Star formation properties of X-ray detected galaxies in COSMOS field: Connection between AGN activity and recent star formation

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Abstract. One of the key outstanding problems in studies of galaxy evolution is understanding the connection between AGN and star formation (SF). Nevertheless, finding the existence of an SF-AGN connection is still not clear which process dominates the energetic output in both local and high redshift Universe. We present 360 X-ray selected obscured (type 2) AGNs at redshift $z < 1.5$. We acquired star formation properties for those X-ray detected AGN which available in the Cosmological Evolution Survey (COSMOS) project. We compared the star formation properties for our X-ray detected AGNs and non-X-ray galaxies using starburstiness. The step further is analyzing the X-ray properties and starburstiness of X-ray detected AGN for proving the existence of a connection. The starburstiness distribution of X-ray detected AGNs shows some excess in low star forming activity compared with the non-AGN objects. This excess might be an interesting topic to analyze the AGN type. For X-ray detected AGNs, We found that X-ray activities arise both in high and lower star forming activity. From those properties relation, we conclude that the AGNs could be triggered by starburst either directly or delayed.

1. Introduction
Most galaxies host a supermassive black hole (SMBH) at their nucleus. A key unresolved issue in galaxy formation and evolution is the role these SMBHs play in shaping their galaxies. Most astronomers agreed that there must be a strong connection because of the observed correlations between an SMBH’s mass and its galaxy’s luminosity, stellar mass, and the stellar motions in the galaxy [1][2]. Star formation is one of the principal markers of galaxy growth. Observations of galaxies have been carried out as the attempts to measure the star formation by correlating the formation rate with the intrinsic luminosity (star formation heats the dust whose infrared emission can dominate the luminosity). However, the emission from the region around a supermassive black hole that is actively accreting, an active galactic nucleus (AGN), can easily be confused with the emission that from star formation. X-rays or the emission of highly excited ions can be used to determine the AGN contributions independently.
AGNs are related to the compact regions at the center of a galaxy that emits more radiation than the rest of the host galaxy. They are now believed to be powered by the accretion of mass onto SMBHs [1]. As the gas accretes onto SMBH, the potential energy of the gas is converted to high luminosity radiation across the electromagnetic wavelengths, from radio to X-ray and up to $\gamma$-ray. The fundamental question in current astrophysics research on AGNs is the origin and evolution of SMBHs as well as their interaction with their host galaxies [2][3]. It still gives a different answer from the previous study due to limited observational data. So far, there are two distinct scenarios that connect AGNs and star formation phenomena: (1) A starburst occurs first and triggers the AGN’s activity later; (2) The AGN’s activity occurs before the beginning of a starburst. If the hypothesis of the co-evolution of an AGN and the bulge of its host is correct, then regardless of whether AGN activity occurs before or after a starburst, the type 2 AGN might represent an important stage in galaxy evolution and are valuable for examining the issue of co-evolution in detail.

2. The data
We use the data produced by the Cosmic Evolution Survey (COSMOS) project. COSMOS is the largest HST survey ever undertaken-imaging an equatorial, $\sim 2 \, \text{deg}^2$ field with single-orbit $I$-band exposures to a point source depth of $I_{AB} = 28$ mag and 50% completeness for galaxies $0.5''$ in diameter at $I_{AB} = 26.0$ mag [4].

The X-ray catalog used in this work is obtained from the Chandra COSMOS Legacy survey [5]. The catalog contains optical and infrared counterparts of the Chandra COSMOS-Legacy Survey (C-COSMOS), a 4.6 Ms Chandra program on the 2.2 deg$^2$ of the COSMOS field. The catalog provides redshift data obtained from the available spectroscopic and photometric catalog within the COSMOS collaboration. We selected the star-forming properties from the COSMOS2015 photo-z catalog [6]. The catalog contains precise photometric redshifts and stellar masses for more than half a million objects over the 2 deg$^2$ COSMOS field. The COSMOS2015 photo-z catalog represents an invaluable resource that can be used to investigate the evolution of galaxies and structures back to the earliest stages of the universe.

2.1. X-ray AGN sample selection
To study the co-evolution of AGNs and star formation, properties of both AGNs and their host galaxies must be examined carefully and simultaneously. In this study, we exclude the type 1 AGN from our sample by using only the non-Broadline AGN (NBLAGN) type from the C-COSMOS Legacy catalog. We take the advantages of choosing this type AGN, so that we can study the host properties from the optical emission and the AGN properties from the X-ray emission.

