



# The X-ray view of merger-induced active galactic nuclei activity at low redshift

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## ABSTRACT

Galaxy mergers are predicted to trigger accretion on to the central supermassive black holes, with the highest rates occurring during final coalescence. Previously, we have shown elevated rates of both optical and mid-IR selected active galactic nuclei (AGNs) in post-mergers, but to date the prevalence of X-ray AGNs has not been examined in the same systematic way. We present *XMM-Newton* data of 43 post-merger galaxies selected from the Sloan Digital Sky Survey along with 430 non-interacting control galaxies matched in stellar mass, redshift, and environment in order to test for an excess of hard X-ray (2–10 keV) emission in post-mergers attributable to triggered AGNs. We find two X-ray detections in the post-mergers ( $4.7^{+9.3}_{-3.8}$  per cent) and nine in the controls ( $2.1^{+1.5}_{-1.0}$  per cent), an excess of  $2.22^{+4.44}_{-2.22}$ , where the confidence intervals are 90 per cent. While, we therefore do not find statistically significant evidence for an X-ray AGN excess in post-mergers ( $p = 0.26$ ), we find a factor of  $\sim 17$  excess of mid-IR AGNs in our sample, consistent with the past work and inconsistent with the observed X-ray excess ( $p = 2.7 \times 10^{-4}$ ). Dominant, luminous AGNs are therefore more frequent in post-mergers, and the lack of a comparable excess of 2–10 keV X-ray AGNs suggests that AGNs in post-mergers are more likely to be heavily obscured. Our results are consistent with the post-merger stage being characterized by enhanced AGN fueling, heavy AGN obscuration, and more intrinsically luminous AGN, in line with theoretical predictions.

**Key words:** galaxies: active – galaxies: interactions – galaxies: Seyfert – infrared: galaxies – X-rays: galaxies.

## 1 INTRODUCTION

The supermassive black holes (SMBHs) that power active galactic nuclei (AGNs) appear to have been in place from the earliest epochs (e.g. Bañados et al. 2018, and references therein), and the ubiquitous presence of AGN throughout cosmic history makes the AGN power source, SMBH growth mechanism, and the effect of AGN on their host galaxies a central topic of study for extragalactic astrophysics (for a review, see Kormendy & Ho 2013). While mergers are a central event in the build-up of galaxies over cosmic history, and are a natural mechanism for nuclear fueling, the relationship between galaxy mergers and periods of AGN activity has remained murky. On one hand, numerous morphological studies of moderate redshift ( $z \sim 0.3$ –2.5) AGN host galaxies have found no significant preference for mergers over isolated galaxies, suggesting that mergers do not play a significant role in the fueling of SMBHs (e.g. Cisternas et al. 2011; Kocevski et al. 2012; Schawinski et al. 2012; Villforth et al. 2014, 2017, 2019). However, an important subtlety appears to be how the AGNs are selected, with obscured AGNs being found more frequently in mergers (Kocevski et al. 2015; Lanzuisi et al. 2015; Ricci et al. 2017; Donley et al. 2018), along with radio-loud AGNs

(Chiaberge et al. 2015) and the most bolometrically luminous and/or reddened AGNs (Koss et al. 2010, 2012; Treister et al. 2012; Glikman et al. 2015; Fan et al. 2016; Koss et al. 2018).

Approaching the question in the opposite direction, studies of galaxy mergers at low redshift find a statistically significant enhanced AGN fraction (Ellison et al. 2011, 2013; Lackner et al. 2014; Satyapal et al. 2014; Goulding et al. 2018; Ellison et al. 2019), and Ellison, Patton & Hickox (2015) have previously shown that for *Sloan Digital Sky Survey* (SDSS; York et al. 2000) galaxies at  $z \sim 0$  the merger–AGN connection depends on selection technique (e.g. optical emission lines, mid-IR colour, radio properties). Such statistical studies of the merger–AGN connection at low  $z$  were made possible by the availability of large, multiwavelength sky surveys such as SDSS, FIRST/NVSS (Becker, White & Helfand 1995; Condon et al. 1998), and the *Wide-field Infrared Survey Explorer* (Wright et al. 2010). To date, however, there have been only two all-sky X-ray surveys: *ROSAT* (Voges et al. 1999), which operated at very soft X-ray energies (0.1–2.5 keV), and the Neil Gehrels *Swift* Observatory Burst Alert Telescope (BAT; Barthelmy et al. 2005), which continuously surveys the sky at very hard X-ray energies (14–195 keV). While both surveys are quite shallow and have poor angular resolution, the sensitivity of BAT to very hard X-rays makes it uniquely capable of detecting both obscured and unobscured AGNs with high reliability and completeness in the local universe. This has enabled important studies of the properties and environments of hard

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X-ray selected AGNs, which have shown that they are associated with an excess of galaxy mergers (Koss et al. 2010, 2011, 2012, 2018, see also Powell et al. 2018). However, while low- $z$  galaxies selected to host hard X-ray AGNs show an enhancement in merger fraction, to date no study has approached the question from the other way around: Do low- $z$  galaxy mergers show an enhancement in X-ray AGNs? Required for such a study is a large sample of galaxies observed in X-rays, with sufficient depth such that non-detections carry physical significance, and preferably observed serendipitously to avoid a selection bias for galaxies believed to host an AGN a priori.

Since its launch in 1999, the *XMM-Newton* telescope has completed over 14 000 observations. Its relatively poor angular resolution (several arcsec) is compensated by its large field of view (radius  $\sim 15$  arcmin) and sensitivity in the 0.2–10 keV band comparable to the *Chandra X-ray Observatory*. Owing to this large field of view, the vast majority of sources found in *XMM-Newton* data are serendipitous, and the latest iteration of the *XMM* source catalogue (4XMM DR9; Webb et al. 2019)<sup>1</sup> has 810 795 detections of 550 124 unique sources. While 4XMM is therefore an invaluable resource for large statistical X-ray studies of the properties of *detected* sources, sources observed by *XMM-Newton* that are not in the 4XMM catalogue cannot be treated as undetected at some flux limit, because the field of view of *XMM-Newton* is divided into multiple CCDs, separated by significant gaps, each with its own sensitivity and bad pixels. As a result, population studies requiring accurate knowledge of whether or not an *XMM-Newton* observation legitimately constrains the X-ray flux of an object, require an independent analysis of the data, performed in a homogeneous manner for all objects.

Additionally, because the intrinsic X-ray luminosities of AGNs are strongly correlated with their mid-IR luminosities (e.g. Asmus et al. 2015; Secrest et al. 2015; Stern 2015), the ratio of the *apparent* hard X-ray (2–10 keV) luminosity of an AGN, which *XMM-Newton* can measure, and its mid-IR luminosity may provide insight into the line-of-sight absorption to the AGN (Satyapal et al. 2017), which is predicted to reach its peak in late-stage galaxy mergers when AGN activity is also more likely to be selected in the mid-IR (Blecha et al. 2018). Finally, while mid-IR selection is insensitive at lower AGN luminosities (relative to its host galaxy), hard X-ray selection remains highly reliable down to luminosities of  $L_{2-10\text{ keV}} \sim 10^{40} \text{ erg s}^{-1}$ , below which XRB activity in extreme starbursts may be a contaminant in lower angular resolution data (e.g. Fornasini et al. 2018; Lehmer et al. 2019).

