# DIRECT EVIDENCE FOR ENHANCED AGN ACTIVITY IN ZCOSMOS GALAXY PAIRS

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## ABSTRACT

Mergers of gas-rich galaxies are expected to play a significant role in the growth of supermassive black holes as shown by numerical simulations. To test this scenario, we construct a sample of 563 galaxies  $(M_* > 2.5 \times 10^{10} M_{\odot})$  in close kinematic pairs over the redshift range 0.25 < z < 1.05that are more likely to be in an early stage of a merger than a well-matched control sample of 2733 galaxies both from the zCOSMOS 20k spectroscopic catalog. Galaxies that harbor an active galactic nucleus (AGN) are identified on the basis of their X-ray emission detected by Chandra. We find that the incidence of AGNs in galaxies with a close neighbor is higher than those without and the level of activity increases with decreasing separation between the galaxies. Our findings are the result of an enhancement of AGN activity by a factor of 2.1 (with a significance of  $3.3\sigma$ ) for pairs of physical separation less than 75 kpc (h = 0.7) and line-of-sight velocity offset less than 500 km s<sup>-1</sup>, relative to isolated galaxies of similar stellar mass. Our study provides observational evidence that galaxy mergers are likely to induce gas inflow to the nuclear region that subsequently fuels a supermassive black hole, and mergers account for about 22% of all black hole growth during these early encounters. Subject headings: galaxies: active — galaxies: interactions — quasars: general — X-rays: galaxies

## 1. INTRODUCTION

There has been a long-standing question in astrophysics, ever since quasars and AGN were firmly be-

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lieved to be powered by accretion (Salpeter 1964) onto supermassive black holes (SMBH); what physical mechanism(s) is (are) responsible for the loss of angular momentum of gas that is initially rotationally-supported and that can then be available to fuel a central SMBH (e.g., Lynden-Bell & Rees 1971)? There have been a number of proposed mechanisms that have been investigated, over the past few decades, such as disk instabilities, galaxy mergers, or supernova-driven winds, just to name a few. More recently, the merger scenario has been a leading contender since numerical simulations demonstrate that such events (Mihos & Hernquist 1996) can generate large mass inflow rates to the nuclear region thus potentially fueling both AGNs and central starbursts (e.g., Hopkins et al. 2008).

In support of the merger scenario, the by-products of major mergers of gas-rich galaxies, the ultra-luminous infrared galaxies (ULIRGs), have been known for decades to be conducive to black hole growth (Sanders & Mirabel 1996). ULIRGS have been shown to have high nuclear concentrations of gas (Scoville et al. 1989) that likely provide an ample fuel reservoir for accretion onto a SMBH. Indeed, the incidence of AGN in ULIRGs (e.g., Kartaltepe et al. 2010) rises substantially with IR luminosity to an unprecedented level (> 50%) for the brightest that reach bolometric luminosities equivalent to quasars.

There has been much effort (e.g., Bahcall et al. 1997; Canalizo & Stockton 2001) over the past decade to determine whether galaxy mergers play a role in fueling quasars by carrying out imaging campaigns of their host galaxies with HST to look for signs of morphological disturbances. Such efforts are challenging because of the glaring light of a nuclear point source and the lack of

adequate control samples. Fortunately, new samples of AGNs have been constructed that appear to alleviate some of these difficulties. In particular, X-ray surveys are identifying an obscured population that makes it easier to discern the morphology of their host. Largearea surveys, with HST coverage and multi-wavelength support such as COSMOS (Scoville et al. 2007), are enabling the construction of adequate control samples. To date, studies based on X-ray selected AGN have not yet demonstrated the role of major mergers of galaxies as triggering AGN activity (Grogin et al. 2005; Gabor et al. 2009; Cisternas et al. 2010), even though remarkable examples of a binary AGN have been found in the COS-MOS field (Comerford et al. 2009; Civano et al. 2010) and elsewhere (e.g., Green et al. 2010; Shen et al. 2010; Fu et al. 2010). One explanation is that deep surveys mainly detect moderate-luminosity AGNs (i.e., "Seyfert" population) thus the fueling mechanisms may differ from the more luminous quasars (Hopkins & Hernquist 2009).

