



Stellar Populations of AGN-host Dwarf Galaxies Selected with Different Methods

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Abstract

In this paper we investigate the stellar populations and star formation histories of 235 active galactic nucleus (AGN)-host dwarf galaxies, consisting of four samples identified separately with different methods (i.e., radio, X-ray, mid-IR and variability), utilizing the synthesis code STARLIGHT and spectra from the Sloan Digital Sky Survey Data Release 8. Our results show that the variability sample is the oldest, while the mid-IR sample is the youngest, for which the luminosity at 4020 Å is dominated (>50%) by the young population ($t < 10^8$ yr). The light-weighted mean stellar age of the whole sample is in general about 0.7 dex younger than the optical sample studied in Cai et al. We compare the population results between fitting models with and without a power-law (PL) component and find that the neglect of a PL component would lead to an under- and over-estimation by 0.2 and 0.1 dex for the light- and mass-weighted mean stellar age, respectively, for our sample of dwarf galaxies, which has a mean fractional contribution of $\sim 16\%$ from the AGN. In addition, we obtain further evidence for a possible suppression of star formation in the host galaxy by the central AGN. We also find that there exists an anti-correlation between the extinction-corrected [O III] luminosity and light-weighted mean stellar age, confirming our previous finding that there is a physical connection between AGN and star-forming activities in AGN-host dwarfs.

Key words: galaxies: dwarf – galaxies: active – galaxies: stellar content

1. Introduction

Dwarf galaxies, which constitute the largest population of galaxies in the present-day universe (Marzke & da Costa 1997), are characterized by diverse morphologies and star formation histories (SFHs; Tolstoy et al. 2009; McQuinn et al. 2011; Weisz et al. 2011b; Gallart et al. 2015). According to the hierarchical clustering model, dwarf galaxies serve as the fundamental building blocks of massive galaxies in the universe (Kauffmann et al. 1993). Black holes (BHs) in low-mass dwarf galaxies may be similar to the first seed BHs (Bellovary et al. 2011) owing to their relatively quiescent merger histories. Furthermore, dwarf galaxies are generally metal-poor (Mateo 1998), making them similar to high-redshift objects. Therefore, dwarf galaxies are important objects for studying the formation and evolution of galaxies, as well as in cosmological simulations.

The evolution of dwarf galaxies may be influenced by both external (such as mergers and interactions) and internal (e.g., active galactic nucleus; AGN) factors. For massive galaxies, AGNs play a crucial role in star formation and evolution through different feedbacks on the host galaxies, which has

been studied comprehensively by observational works and numerical simulations. Some studies suggest that AGNs are likely to disperse gas within galaxies, thereby inhibiting star formation (Dubois et al. 2013; Vogelsberger et al. 2014; Schaye et al. 2015; Dubois et al. 2016; Pillepich et al. 2018). In contrast, some other works show that AGNs may also compress gas, hence triggering star formation (Silk & Norman 2009; Gaibler et al. 2012; Ishibashi & Fabian 2012; Kalfountzou et al. 2012; Nayakshin & Zubovas 2012; Silk 2013; Kalfountzou et al. 2014; Querejeta et al. 2016; Maiolino et al. 2017; Schutte & Reines 2022). To explore the possible connection between AGNs and host galaxies, therefore, it is important to study the stellar populations and SFHs of AGN-host galaxies (e.g., Cid Fernandes et al. 2004; Jin et al. 2018; Mallmann et al. 2018; Cai et al. 2020, 2021; Jin et al. 2022).

Abundant works in literature have systematically investigated the stellar populations of normal dwarf galaxies (Hodge 1989; Mateo 1998; Dolphin et al. 2005; Tolstoy et al. 2009; McQuinn et al. 2010; Weisz et al. 2011a; Zhao et al. 2011; Kauffmann 2014; Zhang et al. 2017; Zheng et al. 2017; Taibi et al. 2022), with a significant focus on objects located within the Local Group (see Tolstoy et al. 2009 for an overview). As shown in Tolstoy et al. (2009), early-type dwarf

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galaxies, such as dwarf spheroidal galaxies (dSphs), have typically not formed stars for at least several hundred million years. Weisz et al. (2011a) analyze the SFHs of 60 dwarf galaxies in the nearby universe ($\lesssim 4$ Mpc) and find that the majority of dwarf galaxies formed the bulk of their mass prior to redshift $z \sim 1$. The authors also show that dwarfs with different morphological types exhibit similar SFHs when age is less than 1 Gyr, while stellar mass formed in recent 1 Gyr is correlated with morphology. A series of works (e.g., Harbeck et al. 2001; Tolstoy et al. 2004; Battaglia et al. 2006; Bernard et al. 2008; Belfiore et al. 2018; Taibi et al. 2022) have also identified a radial gradient in the stellar age and/or metallicity of dwarf galaxies.

Compared with normal low-mass galaxies, however, there are only few studies devoted to investigating the stellar populations of AGN-host dwarfs. Cai et al. (2020, hereafter C20) analyze the stellar populations and SFHs for 136 AGN-host dwarf galaxies from Reines et al. (2013, hereafter R13) selected by the optical emission-line ratio diagnosis diagram (i.e., the BPT diagram; Baldwin et al. 1981), and find that these optically selected AGN-host dwarfs show a wild diversity of SFHs and may have repeated star-forming activities. The authors also obtain a mild correlation between SFH and [OIII] $\lambda 5007$ line luminosity ($L_{[\text{O III}]}$) for objects with $L_{[\text{O III}]} > 10^{39} \text{ erg s}^{-1}$, indicating a physical connection between AGN and star-forming activities. However, the old population ($t > 10^9$ yr) contributes most light for the majority of their sample galaxies and dominates the stellar mass, which is supported by the analysis of the radial stellar populations for a sample of 60 optically selected AGN-host dwarf galaxies (Cai et al. 2021).

However, AGNs selected by the BPT diagram generally show a redder $g - r$ color (R13; Moran et al. 2014; Sartori et al. 2015, C20), indicating a selection effect likely caused by the fact that the optical diagnostic is not sensitive to AGNs when the star-forming host galaxies dominate the emission-line spectra (e.g., Trump et al. 2015; Cann et al. 2019). In other words, the light contribution from AGNs can be heavily contaminated by the host galaxy with ongoing star formation, making it difficult to identify the internal AGN except for red, quenched systems, in which the features of BH accretion can be more prominent. This is more serious for dwarf galaxies, which generally have a lower metallicity (Groves et al. 2006), leading to a lower [N II] $\lambda 6583/\text{H}\alpha$ $\lambda 6563$ ratio and a smaller [OIII] $\lambda 5007/\text{H}\beta$ $\lambda 4861$ spread (Ludwig et al. 2012; Kewley et al. 2013), and thus are more likely to overlap with star-forming galaxies on the top-left of the BPT diagram. As a result, the suppression of star formation by AGNs could be overestimated in AGN-host dwarf galaxies.