Firstly, we matched the X-ray data from C-COSMOS Legacy[5] and COSMOS2015 catalog [6] to get the AGN sample. The matching process was using positional data (RA, DEC) and redshift. The separation upper limit in the position is $1.5''$ and in redshift is in the range of $z_{ph} = z_{sp} \pm 0.15 \times (1 + z_{sp})$. The value is used to avoid the catastrophic errors which will happen in $|[z_{ph} - z_{sp}] / (1 + z_{sp})| > 0.15$[7].

There are three bands of X-ray flux or luminosity that we use in this thesis, among others are the 0.5-10 keV (hereafter the $X_{\text{total}}$-band), 0.5-2 keV (hereafter the $X_{\text{soft}}$-band), and 2-10 keV (hereafter the $X_{\text{hard}}$-band). After the cross matching process, all the objects follow the next step which uses the following X-ray emission diagnostics to classify the objects as AGNs. Here, we applied the total X-ray luminosity ($L_{X\text{total}}$) threshold and the locus of X-ray to optical ratio ($X/O$) by the criteria of [3]:

$$L_{X\text{total}} > 3 \times 10^{42} \text{ergs}^{-1}$$

$$-1 \leq X/O \leq 1,$$
where $X/O = \log f_X/f_O = \log f_{X,soft} + I_{AB}/2.5 + 5.352$.

2.2. Non X-ray galaxy sample selection
The non-AGN sample was taken from the COSMOS2015 catalog [6]. The sample is chosen when it is not included in other X-ray survey catalog, either in XMM-Newton or Chandra X-ray. The COSMOS2015 catalog did the SED fitting from multi-wavelength data, so they also give the type of the objects as galaxy or star by the fitting process, especially for objects detected in NIR. We eliminate all the objects with the type other than a galaxy or type = 0. We also cut the objects in a full sample of mass and redshift in the range of $10^{10}M\odot < M_* < 10^{11.5}M\odot$ and redshift $z_{sp} < 1.5$ respectively. The total objects which present in our research are 55,069 objects.

3. Results and discussion
The evolutionary scenario can be explained using star forming and AGN properties relation. However, it is not easy to detect the relation. The common way to analyze the SF properties of galaxies is to study the relation between SFR and stellar mass and to compare the location of sources with the main sequence (MS) of star-forming galaxies. Starburstiness (RSB) [8] is defined as $R_{SB} = SFR/SFR_{MS}$, which is the distance from the MS. Firstly, we defined the $SFR_{MS}$ adopted from [8] (equation 9), defining $r \equiv \log_{10}(1 + z)$ and $m \equiv \log_{10}(M_*/10^9 M\odot)$:

$$
\log_{10}(SFR_{MS}[M \odot yr^{-1}]) = m - m_0 + a_0 r - a_1 [\max(0, m - m_1 - a_2 r)]^2,
$$

with $m_0 = 0.5 \pm 0.07, a_0 = 1.5 \pm 0.15, a_1 = 0.3 \pm 0.08, m_1 = 0.36 \pm 0.3$, and $a_2 = 2.5 \pm 0.6$. 

Figure 1. $R_{SB}$ distribution of AGN (dark-grey) and non-AGN (light-grey) samples. $R_{SB}$ is in the logarithmic value and the number of galaxies has been normalized.
The distribution of starburstiness is shown in figure 1. It shows that the AGN sample gives some excess in the lower star forming activity stage. This is an interesting result to analyze further the AGN origin. The two-sample Kolmogorov-Smirnov test has been performed and showed that both AGN and non-AGN distribution are different.

We try to find out the origin of the double peaks in figure 1 by defining the color U-B of each galaxy. We defined the green valley with criteria $0.8 \leq (U-B) \leq 1.2$ and bluer galaxy which has $(U-B) > 0.8$. We adopted this criterion from previous works[9].

Figure 2 shows us the green valley’s location is similar to the peak of starburstiness distribution in $R_{SB} \sim -1.5$. It is relevant to the previous study by [10] who found most green valley AGNs are found at redshift $0.5 < z < 1.5$ as our sample is taken. They explained that there are two hypotheses to explain the presence of those green valley. First, two mechanisms could be responsible for changing colors of AGN: AGN contribution, affecting more early-types and making them bluer; and dust reddening, affecting most of all late-types and making them redder. However, they still do not have enough evidence for this scenario. Second, AGN might be hosted by similar galaxies, being later early- and earlier late-type sources, presenting one phase in the evolution of galaxy. The fact that most Green Valley AGNs are found in the redshift range mentioned above could support the hypothesis that green valley AGNs are transition objects, between the blue starburst galaxies and massive, red ellipticals.