We present an alternative test of the merger hypothesis with respect to moderate-luminosity AGN activity that does not consider host galaxy morphology. We instead identify galaxies in the zCOSMOS spectroscopic survey that are in kinematic pairs. These are two galaxies within a given projected separation and line-of-sight velocity difference that likely indicates an early stage in a galaxy merger. We determine the frequency that these galaxies host an AGN based on X-ray emission detected by *Chandra* and compare to a well-defined control sample. We highlight that we are investigating the impact of interactions on scales between  $\sim 10 - 150$  kpc thus our study will provide constraints on merger-driven models of black hole growth before a coalescence phase. Throughout this work, we assume  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\Lambda} = 0.75, \Omega_{\rm M} = 0.25$ , and AB magnitudes.

#### 2. ZCOSMOS 20K GALAXY REDSHIFT SURVEY

zCOSMOS (Lilly et al. 2007, 2009) is a ESO program to acquire spectroscopic redshifts for a large sample of galaxies in the COSMOS field (Scoville et al. 2007) with VIMOS on the VLT. A 'bright' sample of 20,000 galaxies (i < 22.5) is observed with a red grism to provide a wavelength coverage of 5500 - 9500 Å ideal for identifying  $L_*$ galaxies up to  $z \sim 1.2$ . We use this catalog to construct a well-defined sample of galaxies. Specifically, we identify 15,807 galaxies with  $i_{ACS} \leq 22.5$  and spectroscopic redshifts between 0.25 < z < 1.05, each having a quality flag ( $\geq 1.5$ ) that amounts to a confidence of ~ 99% in the redshift measurements for the overall sample. We do not include any serendipitous objects that happen to fall within a slit. Full details on data acquisition, reduction, and redshift measurements can be found in Lilly et al. (2007, 2009)

We further isolate 10,964 zCOSMOS galaxies that fall within the *Chandra* survey area (see below for details, Elvis et al. 2009) since we use the X-rays from this data set to identify those hosting an AGN. Of these, there are 3481 with a stellar mass above  $M_* > 2.5 \times 10^{10} \text{ M}_{\odot}$ and 0.25 < z < 1.05. These limits are chosen to ensure a fairly complete representation of both blue and red galaxies over the given range in redshift (see Silverman et al. 2009b). Derived properties such as stellar mass and rest-frame color (Figure 1) are determined for each galaxy as detailed in Bolzonella et al. (2010) and Pozzetti



FIG. 1.— Rest-frame color U - V versus stellar mass for zCOS-MOS galaxies with 0.25 < z < 1.05 (small circles). Galaxies in kinematic pairs are shown in black while all others are marked in grey. The AGNs are further marked with colored circles (filled=kinematic pair; open=all others). The vertical line marks our chosen mass limit.

et al. (2010).

## 2.1. Kinematic pairs

A major focus of the zCOSMOS survey is the study of galaxies in close kinematic pairs as a laboratory to determine the redshift evolution of the galaxy merger rate (de Ravel et al. 2011) and the physical properties of the galaxies themselves (Kampczyk et al. 2011). We use the zCOSMOS 20k catalog to identify those galaxies with a nearby neighbor. Galaxies in kinematic pairs are specifically selected to have a projected separation dr <100 kpc h<sup>-1</sup> (143 kpc for our chosen h = 0.7) and a lineof-sight velocity difference  $dV < 500 \text{ km s}^{-1}$  (Kampczyk et al. 2011). Based on this selection, we identify 753 galaxies, out of the 3481 (selected by stellar mass and redshift) that are associated with a galaxy pair. Of these, there are 330 with a mass ratio less than 3 to 1, while 563 have a mass ratio between 10 and 1. In Figure 1, we show the stellar mass and rest-frame color of the galaxies in kinematic pairs.