In order to reduce/overcome the influence of selection bias suffered by the optical emission-line method, and to further establish connections between AGNs and hosts, it is necessary to systematically investigate the stellar populations and SFHs

of AGN-host dwarfs selected through different techniques. To this end, in this paper we present a detailed study of the stellar populations for a sample of 235 AGN-host dwarf galaxies, consisting of four subsamples selected with different methods/bands (namely radio, mid-infrared (mid-IR), variability and X-ray), using a simple stellar population (SSP) synthesis method that is capable of yielding the various stellar components, AGN contribution to the optical continuum, and internal extinction. The paper is organized as follows: Section 2 describes the selection of the AGN-host dwarf galaxies, properties of different samples and data reductions. Stellar population synthesis results and discussion are given in Section 3. We summarize our results in Section 4. Where required we adopt a Hubble constant of $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Sample and Data Reduction

2.1. Sample Selection

Here we compile a sample of AGN-host dwarf galaxies from four works that select AGNs using the four aforementioned methods. We briefly describe the sample selection for each subsample in the following.

The Radio Sample (hereafter radio): Reines et al. (2020) observed 111 galaxies ($M_* \lesssim 3 \times 10^9 M_\odot$ and redshift $z < 0.055$), selected by cross-matching the NASA-Sloan Atlas (NSA v0_1_2) with the Faint Images of the Radio Sky at Twenty centimeters (FIRST) Survey catalog (version 2013 June 5), using sensitive, high-resolution observations from the Karl G. Jansky Very Large Array (VLA). After carefully evaluating possible origins for the radio emission, including thermal H II regions, supernova remnants, younger radio supernovae, background interlopers, and AGNs, in the target galaxies, they identify 13 out of 39 compact radio sources that almost certainly host active massive BHs. We adopt these 13 galaxies as the radio-selected sample.

The X-ray Sample (hereafter X-ray): Birchall et al. (2020) present a sample of 61 dwarf galaxies ($M_* \lesssim 3 \times 10^9 M_\odot$ and $z < 0.25$) that exhibit nuclear X-ray activity indicative of an AGN. This sample of galaxies is identified from a parent sample of 4331 dwarf galaxies found within the footprint of both the MPA-JHU catalog (based on Sloan Digital Sky Survey (SDSS) Data Release 8 (DR8)) and 3XMM DR7, after applying the following criteria: (1) the extent of the X-ray source is less than $10''$ to ensure point-like emission that is consistent with an AGN (Rosen et al. 2016); and (2) there is an X-ray excess relative to the contribution, estimated with the star formation rate (SFR), from X-ray binaries (Lehmer et al. 2016) and hot gas in the interstellar medium (Mineo et al. 2012). These 61 X-ray-selected dwarf galaxies constitute our X-ray (parent) sample.

The Mid-IR Sample: In Sartori et al. (2015), the authors identify AGN candidates using mid-IR color cuts (Jarrett et al. 2011; Stern et al. 2012). A source is classified as an AGN when

it meets: (1) $[W1 - W2] \geq 0.8$; and/or (2) $2.2 < [W2 - W3] < 4.2$ & $(0.1 \times [W2 - W3] + 0.38) < [W1 - W2] < 1.7$ (Sartori et al. 2015). Based on a parent sample of 48 416 dwarf galaxies ($M_* \lesssim 10^{9.5} M_\odot$ and $z < 0.1$), obtained by cross-matching the OSSY catalog (Oh-Sarzi-Schawinski-Yi; Oh et al. 2011) with the MPA-JHU catalog, 189 AGNs are identified using the data observed by the Wide-field Infrared Survey Explorer (WISE) telescope.

The Variability-selected Sample (hereafter variability): This sample consists of 192 variability-selected AGNs from Ward et al. (2022), where the dwarf galaxies have $M_* < 10^{9.75} M_\odot$ and $0.02 < z < 0.35$ in the NSA v1_0_1 catalog. The authors cross-matched these dwarfs with two parent samples: the Zwicky Transient Facility (ZTF) optical catalog, and the WISE mid-IR catalog. They find 44 out of 25 714 dwarf galaxies have optical variability, and 148 (with two sources overlapping with the optically variable sample) out of 79,879 dwarf galaxies show mid-IR variability, after performing a statistically significant variability test and removing poor quality photometry and possible supernova objects.

In total, we obtain a parent AGN sample of 437 objects, consisting of 13 radio-, 55 X-ray-, 179 mid-IR-, and 190 variability-selected AGNs, after cross-matching all of the above AGN samples with the NSA⁶ version v1_0_1 catalog, which re-analyzed the SDSS imaging and spectroscopic data using techniques in Blanton et al. (2011) and Yan (2011). A stellar mass (“ELPETRO_MASS” in the NSA catalog) cut of $M_* < 10^{9.5} M_\odot$ and a redshift cut of $z < 0.055$ were further applied to these 437 sources to stay consistent with the optical sample of R13 and cross-matched with the SDSS spectroscopic catalog. Finally, a total sample of 235 unique AGN-host dwarf galaxies (hereafter the whole sample) is obtained after removing a few objects having spectra masked with bad flags, among which twelve are radio-selected from Reines et al. (2020, hereafter R20), forty are X-ray-selected from Birchall et al. (2020, hereafter B20), ninety-seven are mid-IR-selected from Sartori et al. (2015, hereafter S15) (two also in the radio-selected sample, and two in the variability-selected sample) and ninety are variability-selected from Ward et al. (2022, hereafter W22). We also note that six (three mid-IR-selected and three X-ray-selected) sources are also included in the R13 optical sample.

2.2. Sample Properties

Though the current sample is not complete in any sense, it is the largest sample of AGN-host dwarfs with optical spectroscopic data to date. Our sample galaxies span a large range of galactic parameters (i.e., $g-r$ color, stellar mass and morphology type represented by the Sérsic index n), as plotted in Figure 1, which generally show a similar distribution (color-

filled histogram) to the parent sample (solid-line histogram). These results indicate that our sample can be representative of the parent AGN-host dwarf sample.

Compared to the total spectroscopic sample with the NSA dwarf galaxy sample (hereafter “All dwarfs”; dashed-line histogram), they seem to have a similar distribution in the $g-r$ color, as shown in the bottom left panel in Figure 1 (also see Table 1), in contrast to the optical sample (dotted-line histogram) that has a relatively redder color. On closer inspection, a tail toward bluer $g-r$ color can be found in our whole sample, as well as a bump existing (more prominent for the parent AGN sample) around Sérsic index $n = 6$ (bottom right panel in Figure 1). These results likely suggest that there might be some intrinsic differences between AGN-hosts and normal dwarfs. Given the limited size of the AGN-host dwarfs, however, a much larger sample is needed to reach a solid conclusion.