In this work, we carry out a detailed assessment of both X-ray detections and non-detections in a sample of 43 post-merger systems, the merger stage that exhibits the greatest AGN enhancement in the optical and mid-IR (e.g. Ellison et al. 2013; Satyapal et al. 2014), which we then compare to results obtained at mid-IR and visual (optical) wavelengths. Throughout this work, we use a flat  $\Lambda$ CDM cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $\Omega_M = 0.3$ . Unless otherwise noted, all X-ray fluxes quoted in this work are observed-frame 2–10 keV and all X-ray luminosities are rest-frame 2–10 keV and apparent (not corrected for intrinsic  $N_H$ ). All stellar masses and star formation rates (SFRs) are given as  $\log_{10}(M_*/M_\odot)$  and  $\log_{10}(M_*/M_\odot \text{ yr}^{-1})$ .

## 2 METHODS

### 2.1 Post-merger and control selection

Our post-merger sample is assembled from two components: (1) new *XMM* observations of previously identified PMs from the SDSS; and (2) a visual search for PMs in existing *XMM* archival observations. For the first component, we selected post-mergers from a larger, visually-classified sample of galaxy pairs and mergers selected from the SDSS, Data Release 7 (DR7; Abazajian et al. 2009), and described in detail in Ellison et al. (2013), Sections 2.2 and 2.3. Briefly, a galaxy is considered to be a post-merger if it shows strong morphological asymmetry, tidal tails/streams, the outer remnants of another galaxy, or all of the above, and does not have a close companion indicating an ongoing merger or flyby. We limit our sample to those with redshifts between 0.01 and 0.2, and we use stellar masses and SFRs from the MPA-JHU catalogue for DR7,<sup>2</sup> with stellar masses following Kauffmann et al. (2003a), Salim et al. (2007), and SFRs following Brinchmann et al. (2004). We acquired *XMM-Newton* observations for 13 post-mergers during cycle AO15 (proposal ID 078515; PI: Ellison). These observations were designed to detect a heavily-absorbed ( $N_H = 5 \times 10^{23} \text{ cm}^{-2}$ ) AGN with an intrinsic 2–10 keV X-ray luminosity of  $10^{42} \text{ erg s}^{-1}$  with 50 counts between 0.3–10 keV.

To complement our new observations, we searched for post-mergers with archival *XMM-Newton* observations by cross-matching all galaxies with stellar mass measurements from the MPA-JHU catalogue to the *XMM-Newton* observation log from 2019 November 24 to within 15 arcmin, the approximate radius of the EPIC field of view, returning 36 552 objects with 72 635 science observations. We then matched these objects on to the Galaxy Zoo for SDSS DR7 (Lintott et al. 2008, 2011),<sup>3</sup> and visually inspected the SDSS thumbnails for all objects with a merger vote fraction of  $P_{\text{MG}} \geq 0.3$  to identify additional post-mergers.

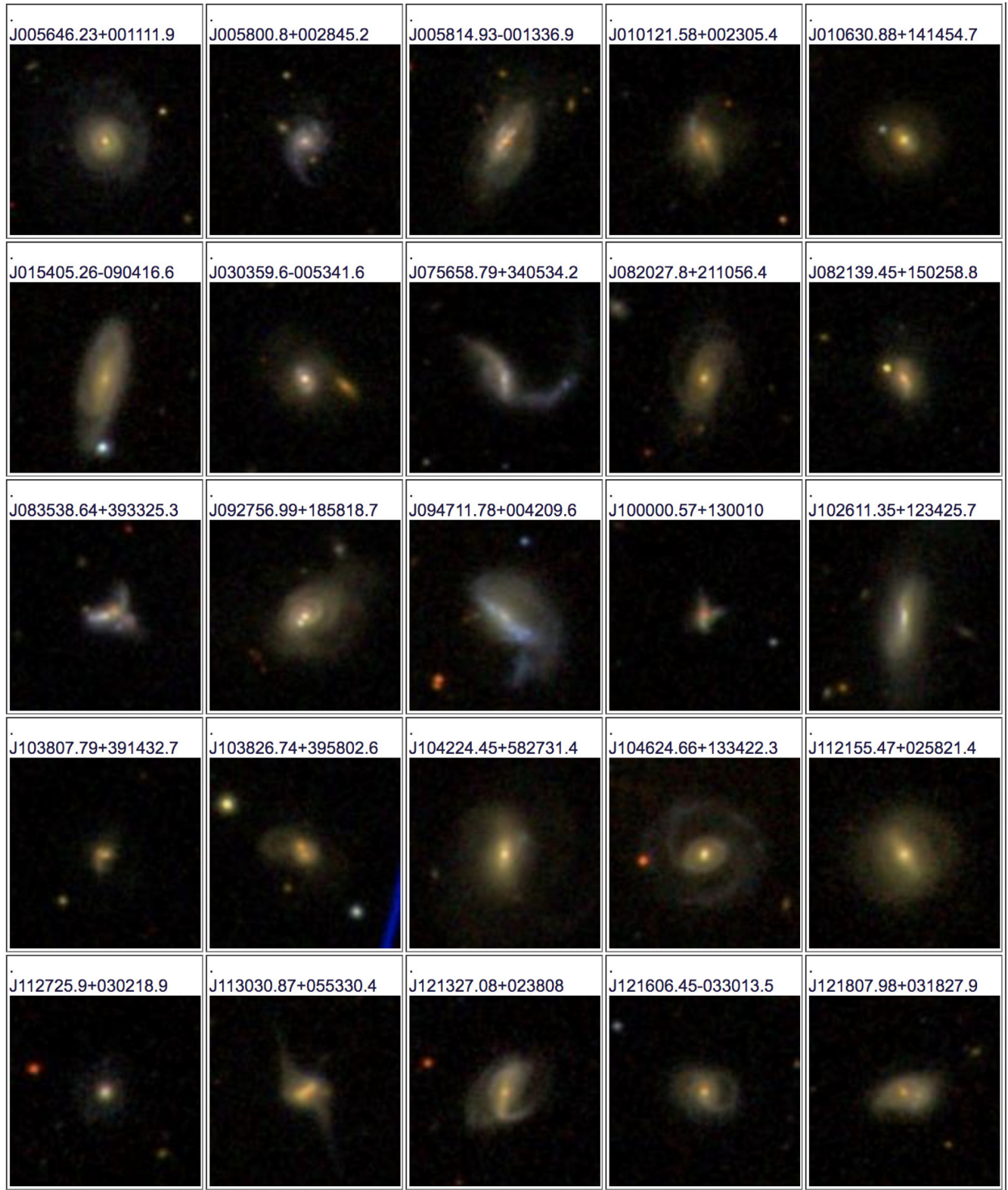
We selected control galaxies in the following manner. For each post-merger, we matched all galaxies not in our post-merger list to within  $\pm 0.1$  dex in stellar mass,  $\pm 0.01$  in redshift, and  $\pm 0.1$  dex in normalized environment parameter  $\delta_5$ , as described in Ellison et al. (2013, Section 2.2). We manually inspected all candidate control galaxies for each post-merger, further flagging interactions, and occasionally finding additional post-mergers. After inspection, we re-ran the control matching procedure, excluding interactions and folding in additional post-mergers, and repeated this process until all candidate controls were inspected and no additional post-mergers were found.