## 3. CHANDRA X-RAY OBSERVATIONS AND AGN IDENTIFICATION

We match our zCOSMOS galaxy sample to the catalog of *Chandra* X-ray sources (Elvis et al. 2009; Puccetti et al. 2009) using a maximum-likelihood routine as detailed in Civano et al. (2011). The *Chandra* observations cover the central 0.9 sq. deg and result in the detection of 1761 point sources above a flux level of  $5.7 \times 10^{-16}$ erg cm<sup>-2</sup> s<sup>-1</sup> in the 0.5-10 keV band. The tiling scheme not only provides a fairly uniform sensitivity but an optimal PSF across the field. We highlight that the resolving power of *Chandra* is important with respect to our study since galaxy pairs have been found to reside in regions of heightened galaxy overdensities (Lin et al. 2010; de Ravel et al. 2011; Kampczyk et al. 2011) where extended X-ray emission, if present, may hamper the detection of point sources. The *Chandra* observations over the C-COSMOS region are sensitive to AGNs with  $L_{0.5-10 \text{ keV}} > 3 \times 10^{42} \text{ ergs s}^{-1}$  out to  $z \sim 1$ .

over the C-COSMOS region are sensitive to AGNs with  $L_{0.5-10 \text{ keV}} > 3 \times 10^{42} \text{ ergs s}^{-1}$  out to  $z \sim 1$ . We identify 337 zCOSMOS galaxies with X-ray emission that primarily falls within the range  $10^{42} \lesssim L_{0.5-10 \text{ keV}} \lesssim 10^{44} \text{ erg s}^{-1}$ . In terms of Eddington ratio, we are sensitive to SMBHs having  $10^{-3} \lesssim L_{\text{Bol}}/L_{\text{Edd}} \lesssim 10^{-1}$  given the stellar masses of their hosts, an assumption of their bulge-to-total mass ratio ( $B/T \sim 0.5$ ), and the local  $M_{BH} - M_{bulge}$  relation. The majority of AGNs have optical emission dominated by their host galaxies and lack broad optical emission lines, both highlighting the importance of X-ray selection to account for the moderately-obscured population at these redshifts (Mainieri et al. 2007; Brusa et al. 2010). It is also possible, although beyond the scope of this paper, to determine the prevalence of heavily-obscured or Compton-thick AGN, missed in X-ray surveys, within the galaxy pair population that can only be identified through optical-line emission (e.g., Bongiorno et al. 2010; Yan et al. 2010) or excess infrared emission (e.g., Fiore et al. 2009).

We compare the properties of our AGN hosts to the underlying galaxy population by selecting those with  $10^{42.0} \leq L_{0.5-10 \text{ keV}} \leq 10^{43.7} \text{ erg s}^{-1}$ , a range that likely results in a purely AGN-dominated sample, in terms of X-ray emission, and avoids the inclusion of more optically-luminous AGNs that can impact the derived rest-frame colors and stellar mass estimates (e.g., Silverman et al. 2008). In Figure 1, we see that their host galaxies are massive  $(M_* > 2.5 \times 10^{10} \text{ M}_{\odot})$  and residual star formation may be present as evident by the slightly bluer colors (< U - V >= 1.6) of AGN hosts as compared to non-active galaxies ( $\langle U-V \rangle = 1.7$ ) of similar stellar mass (e.g., Silverman et al. 2009b; Schawinski et al. 2010; Xue et al. 2010). This is in agreement with Kampczyk et al. (2011) who find that galaxies in zCOS-MOS kinematic pairs have elevated star formation rates, heightened post-starburst signatures and an increase in the numbers of galaxies with irregular morphologies.

### 4. RESULTS

We first highlight some examples of AGNs associated with galaxies in close kinematic pairs that illustrate the diversity in their optical properties and environments. In Figure 2, we show *Chandra* and HST/ACS (F814W) images for three cases. In the top panel, a system of three galaxies at  $z \sim 0.659 \ (right)$  is identified to be kinematically linked. An X-ray source (left) is clearly associated with one of the galaxies undergoing a merger, as is evident from the low-level optical emission linking it to a neighbor (towards the south-east) about 20 kpc away. In addition to a point-like hard X-ray source, diffuse emission is present, as seen in the 2-7 keV image; the extended emission is more prominent in the soft energy band as expected (not shown). In Fig. 2 (middle), two spiral galaxies separated by  $\sim 15$  kpc are likely in the process of merging and one of them hosts a luminous AGN while the other is a post-starburst galaxy based on spectral features (i.e., strong Balmer absorption series) evident in a zCOSMOS optical spectrum (not shown). A third example (*bottom*) clearly shows a barred spiral