In Table 1 we also list the median value and 1σ uncertainty for each (sub)sample, with all data adopted from the NSA catalog. We can see that the mid-IR sample has the lowest mass, with a median value of $10^{8.7} M_\odot$, and the bluest $g-r$ color, with a median value of 0.26. Among these samples, a significantly redder $g-r$ color is found for the optical sample (R13), providing clear evidence of the selection effect introduced by the BPT method.

2.3. Stellar Population Synthesis

In this study, we use STARLIGHT (Cid Fernandes et al. 2005, hereafter C05), a stellar population synthesis code that combines empirical population synthesis with evolutionary synthesis models for our spectral fitting. STARLIGHT fits an observed spectrum with a linear combination of N_* SSPs and returns the fractional contribution of j th SSP N_{*j} to the total synthetic flux at the normalization wavelength λ_0 , parameterized by the population vector $\mathbf{x}$. Our spectra were acquired from SDSS DR8 (Aihara et al. 2011), which has a resolution of $\lambda/\Delta\lambda \sim 1800$ and spectral range 3800–9200 Å. Before the fitting, the Milky Way foreground extinction is corrected using the extinction law of Cardelli et al. (1989) and O’Donnell (1994), assuming $R_V = 3.1$ and A_V is derived from Schlegel et al. (1998) via the NASA/IPAC Extragalactic Database (NED), spectra also shift to the rest frame and are resampled in steps of 1 Å.

Following the similar configuration of Zhao et al. (2011) and C20, we mask obvious emission lines and give double weight to Ca II K $\lambda 3934$ and Ca II triplets which are among the strongest stellar absorption features less affected by nearby emission lines. The observed spectra are normalized at the median value of flux between 4010 and 4060 Å and 4730–4780 Å was adopted as the signal-to-noise ratio (S/N) window. All the SSPs were normalized at $\lambda_0 = 4020$ Å. We use a template base with $N_* = 100$ SSPs covering 25 ages from

⁶ <https://www.sdss.org/dr16/manga/manga-target-selection/nsa>

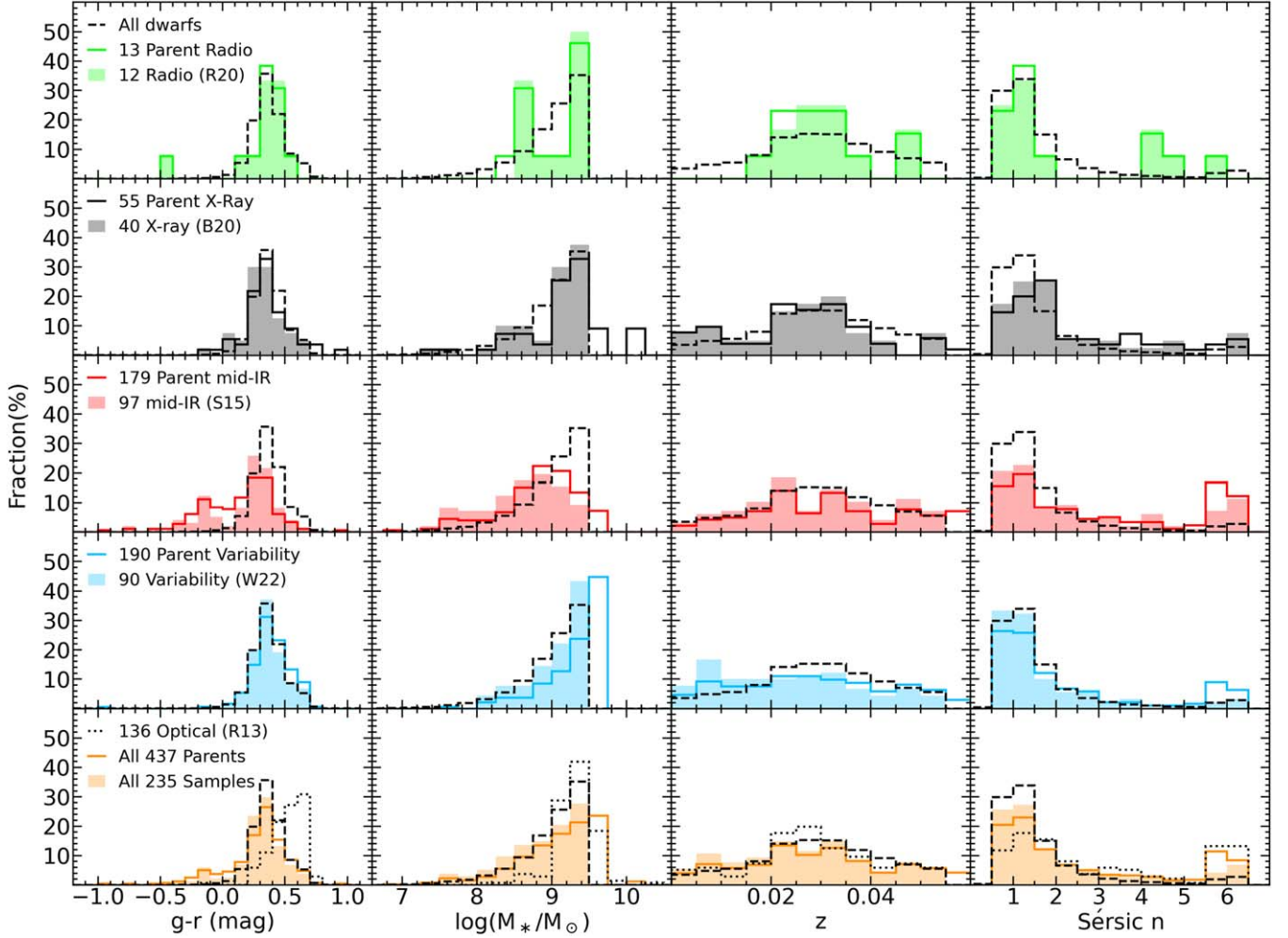


Figure 1. Rows 1–5 show the parameter distributions for distinct AGN-host dwarf galaxy samples (colored filled histograms) and their parent samples (colored solid lines); from top to bottom are radio (lime), X-ray (gray), mid-IR (red), variability (light blue) and all 235 (437) AGN-host dwarf (parent) galaxies (orange). The black dashed line shows the distribution of all dwarfs consisting of 33,728 galaxies with stellar mass $M_* < 10^{9.5} M_\odot$ and redshifts $0.001 \leq z < 0.055$ from the NSA v1_0_1 catalog. The optical sample (black dotted line) is plotted in row 5 (bottom row) for comparison. Each column from left to right shows the $g-r$ color, stellar mass, redshift and Sérsic index. The $g-r$ color has been corrected for the Galactic extinction.

