Active Galactic Nucleus Pairs from the Sloan Digital Sky Survey. III. Chandra X-Ray Observations Unveil Obscured Double Nuclei

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Abstract
We present Chandra ACIS-S X-ray imaging spectroscopy for five dual active galactic nucleus (AGN) candidates. Our targets were drawn from a sample of 1286 [O III]-selected AGN pairs systematically selected from the Sloan Digital Sky Survey Seventh Data Release. Each of the targets contains two nuclei separated by ~3–9 kpc in projection, both of which are optically classified as Type 2 (obscured) AGNs based on diagnostic ratios of the narrow emission lines. Combined with independent, empirical star formation rate estimates based on the host-galaxy stellar continua, the new Chandra X-ray observations allow us to evaluate the dual-AGN hypothesis for each merging system. We confirm two (SDSS J0907+5203 and SDSS J1544+0446) of the five targets as bona fide dual AGNs. For the other three targets, the existing data are consistent with the dual-AGN scenario, but we cannot rule out the possibility of stellar/shock heating and/or one AGN ionizing both gaseous components in the merger. The average X-ray-to-[O III] luminosity ratio in our targets seems to be systematically smaller than that observed in single AGNs but is higher than that seen in dual AGNs selected from AGNs with double-peaked narrow emission lines. We suggest that the systematically smaller X-ray-to-[O III] luminosity ratio observed in dual AGNs than in single AGNs is due to a high nuclear gas column likely from strong merger-induced inflows. Unlike double-peaked-[O III]-selected dual AGNs, the new sample selected from resolved galaxy pairs are not subject to the orientation bias caused by the double-peak line-of-sight velocity splitting selection, which also contributes to lowering the X-ray-to-[O III] luminosity ratio.

Key words: black hole physics – galaxies: active – galaxies: interactions – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies

1. Introduction
The observed growth of structures suggests that mergers of galaxies, and by extension, their central supermassive black holes (SMBHs; Kormendy & Richstone 1995; Ferrarese & Ford 2005), should be common throughout most of cosmic history. The final coalescence of merging SMBHs would produce low-frequency gravitational waves (GWs; e.g., Colpi & Dotti 2011), providing a “standard siren” for cosmology (Hughes 2009) and a direct testbed for strong-field general relativity (Centrella et al. 2010). Unlike LIGO’s stellar mass black holes (Abbott et al. 2016) whose detection is still limited to the relatively nearby universe, merging SMBHs would be detectable close to the edge of the observable universe (Robson et al. 2019). They are being hunted currently by pulsar timing arrays for the more massive, low-redshift population (e.g., Arzoumanian et al. 2018), and in the future by space-borne experiments for the less massive, high-redshift population (e.g., Amaro-Seoane et al. 2017).

While the GWs from merging SMBHs are yet to be detected, it is useful to study their progenitors—pairs of SMBHs selected by their electromagnetic signatures from accreting materials from the surroundings. These so-called “dual active galactic nuclei (AGNs)” are AGN pairs in merging galaxies with typical separations of a few kiloparsecs (Gerke et al. 2007; Comerford et al. 2009; Xu & Komossa 2009). Dual AGNs and AGN pairs in general provide an exciting prospect for understanding massive black hole growth and their merger rates in galaxies in the era of multimessenger astronomy (e.g., Bhowmick et al. 2019). The first concrete evidence for dual AGNs was a serendipitous discovery by Chandra in NGC 6240 (Komossa et al. 2003), a z = 0.02 merging ultraluminous infrared galaxy, which contains two X-ray nuclei separated by ~1″ (~0.7 kpc) in projection. Until recently only a handful of other secure cases were known in the X-rays (e.g., 3C 75 (Hudson et al. 2006), Mrk 463 (Bianchi et al. 2008; Treister et al. 2018), Mrk 266 (Brassington et al. 2007; Mazzarella et al. 2012), and Mrk 739 (Koss et al. 2011); but see also Arp 299 (Ballo et al. 2004) for a candidate), all of which were confirmed by Chandra.

The past decade has seen significant progress in finding concrete evidence for dual AGNs at z < 0.5 thanks to systematic searches using large surveys combined with dedicated follow ups, in particular in the X-rays, mid-IR, and radio (e.g., Green et al. 2010; Fabbiano et al. 2011; Liu et al. 2013, 2018; Comerford et al. 2015; Kocevski et al. 2015; Fu et al. 2015, 2018; Gatti et al. 2016; Koss et al. 2016; Ellison et al. 2017; Satyapal et al. 2017; De Rosa et al. 2018; Vignali et al. 2018; Pfeifle et al. 2019). Liu et al. (2011) identified a sample of 1286 [O III]-selected, spatially resolved AGN pairs from the Sloan Digital Sky Survey (SDSS) Seventh Data Release (DR7; Abazajian et al. 2009). Among the 1286 pairs, 94 have projected nuclear separation r_p < 10 kpc, making them the largest sample of [O III]-selected dual AGN candidates. Each of these galaxies contains two nuclei separated by a few arcsec, both...
of which have individual SDSS spectra. Due to the finite size of SDSS fibers (i.e., fiber collisions), two objects separated by $<55''$ cannot both be spectroscopically observed unless being on overlapping plates. We have corrected for this spectroscopic incompleteness when calculating the frequency of dual AGNs (Liu et al. 2011). Based on the SDSS spectra, both nuclei in the candidates are optically classified as Type 2 (i.e., obscured) AGNs according to diagnostic ionization ratios of narrow emission lines (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Kewley et al. 2001). However, optical diagnostic line ratios only represent indirect evidence for dual AGNs; they cannot conclusively rule out alternative scenarios for the nature of the ionizing sources such as stellar/shock heating, and/or a pair of merging galaxy components ionized by a single active nucleus.

It is generally thought that the X-ray band can provide more direct evidence for nuclear activity. In particular, hard X-rays (defined here as 2–10 keV) are transparent to column densities of $N_{\text{HI}} \lesssim 10^{24} \text{cm}^{-2}$, while Compton-thick AGNs can be revealed at energies $\gtrsim 10$ keV (LaMassa et al. 2011; Lansbury et al. 2015; Nardini 2017).