After downloading and reprocessing the data through the pipeline described in Section 2.2, we allowed only controls with exposure times equal to or *longer* than their corresponding post-merger. We then reduced the *effective* exposure time of the controls to match that of the post-merger by multiplying their X-ray signal-to-noise ratio by  $\sqrt{t_{\text{post-merger}}/t_{\text{control}}}$ , where  $t$  is the exposure time. This ensures that differences in detection fraction are not biased by differences in exposure time, and allows for a much larger number of control galaxies for a given post-merger than would have been possible by trying to find controls with *XMM-Newton* observations matched closely in exposure time. It also has the attractive property that the effective exposure time of a given control is matched *exactly* to the exposure time of its post-merger, and the distribution of exposure times between the sample of post-mergers and their controls is also matched exactly if the number of controls is the same for each post-

<sup>1</sup>[http://xmmssc.irap.omp.eu/Catalogue/4XMM-DR9/4XMM\\_DR9.html](http://xmmssc.irap.omp.eu/Catalogue/4XMM-DR9/4XMM_DR9.html)

<sup>2</sup><https://wwwmpa.mpa-garching.mpg.de/SDSS/DR7>

<sup>3</sup><https://data.galaxyzoo.org>



**Figure 1.** SDSS DR16  $50 \times 50 \text{ arcsec}^2$  thumbnails of the 43 post-mergers studied in this work, ordered by increasing right ascension. Objects detected in X-rays have the logarithm of their rest-frame, apparent X-ray luminosities, in  $\text{erg s}^{-1}$ , listed above their SDSS designations.



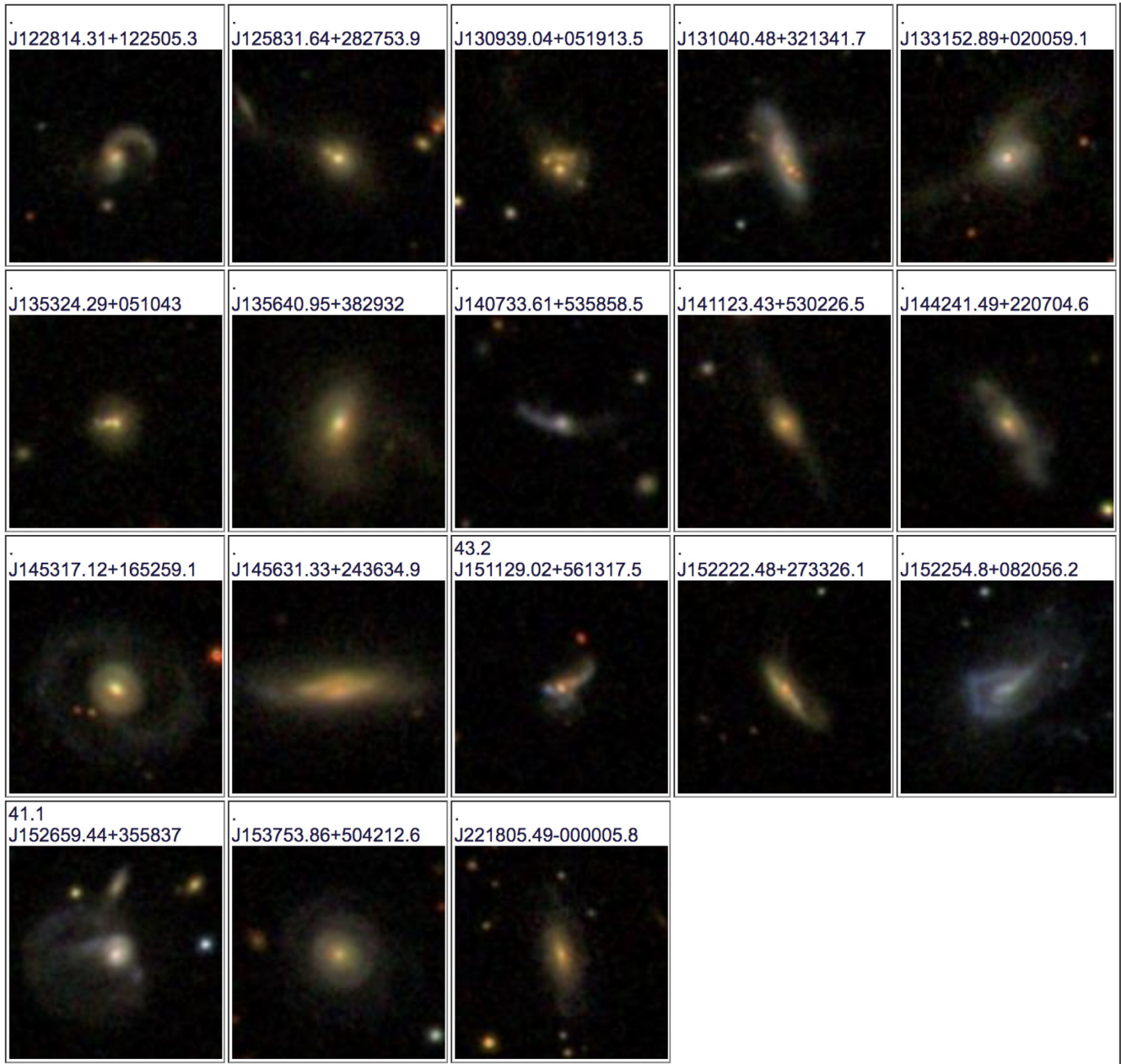


Figure 1. continued.

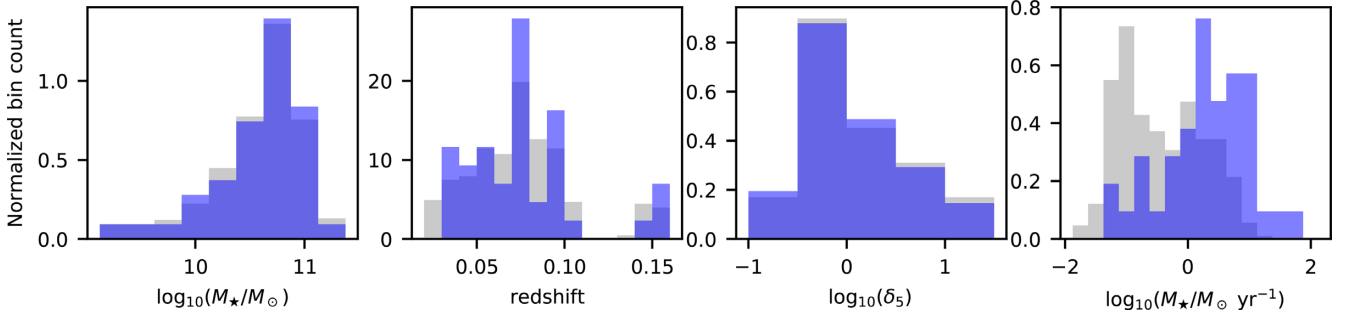
merger. We enforced a specific number of controls per post-merger by discarding post-mergers with fewer than the required number and removing controls with the largest redshift offsets for post-mergers with greater than the required number. Our final sample consists of 43 post-mergers, each with 10 controls (Figs 1, 2, 3; Table 1).

