A Catalog of 204 Offset and Dual Active Galactic Nuclei (AGNs): Increased AGN Activation in Major Mergers and Separations under 4 kpc

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Abstract
During galaxy mergers, gas and dust are driven toward the centers of merging galaxies, triggering enhanced star formation and supermassive black hole (SMBH) growth. Theory predicts that this heightened activity peaks at SMBH separations <20 kpc; if sufficient material accretes onto one or both of the SMBHs for them to become observable as active galactic nuclei (AGNs) during this phase, they are known as offset and dual AGNs, respectively. To better study these systems, we have built the ACS-AGN Merger Catalog, a large catalog (N = 204) of uniformly selected offset and dual AGN observed by the Hubble Space Telescope at 0.2 < z < 2.5 with separations <20 kpc. Using this catalog, we answer many questions regarding SMBH–galaxy coevolution during mergers. First, we confirm predictions that the AGN fraction peaks at SMBH pair separations <10 kpc; specifically, we find that the fraction increases significantly at pair separations of <4 kpc. Second, we find that AGNs in mergers are preferentially found in major mergers and that the fraction of AGNs found in mergers follows a logarithmic relation, decreasing as merger mass ratio increases. Third, we do not find that mergers (nor the major or minor merger subpopulations) trigger the most luminous AGNs. Finally, we find that nuclear column density, AGN luminosity, and host galaxy star formation rate have no dependence on SMBH pair separation or merger mass ratio in these systems, nor do the distributions of these values differ significantly from that of the overall AGN population.

Unified Astronomy Thesaurus concepts: Galaxy mergers (608); AGN host galaxies (2017); Galaxy evolution (594); Active galactic nuclei (16); Galaxy classification systems (582)

Supporting material: machine-readable table

1. Introduction
Mergers between two galaxies, each with a supermassive black hole (SMBH) at its center, result in a pair of SMBHs in the merger remnant. The paired SMBHs slowly spiral toward the center of mass of the newly merged system and remain in a <20 kpc separation dual phase for ~100 Myr (Begelman et al. 1980; Milosavljevic & Merritt 2001), before dynamical friction drives them into a sub-parsec gravitationally bound binary and they eventually coalesce. During this dual phase, significant gas can be driven inward toward the center of the merger remnant and onto the SMBHs, fueling their growth, and making them observable as active galactic nuclei (AGNs); this should also enhance star formation in the host galaxy (e.g., Joseph & Wright 1985; Hopkins et al. 2008; Hopkins & Hernquist 2009; Knappen et al. 2015).

When one or both of the SMBHs are accreting in this dual phase, they are known as offset AGNs (e.g., Comerford & Greene 2014) or dual AGNs (e.g., Gerke et al. 2007; Comerford et al. 2009), respectively. During this phase, the outer stars are tidally stripped away, but the merging galaxies retain their central stellar bulges (Liu et al. 2010; Fu et al. 2011; Rosario et al. 2011); these stellar bulges contain the SMBHs. Therefore, offset AGNs are merging galaxy systems where one stellar bulge hosts an AGN and one does not; presumably the latter hosts a quiescent SMBH. Similarly, dual AGNs are merging galaxy systems in which both stellar bulges host an AGN.

There are strong correlations between observed properties of the SMBH and host galaxy properties, such as the M–σ relation (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Greene & Ho 2006), which seems to indicate a connection between SMBH growth and the evolution of its host galaxy. In order to understand this connection, studies of systems hosting AGNs during periods of growth are necessary. Offset and dual AGNs are powerful observational tools for studies of SMBH and galaxy coevolution as they are direct probes of the state of an SMBH and its host galaxy during a merger event. However, their utility has been limited because the number of known systems is small.

A large sample of offset and dual AGNs could address open questions in the field of SMBH and galaxy coevolution. For example, some simulations predict that major mergers trigger the most luminous AGNs (Hopkins & Hernquist 2009). However, observational studies have found conflicting results about whether the most luminous AGNs are preferentially triggered in mergers, primarily due to the lack of a large, clean sample of AGNs in merging galaxy systems (e.g., Kocevski et al. 2012; Treister et al. 2012; Villforth et al. 2014, 2017). Other simulations predict that the peak of SMBH growth in mergers occurs when the paired SMBHs are separated by 1–10 kpc (Van Wassenhove et al. 2012) or 0.1–2 kpc (Blecha et al. 2013). Observations have not yet been able to test these predictions due to the limited number of known systems with SMBH pair separations <10 kpc, but they do verify the trend in the 10–100 kpc range (Ellison et al. 2011; Koss et al. 2012).
Lastly, a large sample of these systems could test whether findings of increased star formation in mergers (e.g., Cox et al. 2008; Ellison et al. 2008; Patton et al. 2013) also apply to merging systems hosting AGN at small separations.

Since offset and dual AGNs are a promising avenue of approach to study SMBH and galaxy coevolution, there have been many searches recently to find them. While most initial findings of these systems were serendipitous (e.g., Komossa et al. 2003; Bianchi et al. 2008), recent studies have attempted a more systematic approach. One such method is looking for the spectroscopic signatures of the AGNs in these systems, including double-peaked emission lines or single-peaked emission lines with a velocity offset relative to the host galaxy. While some of the galaxies identified in these studies have been confirmed as offset and dual AGNs (Fu et al. 2011; Liu et al. 2013; Comerford et al. 2015; Müller-Sánchez et al. 2015), many have not; this is because in most galaxies, AGN outflows and gas kinematics produce velocity shifted and double-peaked emission lines that mimic the signatures of offset and dual AGNs (Rosario et al. 2010; Shen et al. 2011; Comerford et al. 2012; Fu et al. 2012; Barrows et al. 2013; McCurk et al. 2015; Nevin et al. 2016). Work by Barrows et al. (2016) found offset and dual AGNs by searching for X-ray sources offset from their optical counterpart host galaxies, but the number able to be found using this method was limited due to the spatial resolution limits of the X-ray and optical observations. Still other work has focused on using surveys to search for morphological signatures of mergers, followed by spectroscopy, radio, or X-ray observations to verify their sample (Koss et al. 2012; Fu et al. 2015; Satyapal et al. 2017; Silverman et al. 2020). This accentuates a problem in finding these systems—observations of offset and dual AGNs are difficult because of the high spatial resolution imaging and/or spectroscopy needed to differentiate the stellar bulges associated with an SMBH pair at these separations; this is also why currently known offset and dual AGNs are mostly limited to the low-redshift Universe ($z \lesssim 0.2$).

The Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST) has an angular resolution of 0.05″. This makes it ideal for observations requiring high resolution, such as detecting the multiple stellar bulges associated with offset and dual AGNs. By choosing HST galaxies in deep survey fields, such as GEMS, COSMOS, GOODS, and AEGIS, multiwavelength data can be used to select AGNs, while galaxy morphological fitting can select galaxy mergers. This provides an approach for detecting offset and dual AGNs in greater numbers and at higher redshifts than ever before, enabling them to be used for statistical studies of AGN activation and SMBH–galaxy coevolution for the first time.