Table 1
Basic Information on Different Samples

Sample	Method	Number	$\log(M_*/M_\odot)$	z	$g-r$ (mag)
R20	Radio	12 (13)	9.22 ± 0.20 (9.18 ± 0.28)	0.029 ± 0.007 (0.027 ± 0.008)	0.35 ± 0.11 (0.34 ± 0.12)
B20	X-ray	40 (55)	9.21 ± 0.28 (9.31 ± 0.32)	0.028 ± 0.010 (0.029 ± 0.012)	0.31 ± 0.10 (0.32 ± 0.12)
S15	mid-IR	97 (179)	8.70 ± 0.50 (8.90 ± 0.47)	0.029 ± 0.014 (0.046 ± 0.034)	0.26 ± 0.19 (0.18 ± 0.27)
W22	Variability	90 (190)	9.17 ± 0.41 (9.47 ± 0.28)	0.023 ± 0.017 (0.032 ± 0.023)	0.36 ± 0.09 (0.38 ± 0.12)
R13	Optical	136	9.34 ± 0.21	0.028 ± 0.011	0.53 ± 0.13
All	...	235 (437)	8.95 ± 0.53 (9.22 ± 0.50)	0.026 ± 0.014 (0.034 ± 0.023)	0.31 ± 0.14 (0.32 ± 0.16)

Note. Data in parentheses show the results of parent samples. Columns 4–6 list the median values of stellar mass, redshift and $g-r$ color with the 1σ dispersion estimated using $1.48 \times \text{MAD}$ where MAD is the median absolute deviation of the sample, and the dispersion of a mean value is estimated using the standard deviation of the sample throughout the paper.

1 Myr to 18 Gyr and four metallicities $Z = 0.0001, 0.0004, 0.004$ and 0.008 from Bruzual & Charlot (2003). In addition, a power-law (PL) component with an index of $\alpha = -1.5$ is added to represent an AGN featureless continuum (FC) $F_\nu \propto \nu^\alpha$, and the flux contribution fraction of this nonstellar component at $\lambda_0 = 4020 \text{ \AA}$ is denoted by x_{AGN} . Meanwhile, the samples presented in this paper show strong star formation, implying that the galaxy light may be dominated by star-forming regions of host galaxies, therefore, a pure stellar population model without a PL component is also carried out. The difference between the pure stellar population model and a PL component-joined AGN model will be discussed in Section 3.3.

The galactic intrinsic extinction $A_{V,*}$ is modeled as due to a foreground dust screen with the law of Calzetti et al. (1994) and $R_V = 4.05$ (Calzetti et al. 2000). It should be noted that the $A_{V,*}$ does not require being positive during the fitting, the reasons for which are discussed in C05 and Mateus et al. (2006). If $A_{V,*} < 0$, we rerun the program with a constraint of $A_{V,*} \geq 0$, then compare the results. If light or mass-weighted mean stellar age changed over 0.3 dex or the stellar population contribution fraction changed over 20%, we adopt the re-fitted result. For our samples, 14 out of 25 and 13 out of 18 sources are replaced in the following analysis for synthesis of the AGN-joined model and pure stellar population model, respectively.

As shown in C05, Mateus et al. (2006), Ge et al. (2018) and Woo et al. (2024), the uncertainties of the synthesis results depend on the S/N of the input spectrum. For the whole sample, the S/N varies between 2.5 and 51.5, with a median value of 11.1 ± 7.9 , and the distribution of S/N is shown in Figure 2. For each subsample, the median S/N values are 10.2 ± 5.2 (radio), 16.2 ± 10.5 (X-ray), 8.1 ± 5.6 (mid-IR) and 12.8 ± 6.6 (variability), indicating that in general the derived stellar age, metallicity (see Section 3.2) and stellar extinction ($E(B - V)$) would have uncertainties of $\lesssim 0.15$ dex, $\lesssim 0.15$ dex and 0.05 dex, respectively. We also note that about 14.9% (2.6%) of our sources have $S/N < 5$ (< 3), which may suffer a relatively large uncertainty, i.e., up to 0.3 dex, 0.4 dex and 0.1 dex in the stellar age, metallicity and stellar extinction, respectively (e.g., Mateus et al. 2006; Woo et al. 2024).

3. Results and Discussion

3.1. Pure-Emission Spectra and the BPT Diagram

We measure line fluxes, such as $\text{H}\beta \lambda 4861$, $[\text{OIII}] \lambda 5007$, $\text{H}\alpha \lambda 6563$ and $[\text{N II}] \lambda 6583$, using the pure-emission spectrum, which is obtained by subtracting the synthesized continuum and stellar absorption spectrum returned by STARLIGHT. The fitting is done using a single Gaussian model, then we compare the reduced χ^2 value with a two-component Gaussian model for $\text{H}\beta \lambda 4861$, $\text{H}\alpha \lambda 6563$ and $[\text{N II}] \lambda 6583$. If the χ^2 value of the two-component model is closer to 1 and improved by 20% than the single Gaussian model, the result of the two-component Gaussian model is accepted. We refer to the object

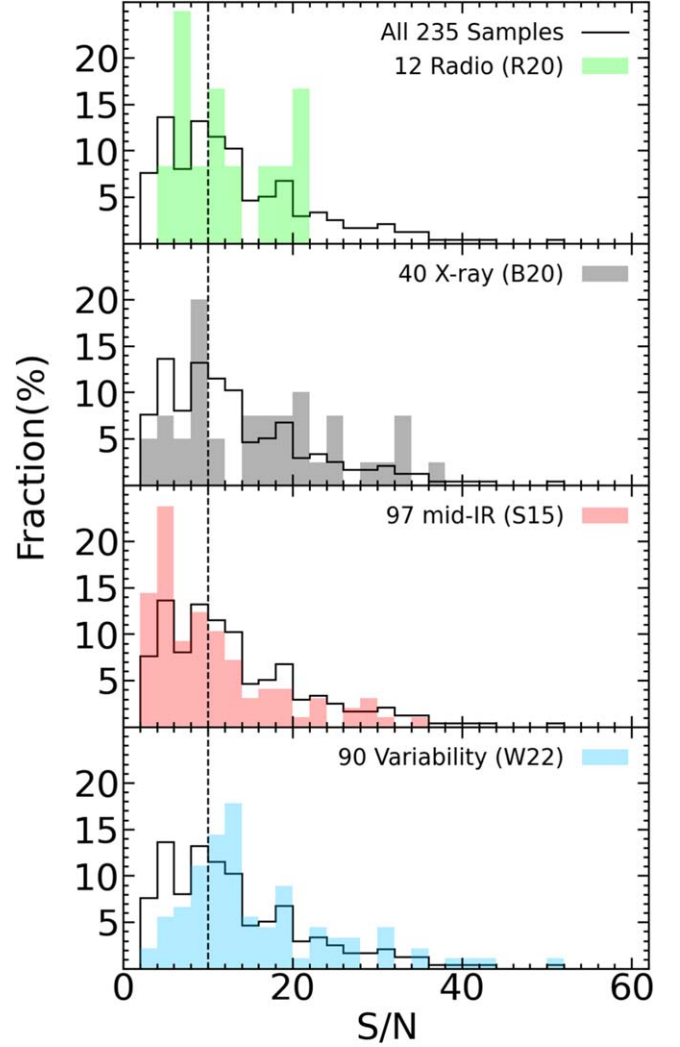


Figure 2. Distribution of S/N for various samples. The dashed line indicates $S/N = 10$.