## 2.2 XMM-Newton pipeline

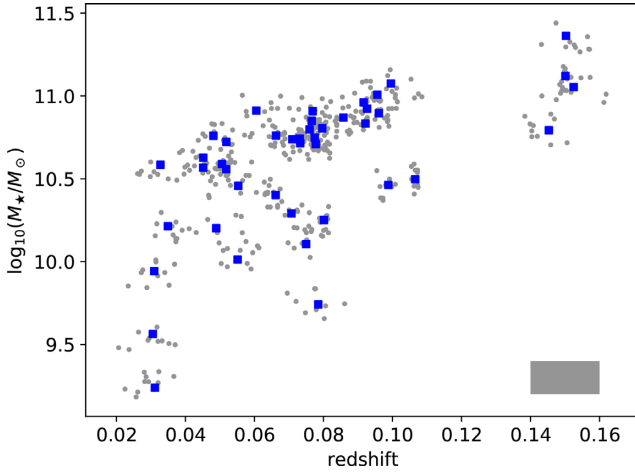
We developed a pipeline that downloads, reprocesses, filters, and extracts source counts and upper limits for *XMM-Newton* data. This carries the advantage that all source counts and upper limits are extracted from the same aperture, using data reprocessed with the same current calibration files (CCFs), and so produces fluxes that are directly comparable between the archival data, including the observations from AO15. Moreover, it also allows us to say whether

or not a source is detected. The pipeline iterates over directories corresponding to each ObsID that contain a set of valid observation data files (ODFs). For each ODF, the SAS (Science Analysis System),<sup>4</sup> version 18.0.0, routine `cifbuild` is called to produce a CCF pertaining to the observation. A SAS summary file is produced using `odfingest`, and then the pn/MOS event files are produced using `epchain/emchain`. For observations containing both scheduled and unscheduled exposures, single pn/MOS event files are produced using `evlistcomb`. The pn and MOS event files are then filtered for science-grade events using `evselect` with the canned screening expressions `#XMMEA_EP/#XMMEA_EM`, and requiring `PATTERN<4` for pn and `PATTERN<12` for MOS. We made high-energy back-

<sup>4</sup><https://www.cosmos.esa.int/web/xmm-newton/sas>



**Figure 2.** Distributions of post-mergers (blue) and their matched controls (grey), normalized such that the total area under the histogram for each population sums to 1. Note that the controls have not been matched in SFR.



**Figure 3.** Post-mergers (blue filled squares) with their matched controls (grey filled circles). There are exactly 10 controls per post-merger. The grey rectangle shows the matching tolerance in redshift and stellar mass around each post-merger.

ground light curves with ( $PI > 10000$  &  $PI < 12000$ ) for pn and ( $PI > 10000$  &  $PI < 15000$ ) for MOS, and we removed periods in which the total counts rate exceeded  $0.35 \text{ counts s}^{-1}$  for pn and  $0.40 \text{ counts s}^{-1}$  for MOS.<sup>5</sup> 2–10 keV X-ray images are produced using *evselect* from which source counts are extracted using *eregionanalyse*. A mean background value is supplied to *eregionanalyse* derived from a source-masked version of the input image, and off-axis vignetting is accounted for by supplying *eregionanalyse* with an exposure map generated using *eexppmap*. The exposure map is also used to ensure that the source region does not fall within a chip gap or other area with censored coverage.

### 2.2.1 Local background

A small fraction of extraction apertures ( $\sim 9.4$  per cent) are within a region of high *local* background, usually either due to the presence of diffuse emission or a neighbouring very bright source. We effectively removed these by flagging all sources with a background rate greater than  $> 1 \times 10^{-5} \text{ counts arcsec}^{-2} \text{ s}^{-1}$  for pn and greater than  $> 5 \times 10^{-6} \text{ counts arcsec}^{-2} \text{ s}^{-1}$  for MOS. A smaller fraction ( $\sim 1.1$  per cent) of source extractions have an anomalously *low* local

background that we found in some cases to be due to *eexppmap* producing an exposure map with CCDs considered to be active when no events were recorded, which can happen when the attitude changes during individual exposures. We effectively removed anomalously low-background sources by requiring a background rate greater than  $2 \times 10^{-7} \text{ counts arcsec}^{-2} \text{ s}^{-1}$  for all data. After making these background cuts, the distributions of local backgrounds are approximately lognormally distributed with means  $-5.48$  for pn and  $-6.01$  for MOS.

### 2.2.2 Uncertainty correction

The mean background value is supplied to *eregionanalyse* as a constant, so the calculated formal error does not account for the uncertainty of the background. To correct this, we added in quadrature to the formal counts rate errors  $\pi R_{\text{src}}^2 \sigma_{\text{bkg}} N^{-1/2} t^{-1} \text{EEF}^{-1}$ , where  $R_{\text{src}}$  is the source extraction aperture in arcsec,  $\sigma_{\text{bkg}}$  is the background standard deviation in  $\text{counts arcsec}^{-2}$ ,  $N$  is the number of  $\text{arcsec}^2$  in the source region, *EEF* is the enclosed energy fraction corresponding to  $R_{\text{src}}$ , and  $t$  is the exposure time at the position of the source.

### 2.2.3 X-ray fluxes

We converted the per-source, per-observation counts rates to rest-frame fluxes by using energy conversion factors (ECFs) we obtained using the *PIMMS* (Portable, Interactive Multi-Mission Simulator), version 4.10, via *WEBPIMMS*.<sup>6</sup> We calculated the redshift-dependent (*K* corrected), filter-dependent ECF for each source using a lookup table, given in Table 2, and linearly interpolating between the redshifts. The per-source, per-observation fluxes were then converted to per-source fluxes across all observations by adding the total energy per  $\text{cm}^2$  across all observations and dividing by the total exposure time:

$$F, \sigma_F = \frac{\sum F_i t_i}{\sum t_i}, \frac{\sqrt{\sum (\sigma_{F_i} t_i)^2}}{\sum t_i}. \quad (1)$$

After filtering for the local background (Section 2.2.1), we found that the distribution of fluxes divided by their errors (*S/N*) follows a normal distribution centred around zero with a sigma of unity for offsets less than 3. We therefore consider detections above  $3\sigma$  (99.9 per cent for a normal distribution) to be a natural demarcation between non-detections and detections, which we employ in this work.

<sup>5</sup><https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epic-filterbackground>

<sup>6</sup><https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl>

**Table 1.** Mean values (and standard errors) of the properties of the post-mergers and their matched control sample, with KS test  $p$ -value.