Here we present a catalog and analysis of 204 offset and dual AGNs identified using a new systematic method for finding offset and dual AGNs in large, multiwavelength HST galaxy surveys. Section 2 discusses our initial sample of galaxies. In Section 3, we present the methods by which we modeled and selected our offset and dual AGN sample from the ACS-AGN Catalog, while Section 4 discusses the biases in our methods and how we corrected for them. Section 5 discusses the AGN and host galaxy properties of our offset and dual AGNs, both in comparison to a general AGN population and in relation to their merger parameters, and Section 6 presents our findings on AGN triggering in mergers. Finally, in Section 7 we discuss our conclusions. Throughout this paper, we use the Planck 2015 cosmology of $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.308$, and $\Omega_\Lambda = 0.692$ (Planck Collaboration et al. 2016).

2. Initial Galaxy Sample

Our parent galaxy sample was the Advanced Camera for Surveys Active Galactic Nuclei Catalog (ACS-AGN; Stemo et al. 2020), hereafter referred to as S20. The ACS-AGN is a catalog of 2585 AGN host galaxies that were imaged with HST/ACS and span a redshift range of $0.2 < z < 2.5$. These AGN host galaxies are located in four deep survey fields: the Galaxy Evolution from Morphologies and SEDs (GEMS) survey (Caldwell et al. 2008), the Cosmological Evolutionary Survey (COSMOS; Scoville et al. 2007), the Great Observatories Origins Deep Survey (GOODS; Dickinson & Giavalisco 2003), and the All-wavelength Extended Groth Strip International Survey (AEGIS; Davis et al. 2007).

These AGNs were selected by applying mid-infrared and X-ray AGN selection criteria to Spitzer and Chandra data available in these survey fields. The mid-infrared color cut described by Donley et al. (2012) was used for Spitzer observed galaxies and a rest-frame X-ray luminosity cut in the 2–10 keV band of $L_{2–10} > 10^{42}$ erg s$^{-1}$ was used for Chandra observed galaxies. Of the 2585 AGN host galaxies in the ACS-AGN Catalog, 1065 are infrared selected and 1945 are X-ray selected.

While redshift data was already available for these galaxies (Griffith et al. 2012), AGN and host galaxy properties were not. These properties were calculated from spectral energy distributions (SEDs) created for each galaxy from multiwavelength photometric data using the SED template fitting software LRT (Assef et al. 2010). Specifically, AGN bolometric luminosity ($L_{\text{AGN}}$) was calculated by integrating the AGN component of the SED model. Stellar mass ($M_*$) was calculated using the relation between the SED modeled (excluding the AGN component) $g' – r'$ color and $M/L_*$ from Bell et al. (2003). Host galaxy star formation rate (SFR) was calculated from the SED modeled (excluding the AGN component) 2800 Å monochromatic luminosity as described in Madau et al. (1998). Finally, the nuclear neutral hydrogen column density ($N_\text{H}$) was calculated from the SED modeled extinction value ($E_{B-V}$) using a conversion factor derived from Maiolino et al. (2001) and Burtscher et al. (2016).

The parent galaxy sample has a median redshift of $(z) \approx 1.15$, and contains AGN host galaxies that cover a significant parameter space: $L_{\text{AGN}}$ [erg s$^{-1}$ cm$^{-2}$] has a range of $10^{42} \lesssim L_{\text{AGN}} \lesssim 10^{47}$, with a median of $10^{44.7}$; $M_*$ [M$_\odot$] has a range of $10^9 \lesssim M_* \lesssim 10^{12}$, with a median of $10^{10.6}$; SFR [M$_\odot$ yr$^{-1}$] has a range of $10^{-1} \lesssim $ SFR $\lesssim 10^2$, with a median of $10^{0.53}$; while $N_\text{H}$ [cm$^{-2}$] has a range of $10^{20.5} \lesssim N_\text{H} \lesssim 10^{23}$, with a median of $10^{21.4}$. This sample is found to lie generally below the star-forming main sequence and also shows correlated behavior between SFR and $L_{\text{AGN}}$, most likely due to a mutual dependence on galaxy mass.

The AGN selection process, SED creation, AGN, and host galaxy property calculation, and analysis are described in more detail in S20.

3. Galaxy Modeling and Merger Identification

The utility of computers in identifying, classifying, and decomposing galaxies in astronomical images has been growing as the effectiveness of image analysis software has
increased. We use two such software packages, Source Extractor (Bertin & Arnouts 1996) and GALFIT (Peng et al. 2002), to identify and model multiple stellar bulge components in HST images of the ACS-AGN galaxies in order to identify offset and dual AGN candidates.

In Section 3.1, we create tiles of the ACS-AGN galaxies. We then use Source Extractor and GALFIT to model the morphology of the ACS-AGN galaxies in Section 3.2. Finally, in Section 3.3, we eliminate false positives and select our offset and dual AGN sample.

3.1. Galaxy Tiling

In order to best select stellar bulges associated with SMBHs, we chose to examine them in the F814W filter of HST/ACS—the reddest available ACS filter that has been used to observe the entire ACS-AGN sample. This band peaks at 8333 Å, with an FWHM of 2511 Å, and is well suited for tracing a galaxy’s stellar component in our sample’s redshift range. Specifically, the F814W band outperforms available shorter wavelength bands, such as the F438W and F606W, at this task because those bands tend to be dominated by light from ionized gas, not stellar emission, which peaks further into the infrared (e.g., Comerford et al. 2017).

Of the four surveys from which our sample is drawn, only the AEGIS and COSMOS surveys were observed and have mosaics in the F814W filter. Fortunately, the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011) observed the remaining fields (GEMS and GOODS) in the F814W and provide mosaics of these observations. It also observed parts of the COSMOS and AEGIS fields, but not in their entirety (for further details, see Grogin et al. 2011). Therefore, where multiple surveys’ observations exist for our sample, the CANDELS mosaics are the deepest available, but only marginally, so where they are available, CANDELS Wide observations increase the depth in the COSMOS field from a 5σ AB magnitude of 27.2–27.7 and from a 5σ AB magnitude of 28.1–28.2 in the AEGIS field. The F814W 5σ depth of the CANDELS Deep + Wide observations in the GEMS and GOODS fields are AB magnitude 28.8.

We gathered HST/ACS publicly available F814W mosaics from the COSMOS (Scoville et al. 2007), AEGIS (Davis et al. 2007), and CANDELS (Grogin et al. 2011) surveys. These mosaics are science products that have undergone significant processing, including calibration (e.g., bias and dark subtraction, gain correction, flat fielding, bad pixel rejection, and low-level background removal), astrometric registration, cosmic-ray cleaning, and have been co-added with MultiDrizzle (Koekemoer et al. 2007).