FIG. 2.— AGNs in close kinematic pairs: Top An AGN (CID=450) at z = 0.658 is part of a system of three galaxies within the central potential of an X-ray emitting galaxy group. The redshifts of the individual galaxies are labelled. On the left, the Chandra hard-band (2-7 keV) image clearly shows the detection of an X-ray point source. On the right, the HST/ACS *i* image is displayed. Middle An AGN (CID=1711) is associated with a pair of interacting, spiral galaxies at z = 0.77. Bottom A system at z = 0.371 with a barred spiral hosting an AGN (CID=3083). In all panels, the optical positions of the zCOSMOS galaxies in pairs are marked with a small cross (red=AGN), and north is up while east is to the left.

galaxy with an AGN and a companion 24 kpc away.

Our objective is to measure the fraction of galaxies that host AGN as a function of whether they are associated with a kinematic pair or not to assess whether early encounters between galaxies induce such nuclear activity. We specifically determine whether a zCOSMOS galaxy with  $M_* > 2.5 \times 10^{10}$  M<sub> $\odot$ </sub> is identified with an X-ray detection by *Chandra*. We allow a galaxy to be associated with a kinematic pair if it has a neighbor satisfying the criteria, given above, on the projected separation and line-of-sight velocity difference. We further restrict the sample to pairs with a mass ratio less than 10 to 1 that allows for a companion to have a mass below our threshold. This mass ratio is chosen to isolate a sample for which strong gravitational interactions are capable of destabilizing gas that can subsequently fuel an AGN.

We follow the technique discussed in Silverman et al. (2009a,b) to determine the AGN fraction of our parent population of galaxies. This method accounts for the spatially-varying sensitivity limits of the *Chandra* observations over the COSMOS field (see Figure 4 of Elvis et al. 2009). The total fraction is the sum of all individual AGN weighted by the effective number of galaxies ca-

 TABLE 1

 Sample statistics-kinematic pair analysis

Type	Redshift	dr kpc	${\rm dv \atop km \ s^{-1}}$	# of AGN (galaxies)	AGN fraction (%)
Pairs Control	0.25 - 1.05 0.25 - 1.05	$< 75 \\> 143$	$<\!$	$\begin{array}{c} 21 \ (217) \\ 120 \ (2733) \end{array}$	$\begin{array}{c} 11.20 \pm 2.25 \\ 5.32 \pm 0.44 \end{array}$
Pairs	0.25 - 0.65	< 75	< 500	$6^{\rm a}$ (89)	$6.51 \pm 2.63$
Control	0.65 - 1.05 0.25 - 0.65	$< 75 \\> 143$	$< 500 \\ > 500$	$ \begin{array}{c} 14^{a}(128) \\ 24^{a}(907) \end{array} $	$\begin{array}{c} 11.34 \pm 2.89 \\ 2.63 \pm 0.54 \end{array}$
	0.65 - 1.05	> 143	> 500	$93^{\rm a}$ (1826)	$6.08 \pm 0.57$
Pairs	0.25 - 1.05	< 143	< 500	40(563)	$8.16 \pm 1.20$
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<sup>a</sup> log  $L_{0.5-10 \text{ keV}} > 42.5$  for the high redshift bin and log  $L_{0.5-10 \text{ keV}} > 42.2$  for the low redshift bin.

pable of detecting the respective AGN of a given X-ray luminosity. The procedure is fully described in Silverman et al. (2009a,b) with the appropriate equations. We remark that the effective number of galaxies, in many cases, falls below the total number of galaxies reported in Table 1. The sampling rates of the random galaxies and AGN are incorporated in this estimate, as an additional weight, since these differ by a factor of 1.74, because 29% of the *Chandra* sources are designated as 'compulsory targets' when designing masks for VIMOS. Therefore, the AGN fraction is not a simple division of two numbers. We estimate the associated  $1\sigma$  error using binomial statistics.