We here present a new Chandra ACIS-S X-ray imaging of five dual AGN candidates drawn from the parent sample of 94 closely separated, dual AGN candidates (Figure 1). Figure 2 shows their optical and X-ray images. Chandra’s high image quality (FWHM $\lesssim 1''$) and its capability of moderate spectral resolution imaging spectroscopy in the X-rays make it ideal for assessing the dual-AGN hypothesis. Unlike previous Chandra searches for dual AGNs in galaxy pairs hosting single AGNs (e.g., Teng et al. 2012), we target merging galaxies where both nuclei are [O III]-selected AGNs.

The paper is organized as follows. Section 2 describes the target selection and their optical properties. Section 3 presents the new Chandra ACIS-S X-ray observations, data reduction, and data analysis. Section 4 shows the results on the X-ray luminosities and spectral properties, the X-ray contribution from star formation, and the nature of the nuclear ionizing sources. Finally, we discuss the implications of our results in Section 5 and summarize the main conclusions in Section 6. Throughout this paper, we assume a concordance cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and use the AB magnitude system (Oke 1974).

2. Target Selection and Optical Properties

Our targets are drawn from a parent sample of 1286 spectroscopic AGN pairs with $r_p < 10$ kpc and line-of-sight velocity offsets $<600$ km s$^{-1}$ selected from a heterogeneous sample of 138,070 optical AGNs from the SDSS DR7. The optical AGN sample consists of 129,277 Type 2 (i.e., narrow-line) AGNs, 5,564 Type 1 (i.e., broad-line) AGNs, 3,117 Type 1 quasars, and 1,12 Type 2 quasars (Liu et al. 2011). The parent AGN pair sample is dominated by Type 2 AGNs whose optical narrow emission-line ratios are characteristic of Seyferts, LINERs, and/or AGN-H II composites.

From the parent AGN pair sample, we select kiloparsec-scale dual AGN candidates by first requiring $r_p < 10$ kpc. We further select systems in which both nuclei have high enough [O III] fluxes to expect at least 50 hard (2–10 keV) X-ray counts in 15 ks for the weaker component (see details below). We additionally exclude systems with existing Chandra observations to avoid duplicate observations (e.g., Mrk 266). For systems with similar [O III] fluxes, targets that are classified as Seyferts based on the BPT diagram are prioritized over those that are classified as AGN-H II composites to maximize the probability of X-ray detections. Therefore, our final target sample consists of five dual AGN candidates. The distribution of our sample is shown in Figure 1. Tables 1 and 2 list their basic photometric and spectroscopic properties. The stellar velocity dispersion was measured by fitting the host-galaxy stellar continuum using the penalized pixel-fitting (pPXF) method (Cappellari & Emsellem 2004; see the Appendix for details). The total stellar mass was given by the MPA-JHU DR7 catalog from fitting the photometry (Kauffmann et al. 2003b; Salim et al. 2007). Figure 3 shows the narrow emission-line ratios measured from the SDSS spectra subtracted for stellar continua using the pPXF fits. It illustrates that the nuclei in our targets are optically classified as Type 2 Seyferts, LINERs, or AGN-H II composites.

3. Observations, Data Reduction, and Data Analysis

3.1. Chandra ACIS X-Ray Imaging Spectroscopy

We observed the five dual-AGN candidates with the ACIS-S on board the Chandra X-ray Observatory between December 2012 and December 2013 April (Program GO-14700264, PI: X. Liu). All targets were observed on-axis on the S3 chip, 5'2'' to 15'0'' away from the aimpoint. Each target was observed for 15 ks (Table 3). The exposure time was set to obtain $\sim$50 counts in the 2–10 keV range from the [O III] weaker nucleus in each merger, although the estimate was too optimistic. We estimated the X-ray counts from the [O III] luminosity for each nucleus (corrected for [O III] emission due to star formation in AGN-H II composites (Kauffmann & Heckman 2009)), assuming an empirical correlation between the 2 and 10 keV (unabsorbed) and [O III] luminosities. Measurements of $L_{2-10\text{keV}}/L_{\text{[O III]}}$ for optically selected Type 2 AGNs span a wide range (Mulchaey et al. 1994; Heckman et al. 2005; Panessa et al. 2006), with values from a few to a few hundred. For the baseline assumption, we adopted...
Figure 2. SDSS $gri$-color composite, $Chandra$ 0.5–8 keV, 0.5–2 keV, and 2–8 keV images of the five [O III]-selected dual-AGN candidates. Each panel is 50″ × 50″. North is up and east is to the left. The targets are ordered with decreasing projected separation (as labeled, with angular distance in parenthesis) from top to bottom. Magenta circles denote positions of the optical nuclei whereas green circles represent the 90% EER of the detected X-ray sources. Table 1 lists their basic properties.
the mean calibration of Panessa et al. (2006) given by,

\[
\log \left[ \frac{L_{\text{2-10 keV}}}{\text{erg s}^{-1}} \right] = (1.22 \pm 0.06) \log \left[ \frac{L_{\text{[O III]}}}{\text{erg s}^{-1}} \right] + (-7.34 \pm 2.53),
\]

where the [O III] luminosities have been corrected for the Galactic and intrinsic NLR extinction by using the Balmer decrement method via \( \alpha_{\text{H}/H}\beta \) ratio. We accounted for systematic uncertainties using the Heckman et al. (2005) relation based on optically selected (single) Type 2 AGNs. An X-ray power-law spectrum was assumed with an absorbing column density \( N_H = 10^{22} \text{ cm}^{-2} \) (typical for our targets for which enough counts were detected for spectral analysis (see below) and for Type 2 Seyferts; Bassani et al. 1999) and a photon index \( \Gamma = 1.7 \) (typical for unabsorbed Seyferts; Green et al. 2009).

We reprocessed the data using CIAO v4.8 and the corresponding calibration files following standard procedure.\(^7\) We examined the light curve of each observation and found no time interval of high background. We produced counts and exposure maps with the original pixel scale (0.0492 pixel\(^{-1}\)) in the 0.5–2 keV (S), 2–8 keV (H), and 0.5–8 keV (F) bands. The exposure maps were weighted by the above fiducial incident spectrum.

