ACTIVE GALACTIC NUCLEUS FEEDBACK AT $z \sim 2$ AND THE MUTUAL EVOLUTION OF ACTIVE AND INACTIVE GALAXIES

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ABSTRACT

The relationship between galaxies of intermediate stellar mass and moderate luminosity active galactic nuclei (AGNs) at $1 < z < 3$ is investigated with a Galaxy Mass Assembly ultra-deep Spectroscopic Survey (GMASS) sample complemented with public data in the GOODS-South field. Using X-ray data, hidden AGNs are identified in unsuspected star-forming galaxies with no apparent signs of non-star forming activity. In the color–mass plane, two parallel trends emerge during the $\sim 2$ Gyr between the average redshifts $z \sim 2.2$ and $z \sim 1.3$: while the red sequence becomes significantly more populated by ellipticals, the majority of AGNs with $L(2-10$ keV) $> 10^{42.3}$ erg s$^{-1}$ disappear from the blue cloud/green valley where they were hosted predominantly by star-forming systems with disk and irregular morphologies. These results are even clearer when the rest-frame colors are corrected for dust reddening. At $z \sim 2.2$, the ultraviolet spectra of active galaxies (including two Type 1 AGNs) show possible gas outflows with velocities up to about $-500$ km s$^{-1}$, which are observed neither in inactive systems at the same redshift, nor at lower redshifts. Such outflows indicate the presence of gas that can move faster than the escape velocities of active galaxies. These results suggest that feedback from moderately luminous AGNs (log $L_X < 44.5$ erg s$^{-1}$) played a key role at $z \gtrsim 2$ by contributing to outflows capable of ejecting part of the interstellar medium and leading to a rapid decrease in star formation in host galaxies with stellar masses $10 < \log(M/M_\odot) < 11$.

Key words: galaxies: active – galaxies: evolution – galaxies: formation

Online-only material: color figures

1. INTRODUCTION

The evolution of galaxies is thought to be deeply linked to active galactic nucleus (AGN) activity because of the tight correlation observed between the masses of present-day galaxy bulges and their nuclear supermassive black holes (see Alexander & Hickox 2012 for a review).

AGNs are expected to provide negative feedback processes that can suppress star formation on galactic scales through the interaction of radiation, winds, and jets with the interstellar medium (ISM) of the host galaxy, leading to the ejection and/or heating of a substantial fraction of the gas (e.g., Di Matteo et al. 2005; Fabian 2012). However, it also seems plausible that the same AGNs can provide some positive feedback by triggering or enhancing star formation (e.g., De Young 1989; Gaibler et al. 2012; Ishibashi et al. 2013).

One promising approach is to investigate the relationship between AGN activity and galaxy evolution in the critical transformation phase believed to occur at $1 < z < 3$, when a significant fraction of galaxies moved from the locus of star-forming systems in the color–mass plane (the so called blue cloud) to the red sequence where spheroidal galaxies with weak or suppressed star formation are located mostly at $z \lesssim 1$ (e.g., Cassata et al. 2008; Brusa et al. 2009; Silverman et al. 2008; Cardamone et al. 2010; Cameron et al. 2011; Kocevski et al. 2012). Deep multi-wavelength data are essential to address these questions from the observational point of view, and recent results suggest that AGN and galaxy evolution are deeply related to each other (e.g., Daddi et al. 2007; Mullaney et al. 2012; Bongiorno et al. 2012; Rovilos et al. 2012; Olsen et al. 2013; Rosario et al. 2013).

The main purpose of this study is to investigate the supposed role of AGN negative feedback during the critical cosmic epoch at $1 < z < 3$. We adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_k = 0.7$.