From these mosaics we created 80 × 80 kpc tiles centered on the ACS-AGN galaxies. This size is significantly larger than the maximum 20 kpc separation radius we are allowing for our offset and dual AGN candidates, but allows for more accurate background estimation and subsequent fitting by GALFIT. For our galaxies that were observed in the F814W by CANDELS, we created tiles from the CANDELS mosaics; for those not within the boundaries of the CANDELS mosaics, we created tiles from the original survey mosaics in the F814W.

Of the 2585 ACS-AGN galaxies, we could not create tiles for 19 of them. These galaxies were in a region of the AEGIS field where no F814W mosaics were available at the time of publication. This left 2566 active galaxies that we created tiles for and could be analyzed for multiple stellar bulges.

3.2. Source Identification and Fitting

Offset and dual AGNs exist in galaxy mergers. In order to find them, we search our active galaxy sample for signs of multiple stellar bulges, which should only exist in galaxy mergers. The dual phase (1–20 kpc stellar bulge separation) of galaxy mergers is especially important because at separations greater than 20 kpc, the galaxies should only be minimally interacting, while at separations less than ~1 kpc, a significant portion of stellar bulges may be coalescing. Therefore, we specifically search for multiple stellar bulges within this range in order to identify offset and dual AGNs.

We can identify which AGN host galaxies contain multiple stellar bulges by modeling them with Source Extractor (Bertin & Arnouts 1996) and GALFIT (Peng et al. 2002). Since these galaxies are already known to host at least one AGN, if we identify them as having multiple stellar bulges, we can deduce that these galaxies are undergoing a merger and host an offset or dual AGN.

In practice, we identified multiple stellar bulges in our active galaxy sample by fitting Sérsic surface brightness profiles to bright sources in the galaxy tiles. Specifically, we passed the active galaxy tiles through Source Extractor; this identifies bright groupings of pixels in the image as possible sources, fits an elliptical profile to them, and outputs basic information such as the source location, its flux, and its position angle. Given the high redshifts in our sample, Source Extractor is ideal as it detects sources via a threshold method, which is more suited to the detection of low-surface brightness objects than peak finding methods (Yee 1991). When detecting sources using Source Extractor, we used a detection threshold of 3σ above background and a minimum source area of 7 pixels.

We then used the outputs of Source Extractor as initial parameters (source position, source position angle) for fitting with GALFIT. GALFIT minimizes χ² (reduced χ²) by fitting various modeled surface brightness profiles convolved with a point-spread function PSF to an input galaxy image. We allowed GALFIT to fit Sérsic surface brightness profiles to the sources in our tiles. By varying the Sérsic index and effective radius, the Sérsic profile can accurately model an extended bulge structure as well as more compact objects, such as AGNs, when convolved with a point-spread function (PSF). This process is shown in Figure 1.

While GALFIT includes many other surface brightness profiles and can fit highly complex galaxy structure, the limited nature of our method keeps our computational load down while still satisfactorily modeling our science targets (stellar bulges). We recognize that galaxies can be more complex than a single Sérsic profile; however, for this work, we are only concerned with GALFIT detecting merging systems, and accurately modeling the bulges’ separation and relative integrated flux (discussed in Section 5.1). In practice, the centroid of a properly modeled Sérsic profile will coincide with the light center of a galaxy component (i.e., the central bulge); therefore, the separations of our merging systems should be well measured. Also, unless there is significant surface brightness profile asymmetry in the merger components, the flux should be correctly proportioned between them according to their physical structure. Significant deviations in the relative flux assignment would require uncommon geometries to occur (e.g., a primary galaxy starburst near the secondary galaxy bulge), and therefore should not have a significant impact on the overall results. Specifically, we found that our methods very
accurately modeled most galaxy components except those with significant, large-scale spiral or asymmetric structure—a minority of our sample; Figure 2 shows this quite well. These outliers may cause some scatter in our data (specifically merger mass ratio), and should be carefully considered when examining individual systems instead of the sample en masse, but should not significantly affect any findings based on the entire sample, such as those discussed in this paper.

The speed at which GALFIT can simultaneously fit multiple profiles to a given image is highly dependent on image size, convolution size, and number of fits. In order to manage the computational load, the sources from Source Extractor were only used as inputs for GALFIT if the source position was within 22 kpc of the center of the image and the source flux was at least 1% of the maximal source flux within the innermost 10 kpc of the image. The position limitation is reasonable as the AGN host galaxy is approximately centered on our image tile and our goal is to identify offset and dual AGNs separated by 20 kpc or less. tile and our goal is to identify offset and dual AGNs separated by 20 kpc or less. The position limitation is reasonable as the AGN host galaxy is approximately centered on our image.

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Other restrictions were also put in place to avoid over fitting. Specifically, we restricted our GALFIT components to be centered within 2.5 kpc of its Source Extractor source. This is in addition to default GALFIT restrictions on model parameters that are unphysical (e.g., effective radius < 0.01 pixel, Sérsic indices < 0.01 or >20, etc.). This forced GALFIT to model only the sources we wanted to model and to only model those sources with realistic bulge profiles. For our process, this meant that adding spurious Sérsic components typically resulted in worse fits than modeling with fewer Sérsic components. Therefore, for each tile we selected the model with the minimum \( \chi^2 \) as the best fit.

Of the 2566 galaxies selected as active for which tiles could be made, 6 could not be modeled due to too many sources being identified by Source Extractor than would be reasonable to computationally model using our methods, with some having as many as 20 sources identified by Source Extractor. These were inspected visually and 2 were selected to be fit using a subset of the sources identified by Source Extractor that appeared to be possible stellar bulges. In all, 350 active galaxies were best fit by a GALFIT model with two or three components, while the rest were either best fit with a single Sérsic component or with no Sérsic component (i.e., only a background component); the ones best fit with no Sérsic component typically had extremely dim surface brightness profiles.

### 3.3. False Positive Reduction

Not all 350 galaxies that were best fit with two or three components by GALFIT truly contain multiple stellar bulges. Even with the initial source limitations imposed prior to GALFIT modeling, there were still a significant number of models with components fit to non-bulge features (e.g., spiral arms, star-forming regions, etc.). In order to reduce these false positives, we put in place further restrictions on our GALFIT component parameters: a centroid separation limit, an integrated flux ratio limit, and a significance above background restriction.

