})$ ($10^{40} \, \text{erg s}^{-1}$) | $L_{0.5–8 \, \text{keV}}(\text{Obs})$ ($10^{40} \, \text{erg s}^{-1}$) |
|---------------|-------------------------------|-----------------------------|-----------------------------|---------------------------------|---------------------------------|
| 18329+5950    | 17                            | 76                          | 72                          | $2^{+35}_{-15}$                  | $40^{+25}_{-19}$                |
| 19354+4559    | 27                            | 121                         | 114                         | $40^{+25}_{-15}$                  | $16^{+5}_{-3}$                  |
| 20550+1656    | 33                            | 149                         | 140                         | $49^{+69}_{-29}$                  | $63^{+9}_{-6}$                  |

**Notes.** Star formation rates, predicted luminosities, and modeled luminosities related to our systems. The IR fluxes are calculated from Equation (1) using the specific flux values presented in the RBGS (Sanders et al. 2003). The star formation rates are calculated from Kennicutt (1998) and Iglesias-Páramo et al. (2006), reproduced in text as Equations (2) and (4), respectively. The predicted X-ray luminosities from SFR alone are found using SFR$_{\text{IP}}$ values and Equation (6), taken from Mineo et al. (2014). Our X-ray values are from our best-fit spectral models described in the text.

In Figure 6, we plot our derived luminosities against SFR and include other known AGNs and AGN–SB composite systems. From this, it is evident that the best-fit models for each of our systems described in Section 3.2 give 0.5–8 keV luminosities that are consistent with the expected values from their SFRs. IRAS 19354+4559 is on the lower end of this range, but we remind the reader that this particular system had the least constrained model as discussed in Section 3.2. The values of these luminosities, both predicted and modeled, are shown for convenience in Table 4. If we adopt our solar metallicity luminosity for IRAS 20550+1656, it is closer to the predicted value from star formation but both are consistent. In their discussion, Mineo et al. (2014) compare the calibration of their relationship to others found in the literature. They find that there are two primary differences in how various studies have generated these associations. The first is how each work proxies their X-ray binary emission and the second is their adopted model for X-ray binary emission. Combined, these two issues

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**Table 4**

IR and X-Ray Luminosities

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**Figure 6.** Comparison between the modeled X-ray luminosities of our three systems with predictions from Equation (6) (solid line). The dashed lines are the 1σ errors on this relation. The data for composites, H II systems, Seyfert 1s, and Seyfert 2s were compiled by Pereira-Santaella et al. (2011) and taken from Lehner et al. (2010) for NGC 23, NCG 5653, and Zw049.057; Miniutti et al. (2007) for MCG-03-34-064; Levenson et al. (2005) for NGC 7130; and Blustin et al. (2005) for NGC 7469. Our LIRGs tend to lie in a region occupied by H II systems, composite AGNs/starbursts, and heavy star-forming galaxies. It should be noted that these galaxies’ luminosities are from 0.5 to 10 keV, whereas Equation (6) is defined for 0.5–8 keV by Mineo et al. (2014), and are thus systematically offset from the relation apart from their scatter by a small amount (≤0.1 dex). The systems presented in this paper and from Mineo et al. (2012) are on a 0.5–8 keV scale. In order of increasing star formation, our points are for IRAS 18329+5950, IRAS 19354+4559, and IRAS 20550+1656. (A color version of this figure is available in the online journal.)
can drop the normalization of Equation (6) by a factor of two or raise it by a factor of 1.5. We elect to work with Equation (6) because of the care in handling both the diffuse and source (here, X-ray binary) emission related to star-forming regions.

4.3. AGNs in LIRGs?

We have employed several methods to determine whether or not our sample contains AGNs or dual AGNs. One indicator would be X-ray point sources. From Figure 1, we see that all three systems are detected in the entire XMM energy bandpass and that IRAS 18329+5950 is composed of two distinct sources. If these X-ray sources were due solely to the presence of an AGN, one would expect that their radial profiles would be similar to the detector’s PSF. From Figure 2, we see that for the most part, the 2–8 keV emission is consistent within errors of the modeled PSF at 5 keV. Given that the FWHM for the PN detector on XMM-Newton is about an 12.5′, amounting to ~8 kpc in the closest system (IRAS 18329+5950), it is impossible to say definitively that the X-ray source is solely from point-like emission.

The second test was to compare the spectra of each system to SB and AGN templates. Both sources in IRAS 18329+5950 and the single source in IRAS 20550+1656 were composed of a MEKAL plasma, typically associated with ionizing photons from OB stars and their supernovae, as well as a power law which could be from either an AGN or X-ray binaries. As for their spectral indices, X-ray binaries are expected, from Persic & Rephaeli (2002), to have power-law slopes of ~1.2, though as stated in Section 1, the full range is Γ ~ 1–2.4, typically between 1–2. The power-law components of both systems of IRAS 18329+5950 as well as IRAS 20550+1656 are within this range. IRAS 19354+4559 is steeper than the others but all of our systems are consistent within error bars with both HMXBs and AGN spectral indices.

Finally, we investigated how our systems’ X-ray luminosities compared to their SFRs. All of our systems’ X-ray luminosities lie within 1σ of the prediction from star formation alone. This implies that their X-ray output is in a regime where it can be attributed mostly, if not entirely, to processes tied to star formation, such as XRBs and diffuse emission.

In all of these tests, we do not find robust evidence for AGN activity in any of our sources, though we cannot definitively rule out AGN activity either.