Following the source detection procedure detailed in Wang (2004) and Hou et al. (2017), we detect X-ray sources in the \( S, H, \) and \( F \) bands in each image. With a local false detection probability \( P < 10^{-6} \) (empirically yielding \(-0.1 \) false detection per field), we detected a total of 124 sources in the field of view covered by the S3 and S2 CCDs. For each detected source, we derived background-subtracted and exposure map-corrected count rates in each individual band from within the 90% enclosed-energy radius (EER), taking into account the position-dependent point-spread function and the local background.

Figure 2 shows the ACIS images of the five targets in the \( F, S, \) and \( H \) bands. Table 3 summarizes the X-ray measurements. Given the low count levels, we do not apply any smoothing to avoid artifacts. As we will show in Section 4.1, our targets are significantly weaker hard X-ray emitters than those predicted from both the Panessa et al. (2006) and Heckman et al. (2005) relations based on single optically selected AGNs, resulting in far fewer counts than expected. Seven of the 10 nuclei in our targets were detected in the \( F \)-band. Six nuclei were detected in both \( S \) and \( H \) bands, whereas one nucleus (J1544+0446a) was detected in the \( S \) band only. Three nuclei (J0805+2818b, J1330–0036a, and J1058+3144a) were undetected in the X-rays.

### 3.2. Spectral Analysis and Hardness Ratio

Three of the seven X-ray detected nuclei have sufficient net counts (\( \geq 50 \)) for spectral analysis. For these nuclei, we extracted spectra from within the 90% EER of each source of interest using the CIAO tool *specextract* and built the Response Matrix Files and Ancillary Response Files; the corresponding background spectrum was extracted typically between two to five times the 90% EER. For nucleus J1544+0446b, with the other X-ray detected nucleus located in the background extraction region given the small projected nuclear separation (4″\(^1\)), we further removed the 90% EER of this continuum from the background to eliminate its contamination. We fit each spectrum with an absorbed power-law model. Due to the low net counts, we adopted the C-statistic (a Poisson log-likelihood function, taking into account the known Poisson background, pstat in XSpec) for the spectral fitting (Cash 1979). Figure 4 shows the fitted spectra. Table 3 lists the spectral fitting results. The best-fit power-law spectral index and the absorption column density are consistent with Type-2 AGN for all three nuclei.

For the other four X-ray detected AGNs with \( < 50 \) net counts, we estimate their spectral properties using hardness ratios (HR). The hardness ratio is defined as

\[
HR = \frac{H - S}{H + S},
\]

where \( H \) and \( S \) are the number of counts in the hard and soft X-ray bands, respectively. We adopt the Bayesian Estimation of Hardness Ratios (Park et al. 2006) to measure the HRs and their uncertainties, which is appropriate for the low count regime. Table 3 lists the HR results.

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\(^7\) [http://cxc.harvard.edu/ciao/](http://cxc.harvard.edu/ciao/)
Table 2
Optical Emission-line Properties of the Five [O III]-Selected Dual AGN Candidates

| Name       | Hβ (2) | Hα (3) | [O III] (4) | [N II] (5) | [S II] (6) | [O I] (7) | [O III] Hβ (8) | [N II] Hα (9) | [S II] Hβ (10) | [O I] Hα (11) |
|------------|--------|--------|-------------|------------|------------|-----------|--------------|---------------|----------------|--------------|
| J0907+5203a| 98.8 ± 0.9 | 361.6 ± 8.1 | 632.4 ± 141.8 | 213.0 ± 81.5 | 172.8 ± 80.2 | 69.1 ± 67.4 | 6.4 ± 4.8 | 0.6 ± 0.3 | 0.5 ± 0.2 | 0.2 ± 0.2 |
| J0907+5203b| 130.9 ± 29.9 | 581.7 ± 40.6 | 492.3 ± 49.1 | 348.1 ± 36.3 | 296.2 ± 33.2 | 98.0 ± 25.6 | 3.8 ± 0.9 | 0.6 ± 0.1 | 0.5 ± 0.1 | 0.2 ± 0.0 |
| J0805+2818a| 390.0 ± 102.2 | 1578.6 ± 180.2 | 3808.5 ± 266.3 | 1023.7 ± 161.4 | 554.2 ± 135.7 | 249.4 ± 72.6 | 9.8 ± 2.6 | 0.6 ± 0.1 | 0.4 ± 0.1 | 0.2 ± 0.0 |
| J0805+2818b| 52.7 ± 43.0 | 150.4 ± 40.2 | 360.1 ± 103.3 | 201.1 ± 60.3 | 74.6 ± 70.1 | 29.3 ± 40.2 | 6.8 ± 5.9 | 1.3 ± 0.5 | 0.5 ± 0.5 | 0.2 ± 0.3 |
| J1330—0036a| 111.6 ± 8.2 | 398.8 ± 49.3 | 264.2 ± 12.2 | 182.0 ± 10.2 | 146.1 ± 56.9 | 28.5 ± 46.9 | 2.4 ± 0.2 | 0.5 ± 0.1 | 0.4 ± 0.1 | 0.1 ± 0.1 |
| J1330—0036b| 367.6 ± 144.1 | 1568.2 ± 227.7 | 1120.1 ± 251.0 | 1426.4 ± 218.5 | 539.2 ± 151.3 | 110.7 ± 106.9 | 3.0 ± 1.4 | 0.9 ± 0.2 | 0.3 ± 0.1 | 0.1 ± 0.1 |
| J1058+3144a| 129.7 ± 15.3 | 377.3 ± 50.1 | 228.2 ± 30.0 | 239.2 ± 20.8 | 132.9 ± 51.0 | 25.9 ± 38.8 | 1.8 ± 0.3 | 0.6 ± 0.1 | 0.4 ± 0.1 | 0.1 ± 0.1 |
| J1058+3144b| 238.7 ± 83.8 | 921.0 ± 127.2 | 759.7 ± 145.9 | 762.2 ± 117.9 | 316.4 ± 85.6 | 64.2 ± 62.1 | 3.2 ± 1.3 | 0.8 ± 0.2 | 0.3 ± 0.1 | 0.1 ± 0.1 |
| J1544+0446a| 46.1 ± 38.5 | 209.1 ± 40.6 | 153.7 ± 57.7 | 613.8 ± 68.4 | 238.2 ± 54.4 | 97.9 ± 44.9 | 3.3 ± 3.1 | 2.9 ± 0.7 | 1.1 ± 0.3 | 0.5 ± 0.2 |
| J1544+0446b| 165.8 ± 62.6 | 749.4 ± 122.0 | 285.9 ± 85.7 | 643.3 ± 105.5 | 364.2 ± 86.3 | 105.7 ± 65.9 | 1.7 ± 0.8 | 0.9 ± 0.2 | 0.5 ± 0.1 | 0.1 ± 0.1 |