When GALFIT models an image, there is no inherent lower limit to component separation and it is only restricted in its upper limit to the size of the image. These limits are unrealistic on the low end and not useful for this work on the high end. Since our goal is to identify offset and dual AGNs, the separation of possible stellar bulges containing SMBHs should be inherently limited to <20 kpc. However, there must also be a lower limit; an absolute lower limit would be the angular resolution of the observing instrument (0.05″ for HST/ACS), but the lower limit of typical bulge sizes is actually the more
Figure 2. Examples of offset and dual AGNs identified and included in the ACS-AGN Merger Catalog. The axes of the tiles are in units of kiloparsecs, with the origin centered on the AGN host galaxy. Each row presents a merger candidate and is organized as follows: HST F814W image (left), GALFIT model (middle), and residual (right). The Catalog IDs of the systems shown are, from top to bottom: 169, 633, 1194, 1195, 1372, 1689, 1966, 2316, 2381, and 2477.
Figure 2. (Continued.)
restrictive lower separation in this case. For example, the nearby \((z = 0.02)\) active dwarf galaxy RGG 118 has a bulge diameter of approximately 1.5 kpc (Baldassare et al. 2017). This 1.5 kpc lower limit is a conservative estimate for possible bulge sizes identifiable in our sample; the moderate to massive galaxies of the ACS-AGN should contain similar or larger bulges, and 1.5 kpc is above the resolution limit of HST for all redshifts present in our sample. Therefore, we impose a separation limit for our modeled stellar bulges of \(>1.5\) kpc and \(<20\) kpc.

In addition, the automated nature of our bulge fitting method frequently results in additional components being fit to non-bulge features such as spiral arms, star-forming regions, and occasionally low-surface brightness, extended features. In order to address these issues, we put in place two further restrictions on the modeled GALFIT components. First, we required that the integrated fluxes of any paired components must be within 5 magnitudes of each other (1%). If we take the integrated flux ratio as a proxy for the stellar mass ratio (see Section 5.1), this constraint limits the possible merger mass ratios of our candidates to \(<100\). This restriction is successful at eliminating many false positives typically related to star-forming regions and some spiral arms and only eliminates the most minor of mergers. Our second restriction is a significance above background criterion; specifically, we require that the modeled flux at the centroid of any fit component must be at least \(5\sigma\) above the background, as modeled by GALFIT. This restriction is excellent at eliminating more extended, low-surface brightness false positive fits, such as those typically associated with diffuse gas features and some spiral arms.

After we removed a large number of false positives through automated means, 280 active galaxies were still identified as hosting multiple stellar bulges. Due to the automated nature of our approach, there were still some false positives included in this set. Therefore, as a final check, this reduced sample was visually examined independently by the three lead authors of this work, with any split determinations resulting in the conservative decision of removal from the sample. We also used this opportunity to refit individual stellar bulge models as needed in order to more accurately model the offset and dual AGN system; this was typically slightly adjusting the centroid of the bulge fit, the axis ratio, or the Sérsic index and effective radius to better reflect the observed data. This final verification and refit resulted in 204 unique systems identified as offset and dual AGNs—187 of these being two-bulge systems and 17 being three-bulge systems. Some examples of offset and dual AGNs that we identified are shown in Figure 2, including the original HST F814W image, the GALFIT model, and the resulting residual.

For the rest of this paper, we will analyze the two-bulge systems and the galaxy pairs containing the AGN host galaxy and the brightest secondary galaxy in the three-bulge systems. While this choice of analyzing only the brightest pairs in triple systems could theoretically lead to a bias in our analysis, we verified that none of the analyses or results presented in the remainder of the paper would be significantly altered if we were to examine all pairs (i.e., both sets of pairs containing the AGN host galaxy in triple systems) or if we were to completely exclude triple systems from any analysis. Differentiating offset from dual AGNs in our sample and analysis of the individual subpopulations, as well as the triple-bulge systems, will be the focus of a future paper (Stemo et al., in preparation).

4. Bias Analysis and Correction

All methods of identifying galaxy mergers are prone to significant selection biases. The process outlined in Section 3 is purposefully conservative and designed to minimize false positives; this in itself is a selection bias. Further, our methods rely upon the ability to properly detect and separate the stellar bulges associated with the AGNs or SMBHs of each merger component, which can be extremely challenging and result in false negatives. Both of these effects need to be accounted for.

As a merging systems bulges near each other, their surface brightness profiles can overlap significantly; but as was discussed in Section 3.3, bulges can be as close as 1.5 kpc before they physically begin to coalesce. This means that physically distinct stellar bulge pairs at small separations can be especially difficult to detect even with HST/ACS’s spatial resolution. This is exacerbated by the high redshift nature of our sample, with a 1.5 kpc separation corresponding to less than 6 pixels in the most extreme region of our redshift range.

In addition to the challenge in resolving small separations, the higher the merger mass ratio (the more dissimilar the masses), the more likely the system is to be modeled as a single component rather than as multiple stellar bulges. As the merger mass ratio increases, the integrated flux ratio also increases. This leads to one surface brightness profile dominating the other; therefore, the model of the lower integrated flux (lower mass) component is less important to the goodness of fit of the overall model.

Both of these factors cause our merger identification pipeline to frequently incorrectly model closely separated and high merger mass ratio galaxy mergers with a single component. This means that our galaxy merger sample is biased toward major mergers (low mass ratio) and mergers at large separations. In order to correct for this, we simulated and modeled 377,000 galaxy mergers across a large swath of parameter space. Examining the resulting GALFIT models of these simulated mergers allowed us to correct for the aforementioned separation and merger mass ratio selection biases.

In Section 4.1, we discuss the creation of the galaxy merger models and the parameter space they cover. In Section 4.2, we detail the GALFIT modeling of the simulated mergers and report the regions of success and failure of our merger identification pipeline. Lastly, in Section 4.3, we discuss the quantification of our selection biases and the process we used to correct for them.

4.1. Simulating Galaxy Mergers

Our merger identification pipeline relies on modeling multiple stellar bulges with Sérsic profiles. Ignoring position, Sérsic profiles only need three variables to be fully defined; these are typically the Sérsic index, effective radius, and intensity at the effective radius. However, we choose to define integrated flux (i.e., total flux) as the last variable instead of intensity at the effective radius for our simulations. Since we are modeling mergers, we also need to define a merger mass ratio and a separation.

In order to properly estimate the biases involved with our approach to identifying galaxy mergers, we created a large number of simulated Sérsic pairs with parameter values that span the expected parameter space, as estimated by our observed HST galaxies, convolved them with an appropriate
PSF for the ACS instrument on HST, and then added noise to the data, which mimicked the observed background of our galaxy tiles.

We simulated all combinations of the following parameter arrays: Sérsic index \( n = \{0.25, 0.5, 1, 3, 6, 10\} \), effective radius \( r_e = \{2, 5, 10, 15, 30, 60, 100\} \), integrated flux \( I = \{10^3, 10^4, 10^5, 10^6, 10^7\} \), merger flux ratio \( \beta = \{1, 2, 4, 8, 16, 40, 100\} \), and separation \( \delta = \{3.5, 10, 15, 25, 50, 100, 150, 196\} \).