To study more about this result and the connection with AGN, we classified the distribution to be four classes: starburst galaxies (SB), normal SFGs on the MS (MS), galaxies below the MS with little star formation activity (sub-MS), and quiescent galaxies (QG). The SB galaxies located above the main sequence are defined as galaxies having $\log(R_{SB}) \geq 0.5$. The MS galaxies are defined as those whose $R_{SB}$ is between $-0.5 \leq \log(R_{SB}) < 0.5$ (within 3 times above and below the MS, or $1\sigma$). The sub-MS galaxies are defined as $-2.0 \leq \log(R_{SB}) < -0.5$. Lastly, we call any galaxies with $\log(R_{SB}) < -2.0$ quiescent (QG).

We can compare the number of AGNs and non-AGNs in each group. We present the AGN fraction (number of AGN sample over the total number of both AGN and non-AGN samples) in
this classification results in 48/4,365 SB (1.11%), 126/21,999 MS (0.57%), 161/16,618 sub-MS (0.97%), and 25/9,582 QG (0.26%) galaxies. As expected, the MS galaxies are dominant, but the number of other populations, particularly SB and sub-MS galaxies, is not negligible. We can also see that the fraction of AGN is declining from higher to lower (R_{SB}) population except for the sub-MS population. Further analyses will use this classification to examine the AGN-host relation in the next section. We will compare the X-ray properties of AGN samples over the R_{SB} classification.

### Table 1. X-ray properties of AGN sample for every R_{SB} class.

| Parameter       | SB     | MS     | sub−MS  | QG     |
|-----------------|--------|--------|---------|--------|
| log (L_{Xtotal})| 43.51 ±0.38 | 43.4 ±0.433 | 43.28 ±0.431 | 43.18 ±0.496 |
| log (L_{Xsoft})  | 42.85 ±0.44 | 42.73 ±0.46 | 42.57 ±0.48 | 42.54 ±0.499 |
| log (L_{Xhard})  | 43.40 ±0.38 | 43.31 ±0.45 | 43.22 ±0.466 | 43.11 ±0.516 |
| AGN fraction (%) | 1.1 ±0.16 | 0.57 ±0.051 | 0.97 ±0.077 | 0.26 ±0.052 |

As shown in table 1, we found that the luminosity of AGN in total (0.5-10 keV), soft (0.5-2 keV), and hard (2-10 keV) bands which represent the AGN properties show flat behavior with large scatter. Therefore, we could not say that AGN is the factor of star forming quenching in its host galaxy with this parameter. Meanwhile, we suggest that AGN activities arise in both high and low star forming activity caused by the direct and delayed effect of starburst event. [2] found that either major or minor merger could trigger AGN activity in a short or longer time up to 0.5 Giga year. We expect that those mergers that arise AGN activity in every class.

Regarding the relation of X-ray properties to star forming activity, we see the other relation of AGN and host galaxy which represented in the AGN fraction. The bottom row in table 1 shows the number of AGN compare to the whole sample of this study. It shows significant decreasing value from higher to lower star forming activity, but the sub-main sequence class show suddenly increasing and we call it an anomaly. This anomaly is expected to come from the high number of significant types of AGN. So this is the main reason to study further of optically AGN in our sample.

4. Conclusion
The main goal of this study is to investigate the differences between AGNs and non-AGNs, as well as the evolutionary connection between an AGN and its host galaxy for obscured AGN samples. The analysis of these full stellar-mass samples at redshift z < 1.5 in the COSMOS field allows us to draw results as follows.

(i) The star-forming properties between AGN and non-AGN show a different in the starburstiness (RSB) parameter which shows an excess in the lower star-forming activity (sub-main sequence class).
(ii) The relation between X-ray and star-forming properties of AGN shown by the X-ray luminosity respect to starburstiness class. All the luminosity show flat behavior from higher to lower star-forming activity with large scatter. So, we expect that AGN activities arise because of direct and delayed effect of starburst event.
(iii) The co-evolution scenario of AGN and its host galaxy could be explained by the AGN fraction which shows decreasing trend except for the excess in the sub-main sequence population. This excess might be an interesting topic to analyze the AGN type. From
those properties relation, we conclude that AGNs show signs of star forming quenching, with AGN properties decreasing from higher to lower star forming activity.

We still have a lot of works for a more reliable conclusion. We plan to take more spectroscopic data for the AGN sample, so we can explore the behavior of AGN’s spectrum and classify them in groups with similar characteristic. We need permission from the previous observation of all our samples in some other sources. The good result will be a good comparison with the previous result in this study. Besides that, we also plan to compare the SED fitting result of the COSMOS2015 photo-z catalog which we use in this study with SED result that considers the AGN contamination in the process. We hope to get a better result from it.

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