with a broad component of Full Width at Half Maximum (FWHM) of at least 500 km s^{-1} in two Gaussian models as a source with a broad line and calculate the line flux after removing the broad component. For the majority of galaxies, a single Gaussian is fitted well, and only 14 sources require a two Gaussian model for $\text{H}\alpha \lambda 6563$.

Finally, there are 171 sources (10 radio, 26 X-ray, 71 mid-IR (two in the radio, and two in the variability), 68 variability) having $S/N > 3$ for all of the four emission lines mentioned above. In Figure 3 we plot the $[\text{OIII}] \lambda 5007 / \text{H}\beta \lambda 4861$ versus $[\text{N II}] \lambda 6583 / \text{H}\alpha \lambda 6563$ diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987). Obviously, the vast majority (95%) of the sample sources are located in the region classified as star formation, and only four sources fall in the AGN-dominated region and five are in the composite region. Such a small

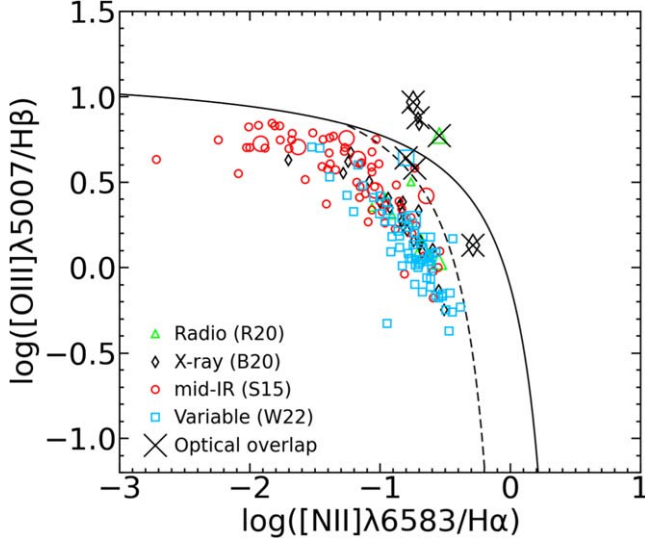


Figure 3. $[\text{OIII}]\lambda 5007/\text{H}\beta$ vs. $[\text{NII}]\lambda 6583/\text{H}\alpha$ BPT diagram for the 171 sources having $S/N > 3$ for all of the four emission lines. Radio-, X-ray-, mid-IR- and variability-selected objects are represented by (lime) triangles, (black) diamonds, (red) circles and (light blue) squares, respectively. The six sources with additional crosses are also included in the R13 optical sample. Larger symbols correspond to the sources showing a broad component in $\text{H}\alpha$ $\lambda 6563$. The sample is vastly overwhelmed (162/171) by pure star-forming galaxies defined by Kauffmann et al. (2003, dashed line), and only four sources lie above the theoretical maximum starburst line (solid line) defined by Kewley et al. (2001).

fraction of AGNs classified by the BPT method has already been noted in the original works that selected these AGN-host dwarfs.

One possible reason is that the emission lines might be dominated by star formation in the host galaxies, for which most of the radiation from the central AGN should be diluted heavily. It is also likely that the low-mass BHs in dwarf galaxies might produce a harder radiation field, as predicted by the theoretical models in Cann et al. (2019), resulting in a net decrease in the $[\text{OIII}]\lambda 5007/\text{H}\beta$ $\lambda 4861$ and $[\text{NII}]\lambda 6583/\text{H}\alpha$ $\lambda 6563$ emission line ratios. Furthermore, the low-metallicity of dwarf galaxies will also lead the observed line ratios to move further into the star-forming region of the diagram.

3.2. Stellar Population Properties

3.2.1. Mean Stellar Age

Following the methods of C05, we calculate the light- and mass-weighted mean stellar ages respectively using $\langle \log t_* \rangle_L = \sum_{j=1}^{N_*} x_j \log t_j$ and $\langle \log t_* \rangle_M = \sum_{j=1}^{N_*} \mu_j \log t_j$, where x_j and μ_j are fractional contributions of the j th SSP with age t_j in stellar luminosity and mass, respectively, and N_* represents the total number of SSPs. The light-weighted mean stellar age reveals the SFH due to the direct relation with the observed spectrum

and reflects the epoch of bright and massive star formation, while the mass-weighted mean stellar age is more physical and associated with the age of the stellar population dominating galactic mass. Similarly, it is convenient to define the light (mass)-weighted standard deviation of the log age, $\sigma_L(\log t_*)$ ($\sigma_M(\log t_*)$) to differentiate a single population from diverse SFHs, namely,

$$\sigma_L(\log t_*) = \left[\sum_{j=1}^{N_*} x_j (\log t_j - \langle \log t_* \rangle_L)^2 \right]^{1/2}$$

$$\text{and } \sigma_M(\log t_*) = \left[\sum_{j=1}^{N_*} \mu_j (\log t_j - \langle \log t_* \rangle_M)^2 \right]^{1/2}.$$

Figure 4 plots the distributions of $\langle \log t_* \rangle_L$ (left) and $\sigma_L(\log t_*)$ (middle) for different samples. The light-weighted mean stellar age $\langle \log t_* \rangle_L$ of all samples in our work is in the range of 10^6 – 10^{10} yr. Among the four samples, the stellar population properties of the variability sample are most similar to those of the X-ray sample. The mid-IR sample is the youngest, with a median value of $\langle \log t_* \rangle_L = 7.74$ (see Table 2), and shows a wider span of $\langle \log t_* \rangle_L$ than the other three samples, in the sense that the youngest ($\langle \log t_* \rangle_L = 6.24$) and oldest ($\langle \log t_* \rangle_L = 9.94$) galaxies both come from the mid-IR sample. The fractions of galaxies having $\langle \log t_* \rangle_L < 10^8$ yr ($\langle \log t_* \rangle_L > 10^9$ yr) are 41.7% (8.3%), 42.5% (17.5%), 57.7% (13.4%) and 23.3% (27.8%), respectively, for the radio, X-ray, mid-IR and variability samples. As we can see, the variability sample has the smallest (but largest) fraction of galaxies of $\langle \log t_* \rangle_L < 10^8$ yr ($\langle \log t_* \rangle_L > 10^9$ yr), and thus it is the oldest sample with the median value of $\langle \log t_* \rangle_L = 8.44$, about 0.7 dex older than the mid-IR sample. Whereas for the radio and X-ray samples, the median values of $\langle \log t_* \rangle_L$ are 8.01 and 8.28, respectively.