Here we are using the merger flux ratio as a proxy for the merger mass ratio. The effective radius and separation are in units of pixels (HST/ACS has a pixel scale of 0.03″ per pixel), while the integrated flux is in units of ADUs. The separations were chosen to span the range of \( 1-20 \) kpc across our entire sample redshift range, while the integrated fluxes were chosen to fully span the range of our observed sample integrated fluxes. We restricted our simulated mergers by limiting the ratio of effective radius to Sérsic index to being less than 40; this was done because galaxy parameters outside of that are not physical. To best mimic the observed background of our galaxy tiles, we added Poisson noise from our simulated models as well as Gaussian noise with a mean of 1200 and standard deviation of 400; these values were estimated from the distribution of our sample’s GALFIT modeled backgrounds.

In total we created 376,992 simulated galaxies to model, consisting of 11,088 simulated single galaxies and 365,904 simulated galaxy pairs.

### 4.2. Modeling the Simulated Mergers

We then ran these simulated galaxies through our merger identification pipeline as detailed in Sections 3.2 and 3.3. Of the 11,088 simulated single galaxies, 5565 were correctly modeled, 5443 were not modeled at all, and 80 were incorrectly modeled with only a background component. The 5443 that were not modeled had low intensity levels; specifically they had intensities (in units of ADUs) at their effective radius of \( I_e < 10^0 \) and central intensities of \( I_0 < 10^{-2.7} \). The 80 that were incorrectly modeled had \( I_e > 10^0 \) and \( I_0 > 10^{-2.7} \), and therefore can be classified as false negatives. Of the 5565 true positives, all had \( I_e > 10^0 \) and \( I_0 > 10^{-2.7} \).

Of the 365,904 simulated galaxy pairs, 64,979 were correctly modeled, 180,724 were not modeled at all, and 120,188 were incorrectly modeled with either a single galaxy component or only a background component. There were only 13 simulated pairs that were modeled with more than two galaxy components. The 180,724 that were not modeled had \( I_e < 10^0 \) and \( I_0 < 10^{-2.7} \), while 69,526 of the 120,188 that were incorrectly modeled had \( I_e > 10^0 \) and \( I_0 > 10^{-2.7} \), and therefore can be classified as false negatives. Of the 64,979 true positives, all had \( I_e > 10^0 \) and \( I_0 > 10^{-2.7} \).

### 4.3. Correcting for Selection Biases

In order to properly account for the biases in our selection pipeline, we calculated the fraction of true positives to true positives plus false negatives; there were 70,544 true positives out of 140,150 true positives and false negatives; we define this as the completion fraction. We calculated the completion fraction at all points across the separation and merger mass ratio axes, which gave us a sparse two-dimensional bias map that we interpolated (Figure 3) in order to allow us to correct our results across the entire separation and merger mass ratio range of our sample. The simulations with \( I_e < 10^0 \) and \( I_0 < 10^{-2.7} \) were considered true negatives (i.e., accurately not found due to being too faint for the background noise—this mirrors a sensitivity limit for true data), while the 13 false positives were ignored as their contribution is trivial to the overall statistics (i.e., less than a 0.001 contribution to the completion fraction).

While examining our biases across our parameter space, we found that when the separation exceeded 50 pixels at the highest merger mass ratio (1:100), our pipeline’s accuracy dropped significantly. This is due to the Source Extractor source flux limitation we used. Since Source Extractor limits the flux ratio between multiple sources to 1:100 prior to modeling by GALFIT, our pipeline becomes insensitive to merger mass ratios \( \geq 85 \). This does not affect our analysis since we have no offset or dual AGNs with merger mass ratios greater than 85, but we include this discussion for completeness.

We applied corrections for these biases to our sample. When examining how AGN activation behaves as a function of bulge separation (see Section 6.1), we first binned by redshift in order to assign pixel separations to our kiloparsec separation bins, then binned into our kiloparsec bins, and lastly binned by merger mass ratio. We then applied a correction factor, the reciprocal of the completion factor calculated at the mean separation and merger mass ratio values of our bins, to offset our biases; we also estimated error values by calculating this correction at the minimum and maximum separation and mass ratio values in each bin.

We repeated this process to examine how AGN activation relates to merger mass ratio (see Section 6.2); the only difference was the binning order, with merger mass ratio first, followed by bulge separation. Lastly, if the error in a bin was less than the Poisson statistic of \( \sqrt{N} \), where \( N \) was the number added as a correction in that bin, we set the error to \( \sqrt{N} \); this was done to account for any errors associated with our assumptions as well as unknown errors so as to not overestimate the accuracy of our methods.

During the GALFIT modeling and bias correction process of this work, strictly Sérsic profiles were used. While we discuss how the use of only Sérsic profiles should not significantly impact the estimated merger properties of our sample in Section 3.2, the use of only Sérsic type simulated galaxies in our bias correction process means that any biases against...
non-Sérsic type galaxies is hard to detect and account for. This
would not necessarily affect any separations or merger mass
ratios more than others, but it could result in an overall lower
detection rate of mergers. While we did not notice a dearth of
spiral or irregular type galaxies while examining our sample by
eye as part of our false positive reduction measures
(Section 3.3), this should be thought of as a selection bias
and considered while examining the data and during any future
use of this sample.

5. Merging Galaxy Properties and Comparison to ACS-
AGN Sample

The ACS-AGN Catalog contains AGN and host galaxy
properties, most derived from SED template fits to photometric
data; these data include redshift ($z$), AGN bolometric
luminosity ($L_{AGN}$), galaxy mass ($M_g$), SFR, and column
density ($N_H$). The process by which these properties are derived
from observations or from SED template fits is explored in
depth in S20. The selection and modeling of our offset and dual
AGN sample in this work allows us to derive some merger
specific properties, such as bulge separation and merger mass
ratio.

In Section 5.1, we discuss how we calculate these merger
specific properties. We then examine the AGN and host galaxy
properties of offset and dual AGNs in comparison to the
general AGN sample of the ACS-AGN Catalog in Section 5.2.
Lastly, we search for any correlations between the AGN, host
galaxy, and merger properties of offset and dual AGNs in
Section 5.3.

All of the properties discussed in this section, and more, are
included in the ACS-AGN Merger Catalog, presented in
Table 1. This catalog is also available in its entirety in fits
format from the original publisher.

5.1. Obtaining Merger Parameters

Two important merger parameters can be obtained from the
GALFIT models: component separation and the integrated flux
of each component. The centroid locations of all fit components
are given by GALFIT in image units (pixel values). Using
these centroid locations, and knowledge of the pixel scale of
the galaxy tiles, we back out the angular separation of the
stellar bulges for our candidates. The angular separation is then
transformed into a projected physical separation using the
angular distance calculated from each galaxy’s redshift.

The second significant merger parameter that can be
obtained from the GALFIT model is merger mass ratio.
GALFIT measures and reports an integrated flux measurement
for each component during its fitting process. We take the ratio
of integrated fluxes between bulge pairs as a proxy for their
stellar mass ratio.