Property	Post-merger ( $N = 43$ )	Control ( $N = 430$ )	$p$ KS
$\log_{10}(M_*/M_\odot)$	$10.59 \pm 0.06$	$10.58 \pm 0.02$	0.95
redshift	$0.076 \pm 0.005$	$0.076 \pm 0.002$	0.97
$\log_{10}(\delta_5)$	$0.15 \pm 0.10$	$0.15 \pm 0.03$	1.00
$\log_{10}(M_*/M_\odot \text{ yr}^{-1})$	$0.34 \pm 0.11$	$-0.44 \pm 0.03$	$2.5 \times 10^{-7}$

**Table 2.** ECFs used in this work, obtained using PIMMS, version 4.10, converting between observed 2–10 keV counts rates and rest-frame 2–10 keV flux uncorrected for intrinsic absorption. ECFs ( $10^{11} \text{ counts cm}^2 \text{ erg}^{-1}$ ) assume a power-law spectrum with  $\Gamma = 1.7$ , Galactic  $N_H = 3 \times 10^{20} \text{ cm}^{-2}$ , and no intrinsic absorption.

Camera	Redshift	Thin	Medium	Thick
pn	0.00	1.224	1.263	1.213
pn	0.05	1.242	1.282	1.231
pn	0.10	1.260	1.300	1.248
pn	0.15	1.276	1.317	1.265
pn	0.20	1.293	1.335	1.282
MOS	0.00	0.436	0.439	0.423
MOS	0.05	0.443	0.446	0.430
MOS	0.10	0.449	0.452	0.436
MOS	0.15	0.455	0.458	0.442
MOS	0.20	0.461	0.464	0.447

### 2.3 Small number statistics

We use binomial statistics (e.g. Gehrels 1986) to account for uncertainties inherent to estimating the fraction  $n/N$  of a population with some property when limited to a small sample size  $N$  (i.e. the fraction of post-mergers with AGNs when the total number of post-mergers is small). When calculating the null hypothesis  $p$ -value of  $n$  AGNs being observed in a sample of size  $N$  given an expected frequency  $f$ , we use `numpy.random.binomial` and quote the probability of  $n$  or a larger number being observed if  $n/N$  is larger than  $f$ , and a probability of  $n$  or smaller being observed if  $n/N$  is smaller than  $f$ . Under the null hypothesis that the frequency of AGNs in post-mergers is the same as that seen in their controls, for example, the best estimate for the expected frequency  $f$  is  $(n_{\text{post-merger}} + n_{\text{control}})/(N_{\text{post-merger}} + N_{\text{control}})$ . To compare the excess of AGNs in post-mergers compared with their controls, defined as  $(n_{\text{post-merger}}/N_{\text{post-merger}})/(n_{\text{control}}/N_{\text{control}})$ , we generate  $10^6$  random samples of each quantity drawn from the binomial distribution using `numpy.random.binomial` and divide these samples, returning the values at percentile  $(100 \pm \text{CL})/2$ , where CL is the confidence limit. In the case where  $n_{\text{control}} = 0$ , we use the upper CL bound on  $n_{\text{control}}/N_{\text{control}}$  and calculate the corresponding limit on  $(n_{\text{post-merger}}/N_{\text{post-merger}})/(n_{\text{control}}/N_{\text{control}})$ . Throughout this work, the confidence interval is 90 per cent, so upper and lower limits may be interpreted as 95 and 5 per cent, respectively.

## 3 RESULTS AND DISCUSSION

### 3.1 X-rays

Two of the 43 post-mergers are detected in X-rays ( $4.7^{+9.3}_{-3.8}$  per cent) above the adopted detection threshold of  $3\sigma$  (Table 3), both of which have rest-frame, apparent X-ray luminosities greater than  $10^{41} \text{ erg s}^{-1}$ . Nine of the 430 control galaxies are detected ( $2.1^{+1.5}_{-1.0}$  per cent), corresponding to an X-ray detection excess in the post-mergers of  $2.22^{+4.44}_{-2.22}$ . While this excess is not statistically

significant ( $p = 0.26$ ), it is consistent with the factor of 3.75 optical AGN excess found in Ellison et al. (2013), but potentially consistent with no excess at all. The 95 per cent upper limit on the X-ray excess of 6.7 is, however, inconsistent with the factor of 11–20 mid-IR AGN excess in post-mergers found by Satyapal et al. (2014), suggesting that the X-ray counterparts of the mid-IR AGNs are not being detected.

We reiterate that we have not controlled for SFR in our assembly of the control sample (Table 1; Fig. 2, right). This was intentional, as we allow for the possibility that the process that fuels star formation may also fuel AGN activity. Indeed, the mean SFR of the post-mergers is  $9.0 M_\odot \text{ yr}^{-1}$ ,  $7.9^{+6.6}_{-4.5}$  times larger than the mean SFR of the controls (Fig. 2), but consistent with the factor of 3.5 excess seen in the sample of post-mergers studied in Ellison et al. (2013), given the uncertainty.<sup>7</sup> While the factor of  $\sim 2$  excess of X-ray detections in the post-mergers is not significant, we explore the possibility that this number has been spuriously enhanced by greater X-ray binary (XRB) activity in the post-mergers owing to their higher SFRs. We calculated the *expected* X-ray luminosity from XRB activity using the equation (3) from Lehmer et al. (2010), which is a function of both stellar mass and SFR, with the best-fitting parameters given in their Table 4. The mean expected X-ray luminosity from XRB activity for the detected objects is  $1.5 \times 10^{41} \text{ erg s}^{-1}$  for the post-mergers and  $1.1 \times 10^{40} \text{ erg s}^{-1}$  for the controls, 1.7 and 2.5 dex lower than the mean observed X-ray luminosities for both populations ( $7.6 \times 10^{42}$  and  $3.8 \times 10^{42} \text{ erg s}^{-1}$ , respectively), and all of the post-mergers and controls are respectively at least 0.82 and 1.6 dex more luminous in observed X-rays than what is expected from XRB activity. Given the 0.34 dex intrinsic scatter of the relation from Lehmer et al. (2010), we conclude that XRBs are not a significant contaminant in the observed X-ray luminosities of our sample.

### 3.2 Mid-infrared

To compare our X-ray based results to other multiwavelength AGN metrics, we matched the 43 post-mergers and their 430 controls to the AllWISE catalogue within the default 10 arcsec tolerance. For matches with offsets greater than 2 arcsec, we manually checked the AllWISE counterpart positions, removing any spurious matches (e.g. because of the presence of a neighbouring foreground star), leaving 42 out of 43 post-mergers and all 430 controls with AllWISE counterparts. The loss of one post-merger did not significantly affect how well-matched the remaining post-mergers are to the controls, having stellar mass, redshift, and environment KS test  $p$  values of 0.99, 0.88, and 1, respectively. The WISE colour  $W1 - W2$  ( $[3.4 \mu\text{m}] - [4.6 \mu\text{m}]$ ), listed for the post-mergers in Table 3, is especially sensitive to the presence of an AGN, nearly independent of extinction (e.g. Donley et al. 2012), and increases with increasing AGN dominance. We find that the mean  $W1 - W2$  colour is

<sup>7</sup>Uncertainty estimated by bootstrapping the post-mergers and controls.