This, then, raises the question: why are there no dual AGNs, or even single AGNs, signatures in our systems? Ideally, obtaining more counts for each of our systems would allow us to more conclusively state whether there are no AGNs or even single AGNs, signatures in our systems. Additional methods would permit us to fit more complex models with higher constraining power that could better discriminate between SB and AGN templates. This is a severe problem with IRAS 19354+4559 in particular, as we could only fit it with a single power-law component which clearly has a soft excess, as shown in Figure 4. Additional spatial resolution, such as with Chandra, would be beneficial as well as it could demonstrate more clearly the extension of the X-ray emission, as in the case of IRAS 20550+1656 in Inami et al. (2010). The biggest obstacle among all of our data was perhaps the loss of large portions of our exposures due to background, especially in IRAS 18329+5950 and IRAS 19354+4559.

It is possible that any AGN present in our systems is Compton thick with large (>10^24 cm^2) column densities, hiding nuclear activity. Knowing that these systems are heavily obscured in the optical, we investigated the location of our systems on a BPT diagram (Baldwin et al. 1981) of N[II]/Hα against O[III]/Hβ. In Figure 7, we show IRAS 18329+5950 and IRAS 20550+1656 (Hβ: Kennicutt et al. 2009, [N II], [O III], and Hα: Moustakas & Kennicutt 2006) alongside data and classifications taken from Veilleux & Osterbrock (1987) as reference, and see that they lie in the same region as the SBs and narrow emission line galaxies (those galaxies with profiles akin to H II and LINER systems), similar to Figure 6. We also looked for mid-IR lines in the literature that would be less subject to internal extinction than the optical ones. The only such data found was for IRAS 20550+1656, where a combination of polycyclic aromatic hydrocarbon, [Ne II], and [Ne III] emission suggested the system was a SB rather than an AGN (Inami et al. 2010).

Our data are consistent with there being no prominent AGN present. What does this imply? The simulations from Hopkins et al. (2006) have a large fraction of SMBH growth due to galaxy mergers and imply that the merger rate should map relatively well onto the quasar activation rate. They find that major accretion occurs even during the first passage. The peak quasar activity is associated with the final merger after dust blowout, though lower luminosity activity is predicted both before and after this phase. However, it is possible that Class III mergers may be too early in the merger process to have strong AGN activity (i.e., enough to distinctly surmount SB emission) in the galaxies involved.

Unfortunately, it is observationally ambiguous how long any single merger has been going on, and thus merging systems without AGNs provide little hint as to how far “behind schedule” they are with respect to simulations such these. This most luminous phase of the AGN is the likely culprit of the correlations presented in Section 1. Other studies, however, argue that fueling during mergers is not the main avenue for activating a central SMBH. Kocevski et al. (2012) find in a sample of 72 systems at larger redshifts (1.5 < z < 2.5) that AGNs are no more likely to possess a disturbed morphology than their control sample systems. In a more local sample (0.3 < z < 1) of 140 AGNs with XMM-Newton data, Cisternas et al. (2011) find that 85% show no signs of recent major mergers, which is not significantly different (<1σ) from this same fraction of their control sample. Grier et al. (2011), using the Spitzer Infrared Nearby Galaxies Survey, find that 60% of galaxies host AGNs...
from X-ray data and these galaxies are not in merging systems. It is possible, however, that most of their BH growth happened in previous major mergers. The presence of AGNs in galaxies with pseudobulges (Mathur et al. 2012 and references therein) clearly points to an alternative path of BH growth.

If the SMBHs in our systems are actually not accreting, rather than simply too weak to be discerned from star formation, then we must look at simulations with more caution. Does intense nuclear star formation or some other merger-related process prevent the ample supply of gas and dust from fueling the SMBHs at early stages? Given the small number of systems reported with dual AGNs and the larger number of attempts to find them through varied methods, there could be an issue with this phase of the hierarchical growth route altogether. Some reported with dual AGNs and the larger number of attempts to prevent the ample supply of gas and dust from fueling the nuclear star formation or some other merger-related process than simply too weak to be discerned from star formation, then clearly points to an alternative path of BH growth.

in previous major mergers. The presence of AGNs in galaxies It is possible, however, that most of their BH growth happened from X-ray data and these galaxies are not in merging systems. The Astrophysical Journal

5. CONCLUSION

We present the results from a search for dual AGNs. Based on the environment arguments presented in Section 1, we selected nearby LIRGs (tending to have lower $L_{IR}$ than those observed at higher redshifts) with galaxy separations near the resolution limit of the XMM-Newton and with evidence of interaction. From our imaging analysis, the only system in which two distinct X-ray sources are resolved is IRAS 18329+5950. Only one of these, the eastern source in IRAS 19354+4559, is possibly be dominated by emission from the central few kiloparsecs. The X-ray luminosities of IRAS 18329+5950, IRAS 19354+4559, and IRAS 20550+1656 are all within 1σ of the predicted value from the Mineo et al. (2014) relationships mapping SFR to X-ray luminosity. This suggests that the X-rays for these galaxies arise from star formation rather than AGNs.

The data for each of our systems is not of sufficient quality to find, or conclusively rule out, the presence of AGNs. These results could be improved upon by searching for other nearby LIRG systems with resolvable nuclear regions. If such systems continue, as the three presented in this paper, to be consistent with star formation related emission alone, then we will be able to place observational constraints on the predictions from simulations presented in Section 1.

Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA), and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

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