Note. (2)-(7) Optical emission-line fluxes and 1σ uncertainties in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$; (8)-(11) Optical diagnostic emission-line ratios and 1σ uncertainties estimated from error propagation.
For the three sources without X-ray detection and one nucleus (J1544+0446a) without X-ray detection in H band, we estimate the X-ray net counts 3σ upper limit using the CIAO tool $aprate$.

4. Results

4.1. X-Ray Luminosities

X-ray emission provides the most direct evidence for nuclear activity. The 2–10 keV hard X-ray band is transparent to column densities of $N_H \lesssim 10^{24}$ cm$^{-2}$. To infer X-ray luminosity, we assume a simple absorbed power-law model. For the three nuclei with enough counts for X-ray spectral analysis, we adopt the best-fit column density and photon index given in Table 3. For the other seven nuclei without enough counts or without X-ray detection, we assume a photon index of 1.7 and an absorption column density $N_H = 10^{22}$ cm$^{-2}$. In Table 4 we list the unabsorbed/intrinsic X-ray luminosity or upper limit of each nucleus in the total, soft, and hard bands, respectively.

The adopted single absorbed power-law model is most likely too simple for the X-ray spectra of obscured AGNs, in which thermal emission from starburst components and/or scattered nuclear emission are often present (e.g., Turner et al. 1997a, 1997b). However, the low counts of our detections do not allow us to test more realistic models. In addition, our estimates of the intrinsic absorbing column may not necessarily reflect the true values in cases of patchy obscuration and/or significant scattering off of an ionized medium in Compton-thick (i.e., $N_H \sim 10^{24}$ cm$^{-2}$ or larger) AGNs (which represent about half of the local Type 2 Seyfert population; Risaliti et al. 1999), as observed in NGC 6240 (e.g., Vignati et al. 1999; Ptak et al. 2003) and in NGC 1068 (e.g., Matt et al. 1997; Guainazzi et al. 1999), although, again, the quality of our data do not allow us to robustly test these possibilities.
The seven X-ray detected nuclei have estimated unabsorbed 0.5–8 keV luminosities ranging from $3.1 \times 10^{40}$ to $4.1 \times 10^{42}$ erg s$^{-1}$. One nucleus J1544+0446a is not detected in the hard band, and the remaining six hard X-ray detected nuclei have estimated unabsorbed 2–10 keV luminosities ranging from $9.0 \times 10^{40}$ to $4.0 \times 10^{42}$ erg s$^{-1}$. Figure 5 shows the comparison of [O III] luminosities (both observed and extinction-corrected) and 2–10 keV X-ray luminosities (both observed and unabsorbed). The estimated upper limits for the four hard X-ray undetected nuclei range from $6.5 \times 10^{40}$ to $5.1 \times 10^{41}$ erg s$^{-1}$ in 2–10 keV. These luminosity estimates are comparable to or smaller than those of the previously known X-ray confirmed dual AGNs (e.g., Komossa et al. 2003; Ballo et al. 2004; Hudson et al. 2006; Bianchi et al. 2008; Koss et al. 2011; Mazzarella et al. 2012).

4.2. X-Ray Contribution from Nuclear Starburst

The estimated intrinsic hard X-ray luminosities of our targets are close to or below $\sim 10^{42}$ erg s$^{-1}$—the characteristic upper limit for the most luminous star-forming galaxies (e.g., Zezas et al. 2001). Hence it is possible that much or all of the luminosity is due to star formation. X-ray spectral shape offers another diagnostic to discriminate between AGN and starburst scenarios. However, the uncertainties of our spectral estimates are too large to draw firm conclusions for the majority of the nuclei.

We use independent star formation rate (SFR) estimates to test the AGN scenario for each nucleus. To estimate the expected X-ray emission due to star formation within similar apertures used to perform our X-ray extraction (typically a radius of 2″), we use the SDSS fiber SFR given by the MPA-JHU DR7 catalog (Salim et al. 2007). For galaxies classified as AGNs or composites according to the optical BTP diagram, which are the case for our targets, the SFRs are estimated by constructing the likelihood distribution of the specific SFR as a function of the 4000 Å break $D_n(4000)$ based on the star-forming sample (Brinchmann et al. 2004) multiplied by the stellar mass.

To derive X-ray luminosities from the fiber SFRs, we adopt the empirical calibration of Ranalli et al. (2003, see also Grimm et al. 2003) based on 23 nearby star-forming galaxies, which is given by

$$L_{0.5–2\text{ keV}}^{\text{SF}} = 4.5 \times 10^{39} \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \text{ erg s}^{-1},$$

$$L_{2–10\text{ keV}}^{\text{SF}} = 5.0 \times 10^{39} \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \text{ erg s}^{-1},$$

with an rms scatter of 0.27 dex and 0.29 dex. In Table 4 we list the fiber SFR estimates and the derived $L_{0.5–2\text{ keV}}^{\text{SF}}$ and $L_{2–10\text{ keV}}^{\text{SF}}$ estimates for each nucleus. Figure 6 compares the expected X-ray luminosities due to star formation against the observed X-ray luminosities in the soft and hard bands. In both bands, the predicted X-ray contribution from star formation for the majority of our targets’ nuclei is below the observed X-ray luminosity, suggesting an additional excitation source from the AGN. We caution, however, that there are significant systematic uncertainties of our estimates of the expected X-ray luminosities due to star-formation-related processes (e.g., uncertainties in the initial mass function, extinction correction; Liu et al. 2013).