**Table 3.** Properties of the 43 post-mergers examined in this work, with their total *XMM-Newton* exposure time, X-ray luminosities (observed, rest-frame 2–10 keV luminosity, with  $3\sigma$  upper limits for non-detections), AllWISE colour, and optical classification (quiescent, star-forming, or AGN classified following Kewley et al. 2001; Kauffmann et al. 2003b; Stasińska et al. 2006). Note that any object meeting the Kewley et al. (2001) AGN criterion also meets the less strict Kauffmann et al. (2003b) criterion, which also meets the even less strict Stasińska et al. (2006) criterion.

Name	RA ( $^{\circ}$ )	Dec. ( $^{\circ}$ )	Redshift	$\log_{10} \left( \frac{M_{\star}}{M_{\odot}} \right)$	$\log_{10} \left( \frac{M_{\star}}{M_{\odot}} \text{yr}^{-1} \right)$	Exposure time (kilosec)	$\log_{10} \left( \frac{L_{2-10 \text{ keV}}}{\text{erg s}^{-1}} \right)$	W1 – W2 (mag)	Optical classification
J0056+0011	14.19265	0.18665	0.051 82	10.6	−0.06	8.7	<41.1	0.159	Q
J0058+0028	14.50334	0.47922	0.080 16	10.3	0.75	7.1	<41.8	0.259	K03
J0058−0013	14.56222	−0.22694	0.070 99	10.7	1.11	6.0	<41.5	0.336	S06
J0101+0023	15.33994	0.38485	0.092 64	10.9	0.49	14.8	<41.4	0.301	K03
J0106+1414	16.62870	14.24853	0.075 98	10.8	−1.21	28.6	<41.4	0.080	Q
J0154−0904	28.52194	−9.07129	0.050 61	10.6	−0.03	1.7	<41.9	0.043	Q
J0303−0053	45.99835	−0.89491	0.066 15	10.4	0.79	14.8	<41.4	0.210	S06
J0756+3405	119.24497	34.09284	0.070 73	10.3	0.67	30.6	<41.3	0.273	SF
J0820+2110	125.11584	21.18233	0.099 54	11.1	−0.05	50.0	<41.3	0.101	Q
J0821+1502	125.41440	15.04969	0.066 26	10.8	0.96	3.2	<42.0	0.314	SF
J0835+3933	128.91100	39.55703	0.098 80	10.5	0.88	4.5	<41.9	0.452	S06
J0927+1858	141.98749	18.97188	0.051 86	10.7	0.65	9.6	<41.1	0.163	S06
J0947+0042	146.79909	0.70269	0.030 55	9.6	0.52	2.5	<41.2	0.254	SF
J1000+1300	150.00241	13.00278	0.055 12	10.0	0.29	22.2	<41.6	0.340	K03
J1026+1234	156.54729	12.57381	0.030 96	9.9	0.13	5.5	<40.8	0.066	SF
J1038+3914	159.53247	39.24243	0.145 32	10.8	0.13	18.7	<42.0	0.621	K01
J1038+3958	159.61144	39.96741	0.150 28	11.4	1.09	5.5	<42.5	–	K03
J1042+5827	160.60191	58.45875	0.045 17	10.6	−1.23	4.4	<41.0	0.009	K01
J1046+1334	161.60277	13.57286	0.091 65	11.0	0.22	15.6	<41.6	0.157	K03
J1121+0258	170.48114	2.97262	0.048 10	10.8	−0.63	5.0	<41.4	−0.015	Q
J1127+0302	171.85792	3.03859	0.074 98	10.1	0.15	19.4	<41.5	0.081	S06
J1130+0553	172.62864	5.89178	0.034 93	10.2	−0.22	14.1	<40.6	0.306	Q
J1213+0238	183.36287	2.63556	0.073 11	10.7	0.37	16.2	<41.5	0.176	K03
J1216−0330	184.02692	−3.50376	0.092 17	10.8	0.28	12.2	<41.5	0.189	K01
J1218+0318	184.53329	3.30776	0.077 77	10.7	0.54	26.5	<41.2	0.185	Q
J1228+1225	187.05964	12.41816	0.152 50	11.1	1.39	39.7	<42.0	0.469	K03
J1258+2827	194.63184	28.46499	0.096 05	10.9	−0.45	13.5	<41.6	0.198	K01
J1309+0519	197.41271	5.32043	0.106 59	10.5	0.94	4.8	<42.1	0.275	K03
J1310+3213	197.66868	32.22826	0.048 92	10.2	0.75	20.6	<41.1	0.370	SF
J1331+0200	202.97039	2.01643	0.085 78	10.9	1.69	13.3	<41.7	1.256	K01
J1353+0510	208.35123	5.17862	0.077 49	10.7	−0.69	0.1	<42.7	0.001	Q
J1356+3829	209.17065	38.49224	0.060 54	10.9	−0.70	7.1	<41.4	0.020	Q
J1407+5358	211.89005	53.98294	0.078 50	9.7	0.34	8.1	<41.7	0.143	SF
J1411+5302	212.84763	53.04072	0.076 87	10.9	−0.15	8.2	<41.4	0.245	K03
J1442+2207	220.67289	22.11795	0.079 64	10.8	1.33	6.0	<41.9	0.342	K03
J1453+1652	223.32134	16.88309	0.045 15	10.6	−0.90	23.5	<40.9	0.013	K01
J1456+2436	224.13055	24.60972	0.032 77	10.6	−0.07	20.1	<40.6	0.844	K01
J1511+5613	227.87092	56.22155	0.150 12	11.1	2.22	9.3	43.2	0.805	S06
J1522+2733	230.59369	27.55726	0.073 27	10.7	0.48	46.1	<41.3	0.291	K01
J1522+0820	230.72835	8.34895	0.031 16	9.2	−0.24	19.6	<40.5	0.303	SF
J1526+3558	231.74767	35.97695	0.055 31	10.5	1.00	32.9	41.1	1.497	K03
J1537+5042	234.47443	50.70353	0.076 61	10.8	0.44	16.4	<41.6	0.144	Q
J2218−0000	334.52289	−0.00162	0.095 59	11.0	0.77	9.4	<41.9	0.189	Q

significantly redder for the post-mergers ( $0.297 \pm 0.047$  mag) than for the controls ( $0.138 \pm 0.005$  mag). While the elevated W1 – W2 seen in the post-mergers is consistent with a greater frequency and/or dominance of AGN activity, to further quantify this, we determined the number of post-mergers and controls with W1 – W2 > 0.5, when *some* amount of AGN contribution is generally required (e.g. Satyapal, Abel & Secrest 2018) even at high specific SFRs (Blecha et al. 2018), W1 – W2 > 0.8, the threshold above which the object is dominated by an AGN, and W1 – W2 > 1.0, at which point the object’s mid-IR emission is almost purely AGN (e.g. Assef et al. 2010; Stern et al. 2012). We find (Table 4) that, given the uncertainties, the post-mergers exhibit fractions of objects with W1 – W2 greater than 0.5, 0.8 consistent with the post-mergers studied

**Table 4.** Number of post-mergers and controls above a given W1 – W2. The fraction  $n/N$  of the total (42 post-mergers and 430 controls; see Section 3.2) is given as a percentage along with the null probability that the number of post-mergers above the W1 – W2 threshold follows the frequency seen in the controls. Uncertainty bounds are  $\pm 95$  percent. For the case where  $n_C = 0$ , the excess corresponds to the lower limit on (%)<sub>p</sub> and the upper limit on (%)<sub>C</sub> that gives a joint confidence limit of 95 per cent.