For comparison, we also plot the distributions of $\langle \log t_* \rangle_L$ and $\sigma_L(\log t_*)$ for the optical sample in Figure 4 using dashed-line histograms. As shown in the figure, the optical sample is generally older than the other four samples, with $\langle \log t_* \rangle_L$ peaking at ~ 9 . Furthermore, it also has a narrower span of $\langle \log t_* \rangle_L$, and only $\sim 11\%$ of the sample galaxies have $\langle \log t_* \rangle_L < 8$. However, all but the radio sample, which has a very limited size, show similar distributions in $\sigma_L(\log t_*)$, suggesting complex and diverse SFHs in all of the AGN-host dwarf galaxies, irrespective of the selection method.

A recent study of the stellar population of 26 changing-look (CL) AGNs by Jin et al. (2022) reported that the CL-AGNs lie between starburst and normal galaxies, and most (88.5%) have $\langle \log t_* \rangle_L > 9$, older than any dwarf sample. In Mahoro et al. (2022), however, 77% of the 17 X-ray selected, far-IR detected AGN-host galaxies have $\langle \log t_* \rangle_L < 9$, and the median age of this sample is $\langle \log t_* \rangle_L = 8.5$, only ~ 0.2 dex older than our X-ray sample. Therefore, the optically selected AGN-hosts,

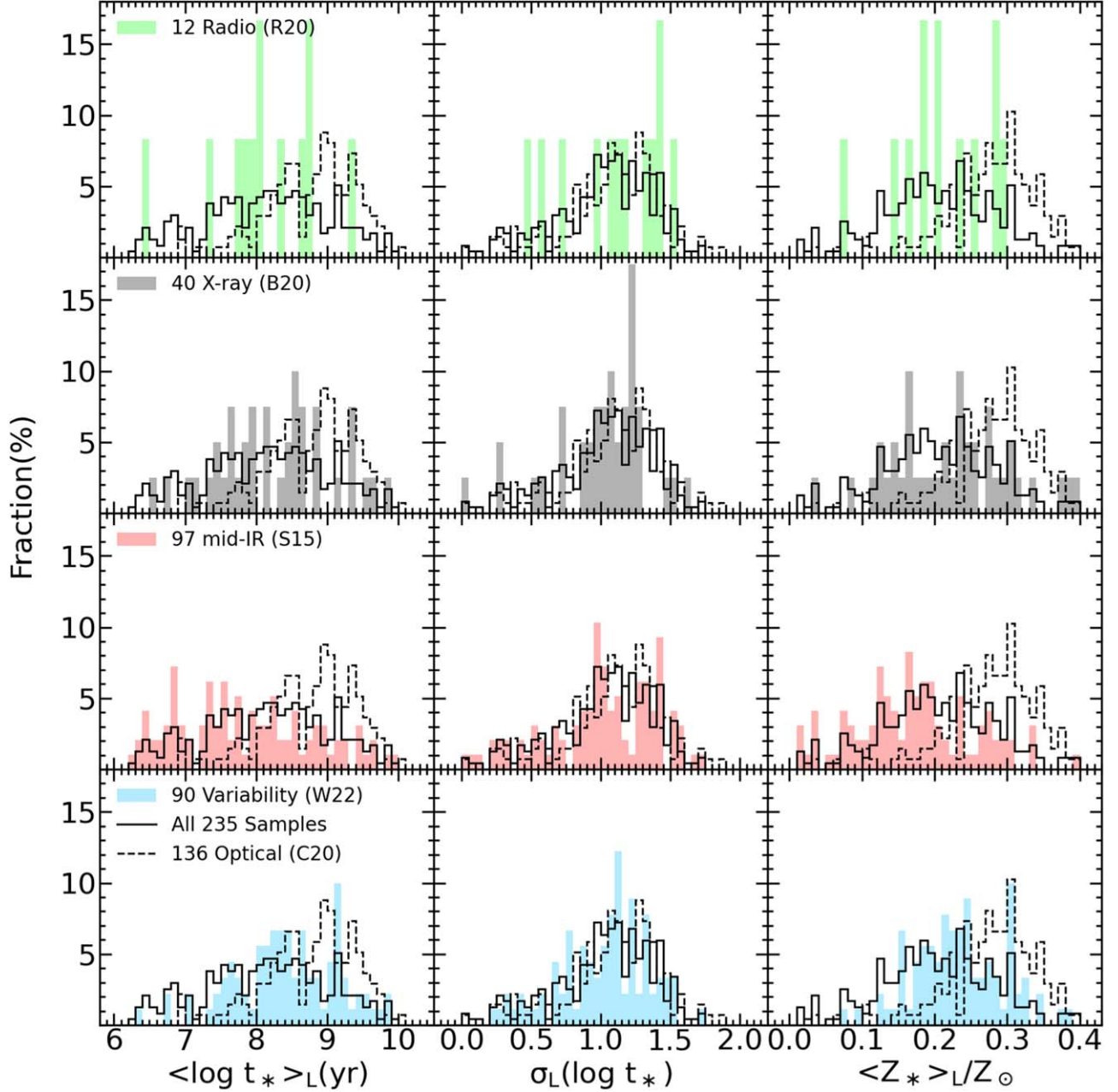


Figure 4. Fraction distributions of $\langle \log t_* \rangle_L$ (left), $\sigma_L(\log t_*)$ (middle) and $\langle Z_* \rangle_L$ (right) for different samples represented by different colored histograms as annotated. In each panel, the whole (black solid line) and the optical (black dashed line) samples are also plotted for comparison.

irrespective of stellar mass, generally have older stellar populations.

3.2.2. Mean Stellar Metallicity

For AGN-host galaxies, it is very difficult (or even impossible) to determine the nebular metallicity due to the AGN contamination of emission lines. Therefore, the stellar metallicity obtained through stellar population synthesis is

especially useful for the study on chemical properties of AGN-host dwarfs (e.g., C20). To this end, we calculate the light- and mass-weighted mean stellar metallicities in a similar way to the mean stellar ages, namely, $\langle Z_* \rangle_L = \sum_{j=1}^{N_*} x_j Z_j$ and $\langle Z_* \rangle_M = \sum_{j=1}^{N_*} \mu_j Z_j$. The distributions of $\langle Z_* \rangle_L$ for each sample are plotted in the right panel of Figure 4. We also list the median values of $\langle Z_* \rangle_L$ and $\langle Z_* \rangle_M$ in Table 2.