2. THE GMASS SAMPLE AND X-RAY DATA

The present study is based on the t Galaxy Mass Assembly ultra-deep Spectroscopic Survey (GMASS) sample, in which galaxies were selected from a region of the GOODS-South/Hubble Ultra Deep Field region with only the criterion of having Spitzer IRAC 4.5 μm magnitudes brighter than 23.0 (AB) (Kurk et al. 2013; K13 hereafter). As shown in K13, the selection at 4.5 μm ensures sensitivity to stellar mass, a favorable k-correction up to $z \sim 3$, less influence from dust extinction, and represents a major difference compared to previous works in this sky region where studies on AGNs were mostly based on X-ray selected samples (see previous references). A fraction of the galaxies have very deep optical spectroscopy with integration times up to $>30$ hr (K13). Photometric spectral energy distributions (SEDs) from $U$- to the IRAC 8 μm band were used to estimate photometric redshifts (photo-z) for galaxies without spectroscopic redshifts and to derive galaxy properties adopting the stellar population models of Maraston (2005), the Kroupa (2001) initial mass function, and
Figure 1. Examples of morphological classes (HST, WFC3+F160W imaging, 4′ × 4′).
Top row, from left to right: elliptical (z = 1.31), elliptical (z = 1.19), disk (z = 1.09), irregular (z = 1.03). Bottom row, from left to right: elliptical (z = 1.91), compact (z = 2.51), disk (z = 1.84), faint (z = 2.45).

Table 1

| Statistics of Morphological Classes a |
|-------------------------------------|
| Elliptical | Compact | Disk | Irregular | Faint |
| 1 < z < 1.7 |
| All        | 40% (49) | 0% (0) | 43% (53) | 16% (20) | 0% (0) |
| No X-rays  | 37% (36) | 0% (0) | 46% (44) | 17% (16) | 0% (0) |
| L X > 10^{41.2} | 50% (13) | 0% (0) | 35% (9) | 15% (4) | 0% (0) |
| L X > 10^{42.3} | 62% (5) | 0% (0) | 25% (2) | 12% (1) | 0% (0) |
| 1.7 < z < 3 |
| All        | 17% (25) | 10% (15) | 17% (24) | 47% (68) | 8% (12) |
| No X-rays  | 14% (16) | 10% (11) | 16% (18) | 51% (57) | 9% (10) |
| L X > 10^{41.2} | 28% (9) | 12% (4) | 19% (6) | 34% (11) | 6% (2) |
| L X > 10^{42.3} | 23% (6) | 15% (4) | 19% (5) | 35% (9) | 8% (2) |

Note. a The fractions (%) and number (in brackets) of morphological classes.

Solar metallicity (K13). These SEDs were also used to derive the rest-frame (U − B) colors (standard Johnson filters) with the method described by Ilbert et al. (2005).

For this study, 266 galaxies were selected from the GMASS sample applying two selection criteria: 1 < z < 3 and a cut in stellar mass, log(M/M☉) > 10, in order to ensure a high completeness in mass across the whole redshift range (see Cassata et al. 2008). At 1 < z < 3, 55% of the sample has reliable spectroscopic redshifts when GMASS spectroscopy is complemented with the public European Space Observatory Very Large Telescope GOODS-South spectra (Balestra et al. 2010). For the remaining 45% of the sample, the photo-z described in K13 was used.

Public Hubble Space Telescope (HST) near-infrared imaging (WFC3 + F160W filter) taken in the framework of the Early Release Science (Windhorst et al. 2010) and CANDELS (Kocevski et al. 2011; Guo et al. 2013) surveys was exploited to assign one of the following visual (rest-frame optical) morphological classes to each galaxy: elliptical, compact, disk, irregular, and faint (Figure 1 and Table 1; see also Talia et al. 2013). The galaxies classified as compact are small roundish objects, whereas the faint galaxy class consists of objects too weak (or invisible) for a reliable classification.

Our selected sample of 266 galaxies was cross-correlated with the catalog of 740 X-ray sources of Xue et al. (2011, hereafter X11) based on the Chandra 4 Ms public data of the Chandra Deep Field South (CDFS), returning 58 matches within a search radius of 1′. The rest-frame 2–10 keV luminosities (L_x) hereafter) were derived from the absorption-corrected rest-frame 0.5–8 keV luminosities tabulated in X11 and assuming a Γ = 1.8 power law. Neutral hydrogen column densities (N_H) were obtained from F. E. Bauer et al. (2013, private communication). The 4 Ms CDFS exposure is complete down to log(L(0.5–8 keV)) ∼ 42.5 erg s⁻¹ across the entire redshift range explored in this work (see Figure 16(b) in X11), which translates into log(L_X) ∼ 42.3 erg s⁻¹ for Compton-thin AGNs (N_H < 10^{23} cm⁻²). This is also the threshold above which AGN activity dominates over star formation (e.g., Ranalli et al. 2003; Bauer et al. 2004).