As was discussed in Section 3.2, our choice to use Sérsic
profiles to model our merger components should result in
accurate measurements of these properties in most cases, but
may cause scatter in their distributions (specifically merger
mass ratio), and caution should be taken when attempting to
examine individual systems instead of the sample en masse.
The distributions of these parameters are shown in Figures 8
and 9, respectively, and will be discussed further in Section 6.

### Table 1

| No. | Field                                | Notes                  |
|-----|--------------------------------------|------------------------|
| 1   | ID                                   | ACS-AGN Catalog specific unique identifier |
| 2   | R.A.                                 | R.A. (J2000, decimal degrees) |
| 3   | Decl.                                | Decl. (J2000, decimal degrees) |
| 4   | Z                                    | Redshift used          |
| 5   | SPECZ                                | Spectroscopic redshift |
| 6   | PHOTOZ                               | Photometric redshift   |
| 7   | Spitzer_AGN                          | If AGN was selected in Spitzer (Boolean) |
| 8   | Chandra_AGN                          | If AGN was selected in Chandra (Boolean) |
| 9   | L_bol_sed_md                         | AGN bolometric luminosity calculated from SED, median (erg s$^{-1}$) |
| 10  | L_bol_sed_lo                         | AGN bolometric luminosity calculated from SED, lower bound (erg s$^{-1}$) |
| 11  | L_bol_sed_hi                         | AGN bolometric luminosity calculated from SED, upper bound (erg s$^{-1}$) |
| 12  | L_x_md                               | 2–10 keV rest-frame luminosity, median (erg s$^{-1}$) |
| 13  | L_x_lo                               | 2–10 keV rest-frame luminosity, lower bound (erg s$^{-1}$) |
| 14  | L_x_hi                               | 2–10 keV rest-frame luminosity, upper bound (erg s$^{-1}$) |
| 15  | L_bol_x_md                           | AGN bolometric luminosity calculated from X-ray, median (erg s$^{-1}$) |
| 16  | L_bol_x_lo                           | AGN bolometric luminosity calculated from X-ray, lower bound (erg s$^{-1}$) |
| 17  | L_bol_x_hi                           | AGN bolometric luminosity calculated from X-ray, upper bound (erg s$^{-1}$) |
| 18  | M_star_md                            | Galaxy stellar mass, median ($M_*$) |
| 19  | M_star_lo                            | Galaxy stellar mass, lower bound ($M_*$) |
| 20  | M_star_hi                            | Galaxy stellar mass, upper bound ($M_*$) |
| 21  | SFR_md                               | SFR, median ($M_\odot$ yr$^{-1}$) |
| 22  | SFR_lo                               | SFR, lower bound ($M_\odot$ yr$^{-1}$) |
| 23  | SFR_hi                               | SFR, upper bound ($M_\odot$ yr$^{-1}$) |
| 24  | Nh_md                                | Nuclear column density, median (cm$^{-2}$) |
| 25  | Nh_lo                                | Nuclear column density, lower bound (cm$^{-2}$) |
| 26  | Nh_hi                                | Nuclear column density, upper bound (cm$^{-2}$) |
| 27  | SFR_norm_md                          | Normalized SFR, median |
| 28  | SFR_norm_lo                          | Normalized SFR, lower bound |
| 29  | SFR_norm_hi                          | Normalized SFR, upper bound |
| 30  | Sep_12                               | Separation between primary (active) and secondary components (kpc) |
| 31  | Ratio_12                             | Galaxy merger mass ratio between primary (active) and secondary components |
| 32  | Sep_13                               | Separation between primary (active) and tertiary components (kpc) |
| 33  | Ratio_13                             | Galaxy merger mass ratio between primary (active) and tertiary components |

Note. Field numbers 1–29 are taken from the ACS-AGN catalog (Steno et al. 2020); AGN selection and derivation of AGN host galaxy properties are found therein. Merger selection and derivations of merger properties are described throughout this paper; note that for field numbers 31 and 33 the reported values are integrated flux ratios that are used as proxies for the merger mass ratio. Lower bound and upper bound are defined as the 16th and 84th percentiles of the distribution, respectively. A “$-$999” value in the table represents no data. The ACS-AGN Merger Catalog is available in its entirety in fits format from the original publisher.

(This table is available in its entirety in machine-readable form.)

5.2. Comparison to the General AGN Sample

With this being the largest catalog of offset and dual AGNs
yet assembled, we examine how this population behaves and
relates to more general populations, such as the population of
all AGN host galaxies.
At first glance, it seems that our merger subsample is overrepresented at lower redshifts (and underrepresented at higher redshifts) when compared with the general AGN population of the ACS-AGN, as seen in Figure 4. Specifically, we find that our offset and dual AGN distribution increases until \( z \sim 1 \) and then decreases. This is surprising given that the merger fraction is thought to increase with redshift, peaking at redshifts near \( z = 1.5 \) (e.g., Carlberg 1990), with work studying deep surveys confirming those predictions (e.g., Ryan et al. 2008; Stott et al. 2013). However, our distribution is in agreement with the merger fraction for massive galaxies in the UltraVISTA/COSMOS catalog, as shown in Man et al. (2016). They explain that the reason for the drop in merger fraction above \( z = 1 \) in their sample is due to being incomplete at higher redshifts as low-surface brightness partners become undetectable.

Therefore, we test whether the trends seen in our offset and dual AGNs’ redshift distribution are also due to this selection bias. In order to do this, we adjusted the surface brightnesses and pixel separations of our sample to what would be observed if they were at the highest redshift in our sample, \( z = 2.5 \); specifically, for surface brightness we multiplied by a factor of \( (d_L(z)/d_L(z = 2.5))^2 \), where \( d_L(z) \) is the luminosity distance at the given redshift, \( z \); this follows the known relation of surface brightness being proportional to \((1 + z)^{-4}\) (e.g., Tolman 1930; Hubble & Tolman 1935; Sandage 1961). We found that the bulge separations of our offset and dual AGNs were not a limiting factor, with all being able to be detected even when adjusted to a \( z = 2.5 \) frame. However, only 16 out of the 204 dual and offset AGNs in our sample had sufficient surface brightness to be able to be detected using the methods outlined in Section 3 when adjusted to a \( z = 2.5 \) frame.

Therefore, we are heavily biased toward selecting only the brightest bulges at high redshifts. If we only examine the subsample of offset and dual AGNs that could be observed even when adjusted to the \( z = 2.5 \) frame (as seen in Figure 4), we find that our distribution peaks near \( z = 1.5 \), falling off at low redshift due to the decrease in survey volume observed as redshift decreases and dropping off rapidly at high redshift due to surface brightness dimming and survey depth limits. Therefore, we find that the redshift distribution of our offset and dual AGN sample recovers the expected merger fraction distribution with redshift of previous works (e.g., Carlberg 1990; Ryan et al. 2008; Stott et al. 2013), once this has been corrected for.