Table 2
Median Values and Dispersion of the Derived Stellar Population Properties

Sample	$\langle \log t_* \rangle_L$	$\langle \log t_* \rangle_M$	$\sigma_L(\log t_*)$	$\sigma_M(\log t_*)$	$\langle Z_* \rangle_L / Z_\odot$	$\langle Z_* \rangle_M / Z_\odot$
All	8.19 ± 0.95	9.67 ± 0.34	1.06 ± 0.32	0.51 ± 0.21	0.20 ± 0.08	0.24 ± 0.14
radio (R20)	8.01 ± 0.76	9.79 ± 0.14	1.14 ± 0.36	0.57 ± 0.18	0.20 ± 0.07	0.24 ± 0.07
X-ray (B20)	8.28 ± 0.84	9.66 ± 0.33	1.08 ± 0.23	0.54 ± 0.17	0.23 ± 0.09	0.25 ± 0.13
mid-IR (S15)	7.74 ± 1.14	9.67 ± 0.41	1.01 ± 0.44	0.53 ± 0.30	0.17 ± 0.07	0.19 ± 0.16
variability (W22)	8.44 ± 0.81	9.68 ± 0.27	1.07 ± 0.30	0.47 ± 0.16	0.23 ± 0.07	0.26 ± 0.12
optical (C20)	8.88 ± 0.69	9.80 ± 0.14	1.12 ± 0.31	0.36 ± 0.07	0.29 ± 0.05	0.30 ± 0.08
$f_r < 20\%$ (S1)	8.31 ± 0.91	9.66 ± 0.36	1.06 ± 0.35	0.47 ± 0.19	0.21 ± 0.08	0.24 ± 0.16
$f_r \geq 20\%$ (S2)	7.91 ± 1.10	9.69 ± 0.32	1.08 ± 0.29	0.58 ± 0.23	0.19 ± 0.08	0.22 ± 0.11
$f_r < f_{r,\text{med}}$ ^a	8.42 ± 1.04	9.67 ± 0.35	1.06 ± 0.31	0.47 ± 0.20	0.21 ± 0.09	0.24 ± 0.16
$f_r \geq f_{r,\text{med}}$	8.01 ± 0.95	9.68 ± 0.32	1.08 ± 0.33	0.57 ± 0.20	0.20 ± 0.07	0.23 ± 0.12
$x_{\text{AGN}} = 0$ (S3)	8.14 ± 0.86	9.82 ± 0.33	1.20 ± 0.31	0.48 ± 0.24	0.17 ± 0.07	0.16 ± 0.12
$x_{\text{AGN}} > 0$ (S4)	8.20 ± 0.95	9.66 ± 0.33	1.03 ± 0.33	0.51 ± 0.21	0.22 ± 0.08	0.25 ± 0.13

Note.

^a $f_{r,\text{med}}$ (=13.6%) is median value of f_r for all samples.

Among the four samples, the mid-IR sample is most metal-poor, with a median value of $\langle Z_* \rangle_L = 0.17 Z_\odot$, and the variability sample is most metal-rich, with a median value of $\langle Z_* \rangle_L = 0.23 Z_\odot$. When considering the optical sample, it has the largest median $\langle Z_* \rangle_L$ of $0.29 Z_\odot$, and about 90% of the optically selected galaxies have $\langle Z_* \rangle_L > 0.2 Z_\odot$, as shown in the bottom right panel of Figure 4 (dashed-line histogram). These differences can be explained with the mass–metallicity relation (MZR; e.g., Zahid et al. 2017; C20), as the mid-IR and optical samples have the lowest and highest (median) stellar masses, respectively, as listed in Table 1.

To further check the MZR for our sample galaxies, we plot stellar mass versus the light- (upper) and mass-weighted (bottom) metallicities in Figure 5, with (red) solid circles representing the median values of each mass bin. We also overplot the star-forming galaxies in Zahid et al. (2017, cyan stars), for which the stellar metallicities are also obtained using stellar population synthesis, and nearby galaxies in Kirby et al. (2013, red stars) and Davies et al. (2017, blue stars). Compared with the optical sample in C20, our dwarfs extend to a much smaller ($\sim 4.5\times$) mass. As shown in the figure, for our AGN-host dwarfs there exists a similar MZR to normal dwarf galaxies. Our result confirms the finding in C20 and provides further evidence that AGNs are unlikely to strongly influence the chemical evolution of their host dwarf galaxies.

On the other hand, we can also see from Figure 5 that there is a large spread in the plot, especially for the mid-IR sample (open circles). This raises a tricky problem of the age–metallicity degeneracy, which confuses old metal-poor systems with young metal-rich ones, and thus would lead to an obvious deviation from the MZR. After investigating the morphologies of the sources significantly deviating from the MZR, we find

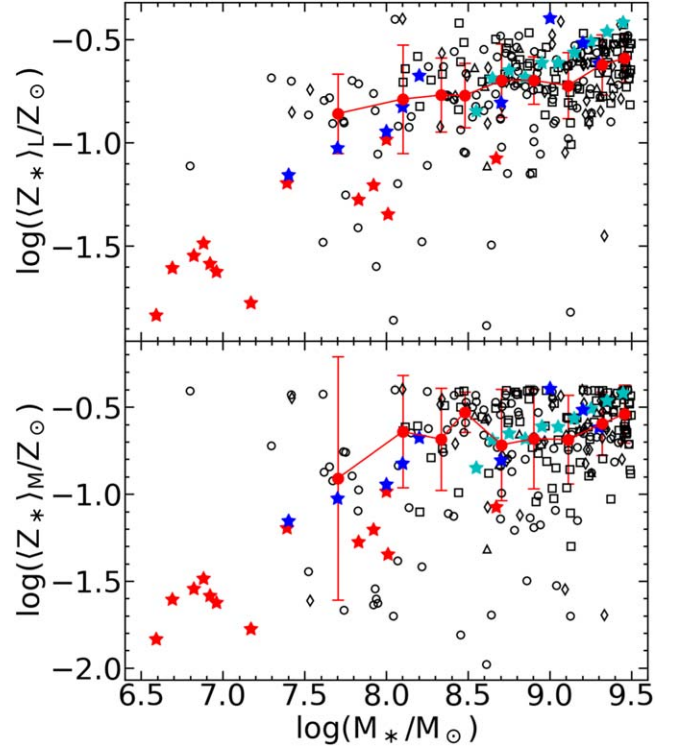


Figure 5. MZR for light-weighted mean stellar metallicity $\langle Z_* \rangle_L$ (top panel) and mass-weighted mean stellar metallicity $\langle Z_* \rangle_M$ (bottom panel). Black open symbols represent all AGN-host dwarf galaxy samples, as in Figure 3. Red solid circles show the median values of $\langle Z_* \rangle$ in each mass bin with error bars giving the dispersion. For comparison, we also plot the metallicities for star-forming galaxies (Zahid et al. 2017, cyan stars), those nearby galaxies measured with spectroscopy of individual blue supergiant stars (Davies et al. 2017, and references therein, blue stars), and dwarf galaxies in the Local Group (Kirby et al. 2013, red stars). All metallicities have been scaled to the solar metallicity ($Z_\odot = 0.02$) adopted in this work.