The Chandra data were also used to derive average X-ray properties of galaxies (such as fluxes and average obscuration) by using a stacking technique based on CSTACK (v3.0) recently modified to include the full 4 Ms exposure. In order to minimize any contamination of detected sources in the stacked signal, all objects with a known X-ray source within 10′ of the centroid were excluded. Furthermore, the stacking analysis has been made within 8′ of the CDFS field center in order to maximize the Chandra point-spread function.

2.1. General Properties of the Sample

Our selected sample probes the regimes of intermediate galaxy stellar masses (10 < log(M/M☉) < 11) and moderate luminosity AGNs (log L_X < 44.5 erg s⁻¹; Figure 2).

The fractions of X-ray sources at 1 < z < 3 are 22% and 13% down to log L_X = 41.3 and log L_X > 42.3, respectively, which are consistent with previous works (e.g., Xue et al. 2010; Olsen et al. 2013) when the increasing fraction of AGNs with stellar mass is taken into account. If the sample is divided into two redshift bins nearly equally populated (1 < z < 1.7, N = 122, z_med = 1.31, 1.7 < z < 3, N = 144, z_med = 2.25), the fraction of X-ray sources with log L_X > 42.3 depends on redshift, increasing from 7% at 1 < z < 1.7 to 18% at 1.7 < z < 3 (see also Brusa et al. 2009).
star-forming galaxies with irregular and disk morphologies (see also Rosario et al. 2013). A smaller fraction of AGNs is hosted by ellipticals and compact galaxies (Table 1).

At $1 < z < 1.7$ the red sequence becomes more established than in the higher redshift bin, containing $\sim 56\%$ of the whole galaxy population (compared to $\sim 22\%$ at $1.7 < z < 3$). The fraction of morphological ellipticals increases to $\sim 40\%$ (compared to $\sim 17\%$ at $1.7 < z < 3$), the majority of which ($\sim 77\%$) are located on the red sequence (versus $\sim 44\%$ at $1.7 < z < 3$). The ellipticals belonging to the overdensity at $z = 1.61$ (Kurk et al. 2009) represent only $16\%$ of the total number of ellipticals in the red sequence. The blue cloud becomes mostly populated by disk and irregular galaxies, while no compact and faint objects are observed. Compared to $1.7 < z < 3$, the AGNs become rarer and are hosted mainly by elliptical and disk galaxies. The fraction of AGNs in the blue cloud decreases from $\sim 21\%$ at $1.7 < z < 3$ to $\sim 9\%$ at $1 < z < 1.7$.

The above results are clearer when the $(U-B)$ colors are dereddened using the dust extinction ($A_V$) derived from the photometric SED fitting (K13) and adopting the Calzetti (2001) extinction curve. Figure 3 shows that the red sequence can be more clearly distinguished from the blue cloud (see also Cardamone et al. 2010), and populated by a fraction of morphological ellipticals increasing from $\sim 52\%$ at $1.7 < z < 3$ to $\sim 81\%$ at $1 < z < 1.7$.

These evolutionary patterns suggest a scenario where the evolutions of galaxies and AGNs are closely related at $z \gtrsim 2$, when AGNs were hosted by star-forming systems, after which ($\sim 2$ Gyr later) the number of AGNs decreased and the number of red sequence galaxies increased. In this picture, the compact galaxies hosting an AGN may represent a transitional phase between the concomitant star-forming and AGN activities in the blue cloud, and the subsequent quenching of star formation and morphological transformation, thus populating the red sequence while the fraction of AGN hosts drops rapidly.

### 4. CLUES ON HIDDEN AGNS AT $1.7 < Z < 3$

The properties of active and inactive galaxies were investigated using their stacked optical spectra. At $1 < z < 1.7$ and $1.7 < z < 3$, the fractions of galaxies with available spectra are $95/122$ and $44/144$ respectively, with a spectroscopic completeness for the X-ray galaxies of $85\%$ and $34\%$. The stacking of optical spectra was done in three steps: (1) the individual spectra were smoothed at the lowest resolution (i.e., $R \sim 200$ of the VIMOS low-resolution grism), (2) each spectrum was rescaled by the average flux in a common spectral region, and (3) the spectra were averaged without any weights. In the AGN sample, we removed the three objects classified as Type 1 AGN (ID2043, ID1155, and ID1350; Figure 4).