The distributions of the rest of the AGN and host galaxy properties (\( M_\star \), \( L_{\text{AGN}} \), SFR, and \( N_{\text{H}} \)) for the offset and dual AGNs closely mirror that of the general AGN population of the ACS-AGN Catalog. This can be seen in Figures 4 and 5, and is verified by Kolmogorov–Smirnov tests for each.
We also examined the AGN and host galaxy properties of our offset and dual AGNs in comparison to samples of non-merging AGN host galaxies matched by redshift and galaxy stellar mass. To do this, we matched each offset and dual AGN in our sample to a set of non-merging AGN host galaxies from the ACS-AGN catalog that had redshifts within 0.1 and galaxy stellar masses within 0.25 dex of the offset or dual AGN system. We required that each dual and offset AGN had a matched sample of at least 10 systems in order to be analyzed. In total, we examined 161 of the 204 dual and offset AGNs along with their matched samples, with the minimum, median, and maximum number of ACS-AGN galaxies in the matched samples being 10, 60, and 133, respectively. We then calculated how the offset and dual AGNs’ $L_{\text{AGN}}$, SFR, and $N_{\text{H}}$ values differed from their matched non-merging AGN host galaxies’ mean $L_{\text{AGN}}$, SFR, and $N_{\text{H}}$ values. The distribution of the differences between the offset and dual AGNs and their matched samples $L_{\text{AGN}}$, SFR, and $N_{\text{H}}$ values are shown in Figure 5. We find that the means of the difference distributions of these properties are all approximately zero, and therefore that the $L_{\text{AGN}}$, SFR, and $N_{\text{H}}$ values of the offset and dual AGNs do not significantly differ from that of non-merging AGN host galaxies.

Figure 5. Histograms of the AGN and host galaxy property values of our merger subsample in comparison to the general AGN population of the ACS-AGN Catalog (left) alongside histograms of the difference in AGN and host galaxy properties of our merger subsample in comparison to non-merging AGN host galaxies matched in redshift and galaxy stellar mass (right); the vertical solid lines indicate the mean difference values, while the vertical dashed lines indicate the difference distributions’ standard deviations. Note that the merger subsample distributions mimic that of the general AGN population and that the means of the difference distributions are approximately zero.
galaxies, even when matched in redshift and galaxy stellar mass.

From these results, we specifically find that at high AGN luminosities, offset and dual AGNs are not overrepresented compared to the general AGN population of the ACS-AGN. Therefore, we find that mergers do not preferentially trigger the most luminous AGN, but instead host AGN with similar luminosities to AGN not in mergers; this is true not only when examining the total sample, but also for the minor mergers (merger mass ratio > 4) and major mergers (merger mass ratio < 4) separately. This is in disagreement with theoretical predictions made by Hopkins & Hernquist (2009) and observations by Treister et al. (2012), but is in agreement with observational work by Kocevski et al. (2012) and Villforth et al. (2014). Further, recent studies by Ricarte et al. (2019) of the ROMULUS simulations (Tremmel et al. 2017) predict that there is no enhancement of SMBH growth in mergers, but instead that SMBH growth approximately follows the host galaxy SFR. These findings, along with trends found by S20, are in agreement with those predictions.

We also do not find any evidence that SFR is enhanced in offset and dual AGNs, instead finding that offset and dual AGNs do not exhibit any shift toward higher SFRs when compared to the overall active galaxy population. Other works have found that star formation is enhanced in mergers in general (e.g., Joseph & Wright 1985; Knapen et al. 2015). Our results indicate that the presence of offset and dual AGNs makes these merging systems unique in this regard. The lack of a shift to higher SFRs in offset and dual AGNs may indicate that the presence of an AGN in the merging system inhibits the expected increase in available material near the center of the merging system; this has been hinted, with observations suggesting that obscured AGN are more likely to reside in mergers (Kocevski et al. 2015; Ricci et al. 2017; Donley et al. 2018; Pfeifel et al. 2019), but the sample sizes have been limited in these studies.

When looking at our relations shown in Figure 6, it is apparent that there is a large amount of scatter in the data, with no tight correlations emerging. Overlaid on top of the data are linear fits; these correspond to exponential and logarithmic fits when examining these properties as functions of bulge separation and merger mass ratio, respectively. Excluding SFR as a function of bulge separation, we find that none of the fits have slopes that are significantly nonzero ($p$-value < 0.05) and that no pair is significantly correlated, as determined by its Spearman rank-order correlation coefficient ($p$-value < 0.05).

However, we know that the ACS-AGN galaxies show correlations between galaxy mass and SFR as well as galaxy mass and AGN luminosity (see S20 for more details); this relation has also been shown to exist for galaxies in mergers (Barrows et al. 2017b). As we can see in Figure 7, galaxy mass is significantly inversely correlated with separation in our sample; this is verified by examining the significance of its fit and Spearman rank-order correlation coefficient. Therefore we examine the specific SFR (sSFR; i.e., SFR divided by galaxy stellar mass) and AGN luminosity divided by galaxy stellar mass ($L_{\text{AGN}}$), in order to correct for any galaxy mass–separation correlation and galaxy mass–merger ratio correlation.

While SFR is significantly correlated with bulge separation, we find that this is due to the correlation between galaxy mass and separation. When examining sSFR and specific AGN luminosity, we find that neither have significant linear trends nor are they correlated at significant levels to bulge separation or merger mass ratio. This can be seen in Figure 7. Where Barrows et al. (2018) find that AGN luminosity increases as merger mass ratio decreases, this work does not find such a relationship. It is possible that nuclear star formation correlates with separation (e.g., U et al. 2019); however, due to the limitations of our methods, we cannot decompose nuclear and global star formation in our sample in order to investigate this.

From these data, we find that there is no observational evidence that nuclear column density, AGN luminosity, or SFR is correlated with bulge separation or merger mass ratio for offset and dual AGNs. We also examined these data by redshift and found that no correlations exist in any redshift bin examined ($0.2 < z < 0.5$, $0.5 < z < 0.8$, $0.8 < z < 1.5$, or $1.5 < z < 2.5$). This stands in contrast to many of the findings outlined above related to SFR increasing as separation decreases and as merger ratio approaches unity in the general population of mergers. Since the primary difference between these two populations is the presence of AGNs, this finding provides another piece of evidence supporting the hypothesis that an AGN can impart negative feedback on its host galaxy,
maintaining a lower level of star formation than would be expected in a merger without AGN. We also find that the most luminous AGN are not preferentially triggered by major mergers; this is in agreement with previous findings by Kocevski et al. (2012) and Villforth et al. (2014, 2017).

6. Results

6.1. AGN Activation Peaks at the Smallest Bulge Separations

One of the major open questions that this sample of offset and dual AGNs can address is whether the fraction of AGNs in mergers peaks at separations below 10 kpc. Theoretical work predicts that SMBH growth peaks at separations of either 1–10 kpc (Van Wassenhove et al. 2012) or 0.1–2 kpc (Blecha et al. 2013). While observations have found that AGN fraction increases from 100–10 kpc, the trend could not be constrained below 10 kpc due to the limited samples at small separations (Ellison et al. 2011; Koss et al. 2012; Barrows et al. 2017a).