We then compare the fraction of galaxies, in pairs, that host an AGN to those, not in pairs, over the redshift range 0.25 < z < 1.05 (Table 1). We define an AGN here as an X-ray point source with  $\log L_{0.5-10 \text{ keV}} > 42.2$  (units of erg s<sup>-1</sup>), unless otherwise noted; the inclusion of a small number (13%) of more luminous AGNs (Log  $L_X \sim 43.7 - 44.5$ ), that may have less accurate stellar mass estimates, has no impact on our results. As motivated by the analysis given below, we limit the sample of galaxies in pairs to those having a close neighbor that satisfies the criteria that dr < 75 kpc and dv < 500 $\mathrm{km} \mathrm{s}^{-1}$ . We find that over the entire redshift range the AGN fraction for the control sample is  $5.3 \pm 0.4\%$ , while the pair sample has a higher AGN fraction of  $11.2 \pm 2.2\%$ . We estimate the significance of the difference in the AGN fraction  $(\Delta = f_A - f_B)$  by numerically integrating the product of the beta distribution (likelihood) of  $f_A$  and  $f_B$  shown in the top and middle panels of Figure 3. Confidence levels (68%, 99%) are estimated by numerically integrating the likelihood of  $\Delta$ . We find that the enhancement  $(2.1\times)$  is significant at the  $3.3\sigma$  level. In Figure 3 (bottom panel), we show the AGN fraction of galaxies in kinematic pairs and the control sample as measured in two redshift bins of equivalent width. We set the minimum X-ray luminosity to roughly the mean sensitivity limit for each redshift bin (0.25 < z < 0.65): 0.65 < z < 1.05: log  $L_X > 42.5$ ). We find that the fraction of galaxies in pairs hosting an AGN is higher in both redshift intervals even when implementing a constant luminosity cut (i.e.,  $\log L_X > 42.5$ ) over the full redshift range. The increase in the AGN fraction with redshift is as expected based on the overall evolution of the luminosity function of AGN.

We expect that AGN activity is more pronounced as two galaxies approach each other with smaller physical separations based on simulations of galaxy mergers. The



FIG. 3.— AGN fraction of galaxies in close kinematic pairs (dr < 75 kpc and dv < 500 km s<sup>-1</sup>) as compared to galaxies with no neighbor within a projected separation of 143 kpc and a velocity offset less than 500 km s<sup>-1</sup>. The beta distribution (likelihood) of the AGN fraction in pairs (top panel;  $f_A$ ), not in pairs (top panel;  $f_B$ ), and the the difference ( $\Delta = f_A - f_B$ ; middle panel) is shown. bottom AGN fraction of galaxies in pairs is given by the filled black circles while the open circle denotes galaxies not in pairs for two redshift intervals. The horizontal bars indicate the redshift range for each value while the vertical bars are the 1 $\sigma$  error.

first signs of accretion, such as those of an AGN, are predicted (Hopkins et al. 2008) to be evident after the first passage of the interacting galaxies with a physical separation of  $\sim 30 - 50$  kpc and about  $\sim 1$  Gyr prior to the final coalescence of both galactic nuclei. Conclusive evidence for such an enhancement of moderate-luminosity AGN activity has been elusive in SDSS samples at lower redshifts (e.g., Li et al. 2008; Ellison et al. 2008).