At $1.7 < z < 3$, the stacked spectrum of active (i.e., detected individually in X-rays) and inactive galaxies was made with nine ($\zeta_{med} = 2.0$) and 30 ($\zeta_{med} = 2.25$) spectra respectively. The spectrum of the active galaxy ID 2171 ($z = 2.145$) was excluded from the stacking because of its strong emission lines, which differ markedly from the other galaxies (Figure 4).

Compared to inactive galaxies, the stacked spectrum of active galaxies shows no Ly$\alpha$ emission and stronger CII $\lambda 1330$ and CIV $\lambda 1550$ emission (Figure 4). Moreover, some ISM absorption lines (e.g., SiII $\lambda 1260$, OI $\lambda 1303$, AlII $\lambda 1670$) have equivalent widths (EWs) systematically larger than in inactive galaxies by a factor of $\sim 2$ ($EW_{rest} \sim 2-4 \AA$).
with \( \log L_X > 42.3 \text{ erg s}^{-1} \) are used, or the stacking also includes the X-ray galaxies with photo-z and all \( L_X \) (for a total of 24/26 objects used by CSTACK). The individual galaxy ID 2171 (not included in the stacking of optical spectra discussed later) has X-ray properties typical of a Compton-thick AGN with \( L_X = 1 \times 10^{43} \text{ erg s}^{-1}, \text{HR} > 0.85, \) and \( N_H > 2 \times 10^{24} \text{ cm}^{-2} \).

On the basis of SED fitting (K13), UV spectral slopes (Talia et al. 2012) and infrared luminosities (M. Talia et al., in preparation), the median star formation rate (SFR) of the X-ray emitting galaxies is consistently \( \sim 100 \text{ M}_\odot \text{ yr}^{-1} \). According to Ranalli et al. (2003), this SFR corresponds to \( L_X \sim 5 \times 10^{41} \text{ erg s}^{-1} \), i.e., ~ 1 dex less than the observed total X-ray luminosity, indicating a negligible contribution of star formation to the observed \( L_X \).

In stark contrast, the X-ray stacked flux of the 30 inactive galaxies (i.e., individually undetected in X-rays) with spectroscopic redshifts is significant only in the soft band (0.5–2 keV). Assuming an unobscured spectrum with \( \Gamma = 2 \), the detected soft-band flux implies an average \( L_X \sim 10^{41.1} \text{ erg s}^{-1} \) at mean redshift \( z = 2.25 \) and can be ascribed to SFR \( \sim 25 \text{ M}_\odot \text{ yr}^{-1} \). These results remain unchanged when the X-ray stacking includes also the galaxies with photo-z (87/112 used by CSTACK).

It is remarkable that, despite the clear presence of AGNs (as shown by the X-ray properties), the UV spectra of active galaxies at \( 1.7 < z < 3 \) do not show any clear features of non-stellar activity, particularly when compared to inactive galaxies of similar redshift and stellar mass. One possibility is that the AGNs are hosted by more obscured galaxies with denser ISM, which would explain the larger EWs of some ISM absorption lines and the lack of Ly\( \alpha \) emission.

5. SEARCHING FOR OUTFLOWS AT \( 1.7 < Z < 3 \)

We searched for ISM gas outflows in the stacked spectra at \( 1.7 < z < 3 \) in order to further investigate the differences between active and inactive galaxies. For this purpose, only the subset of galaxies with the highest resolution spectra from GMASS (\( R \sim 600; \text{K13} \)) were used in order to maximize the radial velocity accuracy and to detect the weak photospheric lines (C\( \text{iii} \lambda 1247, \text{O} \text{iv} \lambda 1343, \text{O} \text{v} \lambda 1371, \text{S} \text{ii} \lambda 1417, \) and \( \text{S} \text{v} \lambda 1501; \) see Leitherer et al. 2011) whose median wavelength was used in each stacked spectrum to define the systemic (zero velocity) reference (topmost spectra in Figure 4).