W1 – W2	$n_p$	$n_C$	(%) <sub>p</sub>	(%) <sub>C</sub>	$p$	Excess
0.5	5	3	$12^{+12}_{-7}$	$0.7^{+1.1}_{-0.5}$	0.00071	$17^{+96}_{-12}$
0.8	4	1	$10^{+11}_{-6}$	$0.2^{+0.9}_{-0.2}$	0.0010	$41^{+\infty}_{-31}$
1.0	2	0	$4.8^{+9.5}_{-3.9}$	$0.0^{+0.7}_{-0.0}$	0.014	$\gtrsim 6.1$



in Satyapal et al. (2014), which exhibited fractions of 0.16 and 0.1, respectively.

We tested the null hypothesis that the post-mergers and their controls exhibit the same frequencies of X-ray and mid-IR AGNs, given the observed excesses. To do this, we generated  $10^7$  samples from four binomial distributions, two for the X-ray AGNs and two for the mid-IR AGNs in the post-mergers and controls, using null hypothesis frequencies as defined in Section 2.3. We divided the post-merger samples by the control samples to generate the X-ray and mid-IR AGN excesses. Divide-by-zero instances were set to  $+\infty$ , and 0/0 instances were discarded. We then divided the X-ray AGN excesses by the mid-IR AGN excesses and counted the number of instances where the X-ray excess was less than the observed value of 2.2 and the mid-IR excess was above the observed value of 17. We find that the probability under the null hypothesis of getting the observed X-ray excess and the observed mid-IR AGN excess is  $2.7 \times 10^{-4}$  for  $W1 - W2 > 0.5$  and  $3.2 \times 10^{-3}$  for  $W1 - W2 > 0.8$ . Post-mergers therefore exhibit a significant decrement in the frequency of X-ray AGNs, given the excess of mid-IR AGNs they show over the controls. Put differently, the non-merger control galaxies have  $\sim 8$  times more X-ray AGNs per AGN with  $W1 - W2 > 0.5$  and  $\sim 18$  times more X-ray AGNs per AGN with  $W1 - W2 > 0.8$  than the post-mergers. Given the tight relationship between the X-ray and mid-IR luminosities of AGNs (e.g. Asmus et al. 2015), this suggests that the observed X-ray luminosities in the post-mergers are significantly attenuated by line-of-sight absorption, a result predicted by numerical simulations (Blecha et al. 2018), and supported by other empirical work (e.g. Ricci et al. 2017; Donley et al. 2018; Goulding et al. 2018). To explore this, we calculated the ratio of the 2–10 keV to 12  $\mu$ m monochromatic luminosities, which can be used to estimate column density  $N_H$  (e.g. Satyapal et al. 2017), for the mid-IR AGNs with  $W1 - W2 > 0.5$ . We converted their  $W1 - W2$  colours to spectral indices (e.g. Wright et al. 2010, table 1) and calculated their rest-frame  $L_{12\mu m}$ . We converted  $L_{12\mu m}$  to predicted  $L_{2-10\text{keV}}$  using the relation for unabsorbed ( $N_H < 10^{22} \text{ cm}^{-2}$ ) AGN shown in Fig. 11 of Satyapal et al. (2017)

$$\log_{10} \left( \frac{L_{2-10\text{keV}}}{\text{erg s}^{-1}} \right) = 0.956333 \times \log_{10} \left( \frac{L_{12\mu m}}{\text{erg s}^{-1}} \right) + 1.60567 \quad (2)$$

(C. Ricci, private communication). For both the post-mergers and the controls, the predicted X-ray luminosities are above the detection threshold, suggesting that the non-detections are physically significant. We set the X-ray luminosity of the three non-detections in the post-mergers and the one non-detection in the controls to the  $3\sigma$  upper limit and calculated the corresponding upper limits on  $L_{2-10\text{keV}}/L_{12\mu m}$ , finding mean values of  $0.07 \pm 0.04$  for the post-mergers and  $0.12 \pm 0.05$  for the controls ( $p = 0.46$ ). Given the low number of objects with  $W1 - W2 > 0.5$ , we therefore cannot distinguish between the post-mergers and the controls. However, under the null hypothesis that there is no difference in  $L_{2-10\text{keV}}/L_{12\mu m}$  between the post-mergers and the controls, the mean value of  $L_{2-10\text{keV}}/L_{12\mu m}$  is  $\sim 0.09 \pm 0.03$ , indicating heavy absorption Satyapal et al. (2017, Fig. 11) in mid-IR AGNs in general. The higher frequency of mid-IR AGNs in post-mergers would therefore correspond to a higher frequency of heavily-absorbed AGNs, consistent with the disparity between the X-ray and mid-IR AGN excess seen in the post-mergers.

**Table 5.** Number of post-mergers (out of 43) and controls (out of 430) falling into a given optical emission line classification: quiescent, star forming, Stasińska et al. (2006), Kauffmann et al. (2003b), or Kewley et al. (2001). Uncertainty bounds contain the 90 percent confidence interval.

Class	$n_P$	$n_C$	(%) <sub>P</sub>	(%) <sub>C</sub>	$p$	Excess
Q	11	282	$26^{+13}_{-11}$	$66^{+4}_{-4}$	$1.4 \times 10^{-6}$	$0.38^{+0.17}_{-0.16}$
SF	7	59	$16^{+12}_{-8}$	$14^{+3}_{-3}$	0.39	$1.2^{+0.8}_{-0.7}$
S06	25	89	$58^{+13}_{-14}$	$21^{+3}_{-3}$	$1.9 \times 10^{-6}$	$2.8^{+0.8}_{-0.7}$
K03	19	69	$44^{+14}_{-13}$	$16^{+3}_{-3}$	$1.0 \times 10^{-4}$	$2.8^{+1.0}_{-0.8}$
K01	8	26	$19^{+12}_{-9}$	$6.0^{+2.2}_{-1.8}$	0.011	$3.1^{+2.4}_{-1.6}$