To search for this behavior in the zCOSMOS pair sample, we measure the AGN fraction while separating the sample into bins of projected separation (dr) and lineof-sight velocity difference (dv). In Figure 4, we compare the results of this exercise with the AGN fraction of galaxies not in pairs that acts as our control sample. Two sets of data points in panel *a* are shown only to illustrate the results and the associated errors for different bin sizes; in no way are the two sets of data independent



FIG. 4.— Fraction of galaxies hosting an AGN shown as a function of both the projected physical separation (a) and line-of-sight velocity difference (b). The open circles in panel a are the measurements based on a finer binning in separation. The right-most data point in both panels gives the AGN fraction of galaxies not in pairs with the horizontal lines showing the  $1\sigma$  error and extended along the abscissa for visual comparison.

of each other. We find that the AGN fraction of galaxies is highest on the smallest scales, in terms of both projected separation ( $dr \lesssim 75$  kpc) and velocity ( $dv \lesssim 500$  km s<sup>-1</sup>) difference, and rises with both decreasing drand dv. The trend is stronger when considering the projected physical separation with the velocity separation. It is clear that the highest incidence (11.2%) of AGN activity occurs in galaxies in kinematic pairs with projected physical separation less than 75 kpc. This physical scale is in remarkable agreement with clustering studies (Serber et al. 2006) of SDSS quasars and  $L^*$  galaxies at z < 0.4 that show that quasars reside within regions of galaxy overdensity on scales of less than 100 kpc.

We recognize that these observed trends may be driven by the dependence of AGN activity on stellar mass and not the close proximity of a neighboring galaxy. To address this, we performed a K-S test to determine whether the stellar-mass distribution of the pairs and the control sample differ in any of the bins (i.e., redshift, dr, dv) implemented in this study. We find that there is no noticeable difference that can be responsible for the results presented herein.

### 5. SUMMARY AND CONCLUSIONS

We have performed a simple test of the merger scenario for triggering moderate-luminosity AGNs. To do so, we have utilized a sample of kinematic pairs identified from the zCOSMOS 20k 'bright' catalog and *Chandra* observations that indicate those harboring AGNs. The X-ray selection of AGN enables us to include those that may be cloaked in star formation that can hamper optical selection. Based on these multi-wavelength observations, we have found that (1) galaxies (0.25 < z < 1.05;  $M_* > 2.5 \times 10^{10} \text{ M}_{\odot}$ ) in kinematic pairs, with physical separations less than 75 kpc and line-of-sight velocity difference less than 500 km s<sup>-1</sup>, exhibit heightened levels of AGN activity (11.1%) relative to galaxies not within these associations (5.3%) by a factor of 2.1 (with

a significance of  $3.3\sigma$ ), and (2) the incidence of AGNs in pairs increases with decreasing projected separation and velocity difference. These results demonstrate that galaxy mergers are conducive environments for AGNs, even those of moderate luminosity ( $L_X \sim 10^{43} \text{ erg s}^{-1}$ ). Our measurement of the fraction of galaxies hosting

AGN, either associated with kinematic pairs or not, can be used to determine the relative importance of galaxy mergers, as compared to other secular (i.e., internal) mechanisms, for black hole growth. We need to consider that zCOSMOS samples  $\sim 50\%$  of all galaxies down to  $i_{ACS} = 22.5$  that results in a completeness of 25% (Kampczyk et al. 2011) with respect to the identification of all pairs to this limiting magnitude falling within the Chandra footprint. While we observe 25% (40/160) of AGNs to be in kinematic pairs, this fraction rises to 48%after accounting for the efficiency of pair identification. The true impact of mergers on AGN activity requires that we remove the contribution of non-merger activity within the kinematic pair sample (i.e., background signal). Therefore, we estimate an excess AGN fraction  $f_x = (f_A - f_B)/(f_A + N_B \times f_B/N_A)$ , where  $f_A$  (8.2%) and  $f_B$  (4.5%) are the AGN fractions in each sample for a given number of galaxies ( $N_A = 1126$ ,  $N_B = 2170$ ) in the zCOSMOS 20k catalog. We find  $f_x = 22\%$  that represents the contribution of early stage encounters to black hole growth. The overall importance of mergers is likely to be higher since those in a late stage or coalescence phase have not been included in our analysis. Indeed, a visual inspection of the HST images of AGNs in our control sample reveals a non-negligible number of interacting or disturbed systems. We conclude that galaxy mergers, even at early stages, are a vital mechanism for which SMBHs grow. Finally, we note that Chandra coverage of the full COSMOS area is imperative to tie together the formation of bulges and their black holes in an environmental context.

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