We find that AGN activation increases significantly below 10 kpc. In Figure 8, we see that the AGN activation is mostly flat from 20–14 kpc, has a bump from 14–11 kpc, drops slightly from 11–4 kpc, and then increases significantly and peaks at

![Figure 6. Relations between AGN and host galaxy properties with the merger parameters of bulge separation (left) and merger mass ratio (right); from top to bottom, the AGN and host galaxy properties examined are: nuclear column density, AGN luminosity, and SFR. The overlaid red dashed lines and gray regions are linear fits to the data and the fits’ 95% confidence regions, respectively. None of the linear fits show any significant correlations except for SFR as a function of separation; this is due to correlations with galaxy mass (see Section 5.3 and Figure 7). Note that the scale for the merger mass ratio axis is Log2.](image-url)
our smallest separation bin, 3–2 kpc. This distribution is in qualitative agreement with previous work examining simulations of dual AGNs by Rosas-Guevara et al. (2019) that shows a bump in dual AGN fraction near 14 kpc and a rise as separations near 5 kpc. It should be noted that we had one system observed between 1.5 and 2 kpc, which is not included in this analysis because it is the only system in that bin.

We also analyze both the major and minor merger subpopulations of our sample in Figure 8; we define major mergers as those with merger mass ratios <4 and minor mergers as those with merger mass ratios >4. We see similar distributions as the total sample, with the exception that the bump near 14 kpc is only found in our major merger sample. This bump coincides with separations corresponding to the merger’s first pericenter passage, typically seen at separations from 10–20 kpc in simulations, when significant gas would be driven inwards, triggering AGN activation (Van Wassenhove et al. 2012; Blecha et al. 2013; Rosas-Guevara et al. 2019). This explains why this bump is only seen in our major merger sample, as first pericenter passage in major mergers should be more dynamic, driving more gas inward than minor mergers, and more readily triggering AGN activation.

Therefore, we confirm the theoretical predictions of Van Wassenhove et al. (2012) and Blecha et al. (2013), and are able...
to extend the trends seen by Ellison et al. (2011), Koss et al. (2012), and Barrows et al. (2017a). Further, we find that we are in good agreement with the smallest separation bin of Koss et al. (2012), which studied a small sample of moderate-luminosity, ultra-hard X-ray selected AGN at low redshifts. They find that 7.8% ± 1.8% of AGN are found in mergers at separations <15 kpc, while we find that 9.3% ± 1.3% of AGN are found in mergers at those separations, after accounting for biases.

It is uncertain whether AGN activation and SMBH growth continues to increase below 2 kpc. As was discussed in Section 3.2, a reasonable estimate of the physical size of a stellar bulge is approximately 1.5 kpc. Further, 1.5 kpc is very close to the limit at which we can accurately resolve two bulges, if they are even physically small enough to exist discretely at those separations. Therefore, we cannot reliably use offset and dual AGN discovered by selecting multiple stellar bulges to study AGN activation and SMBH growth below 2 kpc.

6.2. AGNs Are Preferentially Found in Major Mergers

The second primary question that can be addressed with our sample of offset and dual AGNs is whether the merger mass ratio affects AGN activation. Many others have examined whether major mergers trigger the most luminous AGN. As previously discussed, theoretical work by Hopkins & Hernquist (2009) predicts that major mergers trigger the most luminous AGN, while observational studies on the subject are not in agreement, with some in finding they do (e.g., Treister et al. 2012), and some finding no relation (e.g., Kocevski et al. 2012; Villforth et al. 2014, 2017).

While we also find that there is no relation between merger mass ratio and AGN luminosity (as discussed in Section 5.3), we do find that AGNs are preferentially found in major mergers; this can be seen in Figure 9. Using our corrected values and a merger mass ratio cutoff value of 4:1 between major and minor mergers, we find that 8.0% ± 0.8% of all AGNs are found in major mergers at separations <20 kpc and 4.5% ± 0.4% of all AGNs are found in minor mergers (with merger mass ratios greater than 4 and less than 85) at separations <20 kpc. In total we find that 12.5 ± 1.2% of all AGNs are found in mergers at separations <20 kpc. The overabundance of AGN in major mergers compared to minor mergers is especially significant because it is thought that minor mergers outnumber major mergers three to one (e.g., Bertone & Conselice 2009; Lotz et al. 2011); this means that AGN are overrepresented in major mergers by approximately a factor of 6 when compared to what would be expected if AGN activation had no dependence on merger mass ratio.

We also find that the fraction of AGNs in mergers at separations <20 kpc follows a logarithmic relationship from ratios of 1—16—we find a relationship of percent of AGN in merger mass ratio bin = −Log2(MassRatio)+5, where Mass-Ratio is the center value of the bin. Note that due to the nature of a histogram, this specific relation only applies when using bin widths of powers of 2, but a logarithmic relation would remain regardless.
Figure 9. Histogram of percentage of AGNs in mergers as a function of merger mass ratio, raw numbers are reported in addition to the bias-corrected values. Note that the scale for the merger mass ratio axis is Log2, and that the last bin spans merger mass ratio values from 16–85 due to the small number of galaxies in that range. The dashed vertical line at merger mass ratio = 4 separates major mergers to the left and minor mergers to the right. Note that AGNs in mergers at separations <20 kpc are preferentially found in major mergers. Specifically, using values corrected for selection effects related to bulge separation and merger mass ratio, we find that 8.0% ± 0.8% of all AGNs are found in major mergers (merger mass ratios from 1–4) and 4.5% ± 0.4% of all AGNs are found in minor mergers (merger mass ratios from 4–85), bringing the total percent of AGNs found in mergers to 12.5% ± 1.2%. We also find that the percentage of AGNs found at different merger mass ratios follows a logarithmic relation, decreasing as merger mass ratio increases.

3. We find that mergers do not trigger the brightest AGNs, but instead mergers at separations <20 kpc trigger AGNs with a similar distribution of luminosities as that of the general AGN population. This is true of all mergers, including the major and minor merger subpopulations.

4. We find that SFR, AGN luminosity, and nuclear column density have no significant correlations or dependencies on bulge separation or merger mass ratio, once known correlations with galaxy mass have been accounted for. Further, we find that the distributions of these values for AGNs and AGN host galaxies in mergers at separations <20 kpc do not significantly differ from the distributions of AGNs and AGN host galaxies in general.

These findings show that in mergers where the stellar bulges are separated by <20 kpc, bulge separation and merger mass ratio play an important role in the activation of AGNs, but do not significantly enhance star formation or the luminosity of AGNs in galaxy mergers. This implies that there may be AGN feedback involved in these systems that heats and/or blows out excess material, inhibiting AGN growth and slowing star formation rapidly after AGN activation, returning the system to AGN luminosity and SFRs typically seen in non-mergers.

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