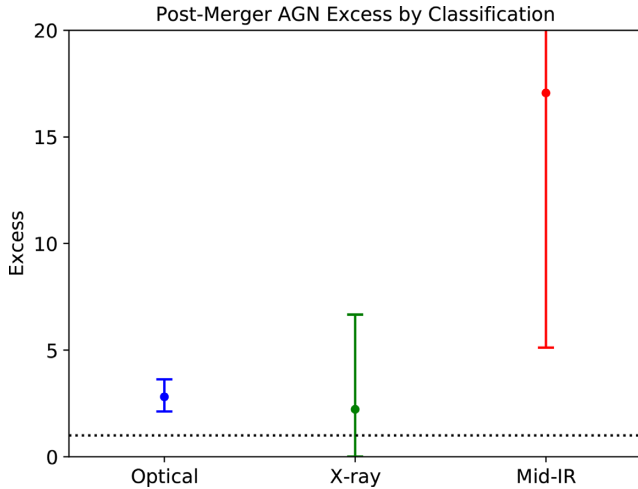
### 3.3 Optical

Finally, we also explored the optical emission line properties of our sample. Using the MPA-JHU catalogue,<sup>8</sup> we categorize all objects into those with emission lines dominated by AGN activity using the Kewley et al. (2001) demarcation, and objects with decreasing AGN contributions using the Kauffmann et al. (2003b) and Stasińska et al. (2006) demarcations, respectively. We require S/N greater than 5 in H $\beta$ , [O III]  $\lambda$ 5007, H $\alpha$ , and [N II]  $\lambda$ 6584 to ensure accurate classification. We consider any objects meeting this S/N threshold but not falling into any AGN classification to be star forming (SF), and any objects not meeting the S/N threshold to be quiescent. As with the X-ray and mid-IR metrics, we provide a table of the fraction of objects in these categories in Table 5. The large majority of mergers are strong emission line systems compared to the controls, although both the post-mergers and the controls have a similar fraction of optically SF systems ( $p = 0.39$ ). The raw fraction of AGNs in both the post-mergers and controls is sensitive to the selection method, becoming smaller as the line ratio criteria become stricter. However, the excess of AGNs in the post-mergers compared to their controls is approximately constant for all three diagnostics, at a value of  $\sim 3$  ( $p \lesssim 0.01$ ), consistent given the uncertainties with the factor of 3.75 found by Ellison et al. (2013) and Satyapal et al. (2014), and significantly lower than the mid-IR AGN excess (Fig. 4), in line with previous findings.

A potential explanation for the small excess of optical AGNs compared to mid-IR AGNs is that the post-mergers have a factor of  $\sim 8$  higher SFR than the controls, with a mean value of  $9.0 \pm 3.9 \text{ M}_{\odot} \text{ yr}^{-1}$ , versus  $1.1 \pm 0.1 \text{ M}_{\odot} \text{ yr}^{-1}$  in the controls, so emission line dilution from star formation is precluding optical AGN classification at lower AGN luminosities (e.g. Trump et al. 2015), a result also supported by Koss et al. (2010). This explanation is disfavoured in our sample, however, as this would imply that optical AGNs in post-mergers should be absent from systems without AGN-dominated *WISE* colour. On the contrary, optical AGNs, hereafter defined as those meeting the Stasińska et al. (2006) criterion to be consistent with Ellison et al. (2011), Ellison et al. (2013), and Satyapal et al. (2014), are  $\sim 5$  times more frequent in the post-mergers than mid-IR AGNs with  $W1 - W2 > 0.5$  (Tables 5 and 4), and of the 24 post-mergers with optical emission line ratios meeting the Stasińska et al. (2006) criterion, 19 of them (79 per cent) have  $W1 - W2 < 0.5$  (Table 3). Indeed, the majority of post-mergers are optical AGNs ( $58^{+13}_{-14}$  per cent; Table 5), consistent with mergers playing a key role in AGN triggering. These results are therefore consistent with a picture of galaxy mergers triggering AGN activity, with dominant, luminous AGNs found more frequently in the final stages of mergers,

<sup>8</sup>[https://www.sdss.org/dr16/spectro/galaxy\\_mpa\\_jhu](https://www.sdss.org/dr16/spectro/galaxy_mpa_jhu)





**Figure 4.** The excess of AGNs in post-mergers over their controls, depending on AGN classification, with error bars containing the 90 per cent confidence interval. The dotted line is at an excess of 1, indicating no difference between the post-mergers and the controls. Optical AGNs (meeting the Stasińska et al. 2006 emission line ratio criteria) exhibit a significantly smaller excess than mid-IR AGNs ( $W1 - W2 > 0.5$  mag), in agreement with previous work; however, the X-ray excess is not significant, with an upper limit of 6.7.

in line with the previous work (e.g. Dietrich et al. 2018). We note that the high frequency of optical AGNs in the post-mergers is not in conflict with the heavy obscuration suggested by our results in Section 3.2, as the latter is strictly only true for the obscuring column along the line-of-sight column of the observer. Other, low-obscuration sightlines to the AGN may allow for ionizing photons to escape and produce narrow line regions, which can be hundreds or even thousands of parsec in extent (e.g. Chen et al. 2019, and references therein).

#### 4 CONCLUSIONS

We have performed an *XMM-Newton* X-ray analysis of 43 post-merger systems selected from the SDSS DR7 along with 430 non-merger control galaxies selected to have statistically consistent redshifts, stellar masses, environments, and identical effective X-ray observation depths. These observations are primarily serendipitous observations from the archive, with additional observations from our AO15 program. We analysed the data in a homogeneous way using a custom *XMM-Newton* data reduction pipeline, producing 2–10 keV rest-frame source flux measurements and upper limits for both detected and undetected objects. We compared our results with the mid-IR (AllWISE) and optical spectroscopic (SDSS/MPA-JHU) catalogue data for our sample, finding that our objects are consistent with having been drawn from the same population as studied in our previous work. Our primary findings are as follows:

- (i) Post-mergers do not exhibit a statistically significant excess of X-ray AGNs over non-merger controls ( $p = 0.26$ ), showing an excess of  $2.22^{+4.44}_{-2.22}$ , where the uncertainties contain the 90 per cent confidence interval.
- (ii) However, for varying AGN mid-IR colour thresholds, these post-mergers exhibit an AGN excess of  $\sim 17$  or more ( $p = 0.001$ ), implying that post-mergers more frequently host intrinsically luminous AGNs. The disparity between the X-ray and mid-IR AGN excesses in post-mergers is highly significant ( $p = 2.7 \times 10^{-4}$ ).

(iii) Post-mergers exhibit an optical AGN excess of  $\sim 3$  ( $p \lesssim 0.01$ ), significantly lower than the mid-IR excess, consistent with previous studies and within the 90 per cent confidence interval of the X-ray excess. By number, however, optical AGNs are more common than mid-IR AGNs; this holds in our post-merger sample as it does in the general AGN population. Indeed, the majority of post-mergers in our sample host optical AGNs, implying that while luminous, bolometrically-dominant AGNs are preferentially hosted in late-stage galaxy mergers, lower level AGN activity is still more prevalent overall.

We emphasise that this study is limited by the small numbers of post-mergers available with *XMM-Newton* observations, and we have taken care to calculate statistical significance as robustly as possible and to not over-state our conclusions. None the less, our results are consistent with the picture of mergers driving gas towards the centres of galaxies, fueling both star formation and AGN activity, with the heaviest AGN obscuration, and the highest AGN luminosities occurring more frequently in the post-merger stage.

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