We also test the contribution to hard X-ray luminosity from low-mass X-ray binaries, which is proportional to stellar mass ($M_*$). Based on the $L_X$–$M_*$ relations from Gilfanov (2004) or Lehmer et al. (2010), the estimated contribution from stellar mass enclosed in the SDSS fiber is negligible compared to the contribution from star-forming activity (typically <10% and never exceeding 30%).

4.3. Results on Individual Targets

4.3.1. SDSS J0907+5203

Both galaxies in the merger are optically classified as Type 2 Seyferts (Figure 3). Both nuclei were detected in both soft and hard X-ray bands. The northern galaxy (J0907+5203b) has...
Seyferts in nearby galaxies

**Figure 5.** Hard X-ray luminosities vs. [O III] luminosities. Left panel: observed 2–10 keV luminosity vs. observed [O III] luminosity. For comparison, hard X-ray selected AGNs, [O III] bright AGNs (Heckman et al. 2005), and a sample of Liu et al. (2013) are shown as blue squares (Type 1 s as filled and Type 2 s as open), gray circles (Type 1 s as filled and Type 2 s as open), and yellow hollow squares, respectively. The mean relation for hard X-ray selected AGNs (both Type 1 and Type 2) and optically selected Type 1 AGNs (Heckman et al. 2005), optically selected Type 2 AGNs (Heckman et al. 2005) and double-peaked [O III]-selected dual AGNs (Liu et al. 2013) are shown by blue dashed–dotted–dotted, gray dashed, and yellow dotted lines. Right panel: unabsorbed 2–10 keV luminosity vs. extinction-corrected [O III] luminosity. For comparison, newly optically selected Seyfert galaxies (Panessa et al. 2006) are shown as gray circles. The gray dashed–dotted line is the mean relation for mixed Seyferts in nearby galaxies (Panessa et al. 2006) and the yellow dotted line is that for double-peaked [O III] selected dual AGNs (Liu et al. 2013).

**Table 4**

| Name | log\(L_{X,0.5-8}\) | log\(L_{X,0.5-2}\) | log\(L_{X,2-10}\) | log\(L_{X,2-10,obs}\) | log\(L_{[O III],obs}\) | log\(L_{[O III],lum}\) | SFR | log\(L_{SF}\) | log\(L_{SF}\) |
|------|-----------------|-----------------|----------------|----------------|----------------|----------------|-----|----------------|----------------|
| J0907+5203a | 41.67±0.08 | 40.68±0.26 | 41.75±0.01 | 41.71±0.09 | 40.76±0.09 | 40.94±0.09 | 0.59±1.61 | 39.42±0.57 | 39.47±0.57 |
| J0907+5203b | 42.35±0.04 | 41.89±0.10 | 42.27±0.05 | 42.20±0.05 | 40.66±0.04 | 40.98±0.04 | 1.28±2.05 | 39.76±0.52 | 39.81±0.52 |
| J0805+2818a | 42.24±0.09 | 41.99±0.12 | 42.01±0.15 | 41.97±0.15 | 42.27±0.03 | 42.53±0.03 | 11.68±13.50 | 40.72±0.37 | 40.77±0.37 |
| J0805+2818b | <41.87 | <41.81 | <41.71 | <41.68 | 41.25±0.11 | 41.21±0.11 | 2.24±3.31 | 40.00±0.30 | 40.05±0.30 |
| J1330–0036a | <40.90 | <40.71 | <41.05 | <41.01 | 40.29±0.02 | 40.45±0.02 | 0.35±0.49 | 39.20±0.38 | 39.24±0.38 |
| J1330–0036b | 41.16±0.13 | 40.84±0.13 | 40.96±0.14 | 40.92±0.14 | 40.92±0.11 | 41.21±0.11 | 3.98±5.57 | 40.25±0.45 | 40.30±0.45 |
| J1058+3144a | <41.32 | <41.20 | <41.30 | <41.26 | 40.50±0.05 | 40.51±0.05 | 1.95±2.73 | 39.94±0.38 | 39.99±0.38 |
| J1058+3144b | 42.61±0.05 | 42.13±0.14 | 42.61±0.05 | 42.47±0.05 | 41.03±0.08 | 41.24±0.08 | 2.44±3.15 | 40.04±0.50 | 40.09±0.50 |
| J1544+0446a | 40.49±0.24 | 40.35±0.26 | 40.81 | 40.77 | 39.8±0.14 | 40.16±0.14 | 0.37±1.09 | 39.22±0.59 | 39.27±0.59 |
| J1544+0446b | 41.87±0.06 | 41.43±0.24 | 41.75±0.07 | 41.63±0.07 | 40.08±0.11 | 40.42±0.11 | 0.91±0.72 | 39.61±0.54 | 39.66±0.54 |

Note. (2)–(4) Unabsorbed luminosity in 0.5–8 (F), 0.5–2 (S) and 2–10 keV bands. The luminosity of targets marked with footnote “a” are derived from the fitted spectrum, while the others are converted by assuming an absorbed power law with a photon index of 1.7 and an absorption column density; (5) observed luminosity in 2–10keV bands; (6)–(7) observed and extinction-corrected [OIII] luminosity; (8) fiber star formation rate in units of given by the MPA–HU DR7 catalog inferred from \(D_0(4000)\); (9)–(10) 0.5–2 (S) and 2–10keV bands X-ray luminosities due to star formation.

enough counts for X-ray spectral analysis, which suggests moderate nuclear obscuration, with an estimated column density of \(N_H \approx 2.6^{+1.1}_{-1.0} \times 10^{22} \) cm\(^{-2}\). The spatial profiles of the two nuclear X-ray sources are consistent with the AGN scenarios for both galaxies. For both galaxies, the expected star-formation-induced X-ray luminosities are too low to explain the observed values in both soft and hard X-ray bands (Figure 6), consistent with the dual AGN scenario.