In the stacked spectrum of the 24 inactive galaxies, the main ISM absorption lines (Si\( \text{ii} \lambda 1260, \text{O} \text{i} \lambda 1302, \text{C} \text{ii} \lambda 1334, \) Si\( \text{ii} \lambda 1526, \) Si\( \text{iv} \lambda \lambda 1393, 1402, \) Fe\( \text{ii} \lambda 1608, \) and Al\( \text{ii} \lambda \lambda 1670 \)) show a median blueshift of \(-70 \pm 100 \text{ km s}^{-1} \), consistent with other results on inactive galaxies (e.g., Shapley et al. 2003; Steidel et al. 2010; Talia et al. 2012).

In contrast, for the stacked spectrum of seven active galaxies, we detect larger blueshifts (with \( \Delta V \) between \(-600 \) and \(-120 \text{ km s}^{-1} \)) for the same lines, with a median value of \(-340 \pm 150 \text{ km s}^{-1} \). Similar blueshifts (ascribed to outflows) have also been observed in other active galaxies at \( 1 < z < 3 \) (Nesvadba et al. 2006; Hainline et al. 2011; Harrison et al. 2012).

For the typical size (\( r_e \sim 5 \text{ kpc} \)) of the active galaxies of Figure 4, the expected escape velocity is \( V_{\text{esc}} = \sqrt{2GM/r} \sim 350 \text{ km s}^{-1} \), where \( \log (M/M_\odot) = 10.9 \) is the sum of the median stellar mass (\( \log (M/M_\odot) = 10.4 \)) and the total gas mass (\( \text{H} + \text{H}_2 \)) (\( \log (M_{\text{gas}}/M_\odot) \sim 10.7 \); Magdis et al. 2012, Equation (27)). This \( V_{\text{esc}} \) is comparable to the measured median velocity, and lower than the highest observed speeds. The real
These results do not change significantly when the X-ray stack-LX implies \( \sim 30(5) \) at 1.22, all galaxies have very similar properties (Figure 4). The absence of [Ne\(\lambda\)3426 emission (expected in case of AGN photoionization) in the stacked spectrum of X-ray galaxies may be due to attenuation by dust extinction and/or the gas density being higher than the critical density of this line (see Mignoli et al. 2013).

Even with the high resolution of the GMASS spectra, the search for gas outflows in this redshift range is uncertain because it is impossible to clearly distinguish either the [O\(\lambda\)II]3727 and Mg\(\mu\)\(\lambda\)2800 doublets, or the ISM and photoionizing absorption components of Mg\(\mu\). For instance, adopting 3727.5 Å as the systemic centroid of the unresolved [O\(\lambda\)II]3726+3729 doublet (as in Bradshaw et al. 2013), the stacked spectra of active and inactive galaxies show Mg\(\mu\)\(\lambda\)2800 velocity offsets in the range of \(-200\) to \(-50\) km s\(^{-1}\) with a typical uncertainty of \(\sim 100\) km s\(^{-1}\).

In contrast to those identified at 1.7 < z < 3, the single Type 1 AGN (ID 1350, z = 1.209, log \(L_X\) in 43.97 erg s\(^{-1}\), Figure 4) appears to have no intrinsic absorption and properties that are indeed typical of an unabsorbed Type I AGN with a blue continuum.

Interpreted with our findings in Section 3, these results suggest that the AGN activity and its effects on the host galaxies have faded gradually from 1.7 < z < 3 to 1 < z < 1.7.

7. SUMMARY

We have presented evidence of a link between the migration of galaxies from redshift \(z \sim 2\) to \(z \sim 1\) onto the red sequence and a parallel decrease in the activity of AGNs with \(L_X > 10^{42.3}\) erg s\(^{-1}\). At \(z \sim 2\), the AGNs often remain hidden in unsuspected star-forming galaxies.

We tentatively detect gas outflows at speeds of up to about \(-500\) km s\(^{-1}\), which are comparable to or larger than the galaxy escape velocities, and present only in active galaxies at \(z \sim 2\). This suggests that AGN feedback, in addition to star formation, contributes to these gas outflows, removing some fraction of the gas permanently from the galaxy, leading to so-called star-formation quenching, and allowing a fraction of galaxies to migrate onto the red sequence.

Deeper spectroscopy is needed to confirm and extend these results to larger samples. The synergy of future massive imaging-spectroscopy surveys (e.g., Euclid; Laureijs et al. 2011) and X-ray missions such as eROSITA (Merloni et al. 2012) and Athena+ (Georgakakis et al. 2013) will be crucial to fully unveil the evolutionary links between galaxies and AGNs.

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