4.3.2. SDSS J0805+2818

The NW nucleus (J0805+2818a) in the merger is optically classified as a Type 2 Seyfert whereas the SE nucleus (J0805+2818b) a Type 2 Seyfert or a LINER (Figure 3). Only the NW nucleus was detected in both soft and hard X-ray bands; the SE nucleus was detected in neither. The host galaxy of the SE nucleus shows strong Balmer absorption features in the SDSS spectrum characteristic of post-starburst galaxies.
For the NW nucleus, both the spatial profile of the X-ray source and the comparison between the observed to the expected star-formation-induced X-ray luminosities (Figure 6) are consistent with the AGN scenario. For the SE nucleus, on the other hand, the upper limits of the X-ray luminosities (Figure 6) are still consistent with the presence of an additional AGN, although the possibility that one AGN in the NW nucleus ionizes gas in both galaxies cannot be ruled out.

4.3.3. SDSS J1330−0036

The NW nucleus (J1330−0036a) in the merger is optically classified as an H II/AGN composite whereas the SE nucleus (J1330−0036b) a Type 2 Seyfert (Figure 3). Only the SE nucleus was detected in both soft and hard X-ray bands; the NW nucleus was not detected in either. The host galaxy of the NW nucleus shows strong Balmer absorption features in the SDSS spectrum characteristic of post-starburst galaxies (Figure 7). For the SE nucleus, the observed X-ray luminosities are similar to those expected from star-formation-induced X-ray luminosities (Figure 6), although an additional AGN component cannot be ruled out given significant uncertainties in the estimates. For the NW nucleus, on the other hand, the upper limits of the X-ray luminosities (Figure 6) are still consistent with the presence of an additional AGN, although the possibility that one AGN in the NW nucleus ionizes gas in both galaxies cannot be ruled out.

4.3.4. SDSS J1058+3144

The SW nucleus (J1058+3144a) in the merger is optically classified as an H II/AGN composite whereas the NE nucleus (J1058+3144b) a Type 2 Seyfert (Figure 3). Only the NE nucleus was detected in both soft and hard X-ray bands; the SW nucleus was not detected in either. The NE nucleus has enough counts for X-ray spectral analysis, which suggests moderate nuclear obscuration, with an estimated column density of $N_H \approx 6.4^{+6.3}_{-4.5} \times 10^{22} \text{cm}^{-2}$. For the NE nucleus, both the spatial profile of the X-ray source and the comparison between the observed to the expected star formation-induced X-ray luminosities (Figure 6) are consistent with the AGN scenario. For the SW nucleus, on the other hand, the upper limits of the X-ray luminosities (Figure 6) are still consistent with the presence of an additional AGN, although the possibility that one AGN in the NW nucleus ionizes gas in both galaxies cannot be ruled out.

4.3.5. SDSS J1544+0446

The SW nucleus (J1544+0446a) in the merger is optically classified as a LINER whereas the NE nucleus (J1544+0446b) a LINER, Type 2 Seyfert or composite (Figure 3). The NE nucleus was detected in both soft and hard X-ray bands; the SW nucleus was detected only in the soft X-ray band. The NE nucleus has enough counts for X-ray spectral analysis, which suggests moderate nuclear obscuration, with an estimated column density of $N_H \approx 3.9^{+1.3}_{-0.6} \times 10^{22} \text{cm}^{-2}$. For the NE nucleus, both the spatial profile of the X-ray source and the comparison between the observed to the expected star formation-induced X-ray luminosities (Figure 6) are consistent with the AGN scenario. An additional AGN component is likely also for the SW nucleus because the observed soft X-ray luminosity is significantly larger than that expected from star-formation-related activity, despite significant uncertainties.

It is noteworthy that those target galaxies without X-ray detection tend to have a blue color in the composite SDSS image (Figure 2). These seem to be relatively small galaxies with young stellar populations. One possibility is that the X-ray emission from these galaxies is dominated by star formation and they are more likely to host a dwarf SMBH that is harder to detect. Whether this is a definitive trend can only be answered with a sizable sample of close pairs.

In summary, the new Chandra X-ray observations support the dual-AGN scenario for two of our five [O III]-selected targets (SDSS J0907+5203 and SDSS J1544+0446). For the other three targets (SDSS J0805+2818, SDSS J1330−0036, and SDSS J1058+3144), the existing data are still consistent.
with the dual-AGN scenario, although the possibility of only one AGN ionizing both components in the mergers cannot be ruled out.

5. Discussion

5.1. Systematically Smaller X-Ray-to-[O III]-luminosity Ratio in Dual AGNs Than in Single AGNs

Figure 5 shows the relation between the hard X-ray luminosity and the [O III] luminosity for each nucleus in our targets. We compare the X-ray-to-[O III]-luminosity ratio of our new targets studied in this work to those observed in both single AGNs and dual AGNs systematically selected from double-peaked [O III] emission lines (Liu et al. 2010a, see also Wang et al. 2009; Smith et al. 2010; Ge et al. 2012; Lyu & Liu 2016; Yuan et al. 2016). We examine both the relation between the observed hard X-ray luminosity \( L_{\text{X,2-10 keV, observed}} \) and the observed [O III] luminosity \( L_{\text{[O III] observed}} \) and that between the unabsorbed hard X-ray luminosity \( L_{\text{X,2-10 keV, unabsorbed}} \) and the extinction-corrected [O III] luminosity \( L_{\text{[O III], extinction-corrected}} \). We use the appropriate comparison samples for the two cases separately, because usually either the observed or the corrected luminosity is available in any given literature sample.

For the \( L_{\text{X,2-10 keV, observed}}/L_{\text{[O III] observed}} \) relation (left panel of Figure 5), the comparison samples include 47 hard X-ray (3–20 keV) selected local AGNs and 55 optically selected local [O III]-bright AGNs (Whittle 1992; Xu et al. 1999) studied by Heckman et al. (2005), and 8 optically selected Type 2 quasars from Ptak et al. (2006) at redshifts \( z \sim 0.3–0.8 \). Heckman et al. (2005) showed that single, optically selected Type 2 AGNs (the gray dashed line) have systematically lower \( L_{\text{X,2-10 keV, observed}} \) (by an average of 1.0 dex) at a given \( L_{\text{[O III] observed}} \) than hard X-ray selected AGNs (both Type 1 and Type 2) and optically selected Type 1 AGNs (the blue dashed–dotted–dotted line), as expected for heavily absorbed AGNs (see also Mulchaey et al. 1994; Panessa et al. 2006). Liu et al. (2013) have shown that the four dual AGNs (individually as the yellow standing glasses and collectively as the yellow dotted line) selected from the parent sample of Type 2 AGNs with double-peaked [O III] emission lines (Liu et al. 2010b) have systematically smaller \( L_{\text{X}}/L_{\text{[O III]}} \) (observed) ratios (by \( \sim 0.8 \pm 0.2 \) dex on average) than even optically selected single Type 2 AGNs. Our new targets seem to have X-ray-to-[O III]-luminosity ratios that are on average in between that observed in single, optically selected Type 2 AGNs and that observed in the dual AGNs selected from double-peaked [O III] emission lines (with some ambiguities and uncertainties due to the upper limits of several measurements).

A similar trend is also seen in the \( L_{\text{X,2-10 keV, unabsorbed}}/L_{\text{[O III] extinction-corrected}} \) relation as shown in the right panel of Figure 5. Again, our new targets seem to have X-ray-to-[O III]-luminosity ratios that are on average in between that observed in single AGNs (the gray dashed–dotted line) and that observed in dual AGNs selected from double-peaked [O III] emission lines (the yellow dotted line). The comparison sample of single AGNs includes 47 Palomar Seyfert galaxies (optically selected Type 1 and Type 2 Seyferts drawn from the Palomar survey of nearby galaxies by Ho et al. 1995) from Panessa et al. (2006). Panessa et al. (2006) has demonstrated that after properly accounting for absorption correction (including for Compton-thick sources), optically selected Type 1 and Type 2 Seyferts follow the same \( L_{\text{X,2-10 keV, unabsorbed}}/L_{\text{[O III], extinction-corrected}} \) relation. In particular, optically selected Type 2 Seyferts, which were significantly X-ray weaker than Type 1 Seyferts, also obey the same relation, after the “Compton-thick” luminosity correction. Liu et al. (2013) has shown that after correction for gas absorption and dust extinction, the unabsorbed hard X-ray luminosities of double-peaked-[O III]-selected dual AGNs appear to be \( \sim 2.4 \pm 0.3 \) dex smaller (at \( \log L_{\text{[O III]}} \) of 42.0) than those expected from the Panessa et al. (2006) relation, \( \log L_{\text{X}} = 1.22\log L_{\text{[O III]}} - 7.54 \), although the absorption correction of dual AGNs may have been significantly underestimated.

5.2. Interpretation: Enhanced Nuclear Absorption from Merger-induced Gas Inflows

Liu et al. (2013) has suggested that the observed X-ray weak tendency in dual AGNs selected in Type 2 AGNs with double-peaked narrow [O III] lines is caused by a combination of a higher nuclear gas column, which may be induced by merger events, and an orientation bias related to the double-peak narrow emission-line selection. In contrast to the Liu et al. (2013) sample, our targets are not subject to the orientation bias due to the line-of-sight velocity splitting requirement caused by the double-peaked [O III] selection. On the other hand, our sample is likely to have a higher nuclear absorption from merger-induced gas infloows than that in single local AGNs, similar to the case of double-peaked-[O III]-selected dual AGNs. Arising from the narrow-line regions that are much further out, the [O III] emission is less subject to nuclear gas absorption and dust obscuration than the hard X-ray emission from the black hole accretion disk corona, which would explain the systematically smaller hard-X-ray-to-[O III]-luminosity ratios observed in dual than in single AGNs. The fact that our targets seem to have hard-X-ray-to-[O III]-luminosity ratios that are smaller than that seen in single AGNs but larger than that observed in double-peaked-[O III]-selected dual AGNs is consistent with the conclusion of Liu et al. (2013) that a combination of two effects (i.e., both merger-enhanced absorption and obscuration and an orientation selection bias) are at work for double-peaked-[O III]-selected dual AGNs.

6. Conclusions

Dual AGNs are crucial to our understanding of the accretion and dynamical evolution of SMBHs in mergers, the effects of merger-induced activity on galaxy evolution, and the initial conditions of close binary SMBHs. Building on Chandra’s previous success on its unique power in resolving dual AGNs, here we have studied the X-ray properties of a sample of five optically selected dual AGN candidates. Our targets were drawn from a sample of 1286 [O III]-selected AGN pairs (both Type 1 and Type 2 sources) systematically selected from the SDSS DR7. Each of the targets contains two nuclei separated by 3–9 kpc in projection, both of which are optically classified as Type 2 (obscured) AGNs based on diagnostic ratios of the optical narrow emission lines. While being systematically selected from the largest sample of dual AGN candidates, the optical classification was inconclusive. Furthermore, because the double nuclei are close (with physical projected separations of a few kiloparsecs), there may be only one AGN ionizing both galaxies, producing two optical emission-line nuclei. Arguments based on the spatial distribution of ionization parameters estimated from optical emission lines cannot conclusively discriminate between the single- and dual-AGN scenarios (e.g., Liu et al. 2010b).
Chandra ACIS-S X-ray imaging presented here helps solve the problem by resolving and localizing the ionizing sources directly in the X-rays. The X-ray confirmation of a systematically selected sample also helps place the optically inferred dual-AGN frequency on firmer ground (Liu et al. 2011). Our main findings are summarized as the following:

1. **Chandra’s superb spatial resolution and sensitivity in the X-rays allowed us to localize the ionizing sources and determine their X-ray properties.** Seven of the 10 nuclei were detected in the full 0.5–8 keV band. Six were detected in both soft (0.5–2 keV) and hard (2–8 keV) bands, whereas one nucleus was detected in the soft band only. Three nuclei were undetected in the X-rays (Table 3).

2. The hard X-rays directly probe the accretion disk corona of the accreting SMBHs, providing a more robust estimate of the intrinsic AGN luminosity than using [O III] λ5007 luminosity as a surrogate. In 3 of the 10 nuclei we observed enough counts to perform spectral fittings to constrain the X-ray spectral properties and absorption column densities. We fit each X-ray spectrum with an absorbed power-law model. The best-fit power-law spectral indices and the absorption column densities are consistent with them being Type 2 AGNs for all three nuclei. For the other four X-ray detected nuclei, we have estimated their spectral properties and luminosities using HRs. For the three sources without X-ray detection, we estimate the X-ray net counts 3σ upper limit using the CIAO tool apropate (Section 3.2).

3. Combined with independent SFR estimates empirically calibrated based on the host-galaxy stellar continua, the new Chandra X-ray observations allowed us to evaluate the dual-AGN hypothesis for each target. We have confirmed two (SDSS J0907+5203 and SDSS J1544+0446) of the five targets as bona fide dual AGNs. For the other three targets, the existing data are consistent with the dual-AGN scenario, but we cannot conclusively rule out the possibility of stellar and/or shock heating and/or one AGN ionizing both gaseous components in a merger (Section 4.3).

4. The average X-ray-to-[O III] luminosity ratio in our targets seems to be systematically smaller than that observed in single AGNs but is higher than that seen in dual AGNs selected from AGNs with double-peaked narrow emission lines. We suggest that the systematically smaller X-ray-to-[O III] luminosity ratio observed in dual AGNs than in single AGNs is due to a high nuclear gas column density from strong merger-induced inflows. Unlike double-peaked-[O III]-selected dual AGNs, the new sample selected from resolved galaxy pairs is not subject to the orientation bias caused by the double-peaked line-of-sight velocity splitting selection, which also contributes to lowering the X-ray-to-[O III] luminosity ratio (Figure 5).

Our sample size is still too small for a statistical analysis to compare with theoretical predictions from simulations in a meaningful way (e.g., Capelo et al. 2017; Blecha et al. 2018; Rosas-Guevara et al. 2019; Solanes et al. 2019). To put the conclusions on a firm statistical ground, future wide-field, high-resolution, and high-sensitivity X-ray telescopes (such as Lynx X-ray Surveyor; The Lynx Team 2018) may detect thousands of dual AGNs, which will be needed to fully understand black hole growth in mergers and dual AGNs (e.g., Burke-Spolaor et al. 2018; Koss et al. 2019).

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**Facilities:** Chandra X-ray Observatory (ACIS), Sloan.

**Appendix**

In this appendix, we present details of our spectral fitting analysis to carefully measure the host-galaxy stellar continuum and to model the emission-line fluxes over the host-subtracted spectrum. For the host-galaxy spectral fitting, we adopt the pPXF method³ (Cappellari & Emsellem 2004). The method works directly in the pixel space and uses the maximum penalized likelihood formalism to extract as much information as possible from the spectra while suppressing the noise in the solution. After subtracting the host-galaxy continuum using the pPXF best-fit solution, we then model the emission-line-only spectrum using the spectral fitting code qsofit⁹ (Shen et al. 2019). Figures 7 and 8 show the fitting results for all the 10 nuclei in our targets.

³ https://pypi.org/project/pixf/
⁹ https://github.com/legolason/PyQSOFit
Figure 7. Spectral fitting results for the two nuclei in J0907+5203, J0805+2818, and J1330-0036 from top to bottom. For each nucleus, the upper panel shows the best-fit model from the pPXF fit for the host-galaxy stellar continuum shown in red overlaid on top of the SDSS spectrum shown in black. Also shown are the host-galaxy-subtracted emission-line spectrum in magenta, the total model (i.e., host+emission line) in orange, and the total residual (i.e., data-model) in green. The bottom panels show the best-fit model (in red) for the host-subtracted emission lines from the qsofit analysis overlaid on top of the data (in black).
Figure 8. Same as Figure 7, but for J1058+3144 and J1544+0446.

References

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, PhRvL, 116, 061102
Amaro-Seoane, P., Audley, H., Babak, S., et al. 2017, arXiv:1702.00786
Arzoumanian, Z., Baker, P. T., Brazier, A., et al. 2018, ApJ, 859, 47
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Ballo, L., Braito, V., Della Ceca, R., et al. 2004, ApJ, 600, 634
Bassani, L., Dadina, M., Maiolino, R., et al. 1999, ApJS, 121, 473
Bhowmick, A. K., Di Matteo, T., & Myers, A. D. 2019, arXiv:1902.05954
Bianchi, S., Chiaberge, M., Piconcelli, E., Guainazzi, M., & Matt, G. 2008, MNRAS, 386, 105
Blecha, L., Snyder, G. F., Satyapal, S., & Ellison, S. L. 2018, MNRAS, 478, 3056
Brassington, N. J., Ponman, T. J., & Read, A. M. 2007, MNRAS, 377, 1439
Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151
Burke-Spolaor, S., Blecha, L., Bogdanović, T., et al. 2018, in ASP Conf. Ser. 517, Science with a Next Generation Very Large Array, ed. E. Murphy (San Francisco, CA: ASP), 677
Capello, P. R., Dotti, M., Volonteri, M., et al. 2017, MNRAS, 469, 4437
Cappellari, M., & Emsellem, E. 2004, PASP, 116, 138
Cash, W. 1979, ApJ, 228, 939
Centrella, J., Baker, J. G., Kelly, B. J., & van Meter, J. R. 2010, RvMP, 82, 3069
Colpi, M., & Dotti, M. 2011, ASL, 4, 181
Comerford, J. M., Gerke, B. F., Newman, J. A., et al. 2009, ApJ, 698, 956
Comerford, J. M., Pooley, D., Barrows, R. S., et al. 2015, ApJ, 806, 219
De Rosa, A., Vignali, C., Husemann, B., et al. 2018, MNRAS, 480, 1639
Ellison, S. L., Secrest, N. J., Mendel, J. T., Satyapal, S., & Simard, L. 2017, MNRAS, 470, L49
Fabbiano, G., Wang, J., Elvis, M., & Risaliti, G. 2011, Natur, 477, 431
Ferrarese, L., & Ford, H. 2005, SSRv, 116, 523
Fu, H., Steffen, J. L., Gross, A. C., et al. 2018, ApJ, 856, 93
Fu, H., Wrobel, J. M., Myers, A. D., Djorgovski, S. G., & Yan, L. 2015, ApJL, 815, L6
Gatti, M., Shankar, F., Bouillot, V., et al. 2016, MNRAS, 456, 1073