that those having low masses but high metallicities tend to be early-type (Sérsic index $n > 3$) galaxies with young $\langle \log t_* \rangle_L$, while those with large masses but low metallicities tend to be late-type (Sérsic index $n < 3$) galaxies with old $\langle \log t_* \rangle_L$. This result is opposite to the general finding that late-type galaxies have younger $\langle \log t_* \rangle_L$, providing other evidence that the age–metallicity degeneracy should have severely affected a small part of our sample galaxies.

3.2.3. Star Formation Histories

In order to reduce the uncertainties in the individual components (C05), and to obtain a general view of the SFHs of these AGN-host dwarfs, we arrange their stellar populations into three groups, namely, young ($t < 10^8$ yr), intermediate-age ($10^8 < t < 10^9$ yr), and old ($t > 10^9$ yr) populations, denoted by x_Y (μ_Y), x_I (μ_I) and x_O (μ_O) respectively, in line with previous studies (e.g., C05; C20). For $S/N \geq 10$, the uncertainties can be $\Delta x_Y \leq 0.05$, $\Delta x_I \leq 0.1$ and $\Delta x_O \leq 0.1$ (C05). Figure 6 shows the distributions of luminosity contribution fractions in different population groups. Compared with the optical sample, for which the fraction increases with decreasing x_Y , our whole sample has a flatter distribution in x_Y . Furthermore, the trend of x_O for the optical sample is opposite to our whole sample, which generally shows a smaller fraction as x_O increasing.

For each of our samples, 25.0% (radio), 35.0% (X-ray), 52.6% (mid-IR), and 22.2% (variability) of the galaxies have their x_Y larger than 50%. Generally, a much smaller fraction of the galaxies have $x_I > 50\%$, i.e., 25.0%, 12.5%, 8.2%, and 11.1% respectively for the corresponding samples. In the radio, X-ray, and variability samples, we also find that a small fraction ($< 10\%$) of the sources have extremely large x_Y ($> 90\%$). While for the mid-IR sample, a much larger fraction ($\sim 20\%$) of the member galaxies have $x_Y > 90\%$, and the young population dominates the luminosity.

Although the variability sample has the smallest contribution from the young population, the fraction is still larger than that of the optical sample, for which only 18 (13.2%) sources have $x_Y > 50\%$ and no source shows $x_I > 50\%$. The most significant difference is between the contributions from the old population: 97 (71.3%) out of 136 sources of the optical sample have $x_O > 50\%$, whereas only 33.3%, 30.0%, 24.7%, and 46.7% objects, respectively for the radio, X-ray, mid-IR, and variability samples, have $x_O > 50\%$. These results indicate that most of our sample galaxies should have experienced star-forming activities in the recent 1 Gyr.

Furthermore, C20 show that for the optically selected AGN-host dwarfs with stellar mass of $10^9 - 3 \times 10^9 M_\odot$, only 4% have $\mu_Y > 5\%$, far less than the fraction of 25%–40% found by Kauffmann (2014) for the same mass range. The authors suggest that the much lower fraction may be caused by the suppression of AGNs in the current star formation of the host galaxies, and/or the selection bias inherent to the optical

sample. For our galaxies within the same mass range, the fractions having $\mu_Y > 5\%$ are 14.3%, 14.8%, 9.1%, and 5.8%, respectively, for the radio, X-ray, mid-IR and variability samples, resulting in a final fraction of 9.5% (10/105) for the whole sample. Our results, which are unlikely to suffer from the selection effect, further suggest that AGNs in dwarfs likely suppress the current star formation of the host galaxy, consistent with the finding in Cai et al. (2021) that AGN-host dwarfs have an older light-weighted age than the control sample.

3.2.4. Pseudo-Radial Profile

The spectra used in this work are obtained from fixed-size 3''-diameter fibers of SDSS, which cover different physical scales and light fractions of the entire galaxy, depending on the distance of the target. For our whole sample, it corresponds to a physical size of about 64 pc and 3.3 kpc for the closest and farthest sources, respectively. Whereas, the light fraction, $f_r (\equiv 100 \times 10^{-0.4(m_{\text{fiber}} - m_{\text{Petro}})})$, which describes the covering fraction of the fixed-size aperture and is calculated with the fiber and total galaxy magnitudes in the r band following Zhao et al. (2011), is in the range of $\sim 0.6\%$ –100%, and has a median value of $f_{r,\text{med}} = 13.6\%$. Therefore, more than a half of our sample galaxies have f_r less than 20%, which is required to minimize the aperture effect as demonstrated in Kewley et al. (2005). Indeed, there is a significant difference (0.4 dex) between the median $\langle \log t_* \rangle_L$ for the two subsamples (S1 and S2) divided by $f_r = 20\%$, as shown in Table 2 (also see Table 3), and the subsample (S2) with a larger f_r has a younger light-weighted stellar age, suggesting that the inner part might be older.

In order to overcome the limitation caused by the fixed-size aperture, and further investigate the AGN influence on the host galaxy, we define a normalized radius, namely $R = 1''5/R_e$, where R_e is the radius enclosing 50% of the galaxy light in r band. In this way, we can alleviate the aperture effect and obtain a pseudo-radial profile of the stellar populations, as shown in Figure 7. It can be seen from the top panel that there exists a negative gradient in the mean light-weighted stellar age for $R \lesssim 1$, similar to previous works for normal galaxies (González Delgado et al. 2015; Li et al. 2015; Morelli et al. 2015; Roig et al. 2015; Zheng et al. 2017), which implies an inside-out formation scenario. However, Cai et al. (2021) find a flat radial-profile of $\langle \log t_* \rangle_L$ for their optically selected AGN-host dwarfs, suggesting that the AGN effect seems to result in an overall quenching of the host galaxy. We speculate that the AGN-host dwarfs in the current work and Cai et al. (2021) are at different evolutionary stages, in the sense that our sample galaxies have abundant cold gas to fuel the AGN and star formation (early stage), while the sources in Cai et al. (2021) have little gas to support the star formation (late stage). This aspect needs more Integral Field Unit (IFU) data of AGN-hosts

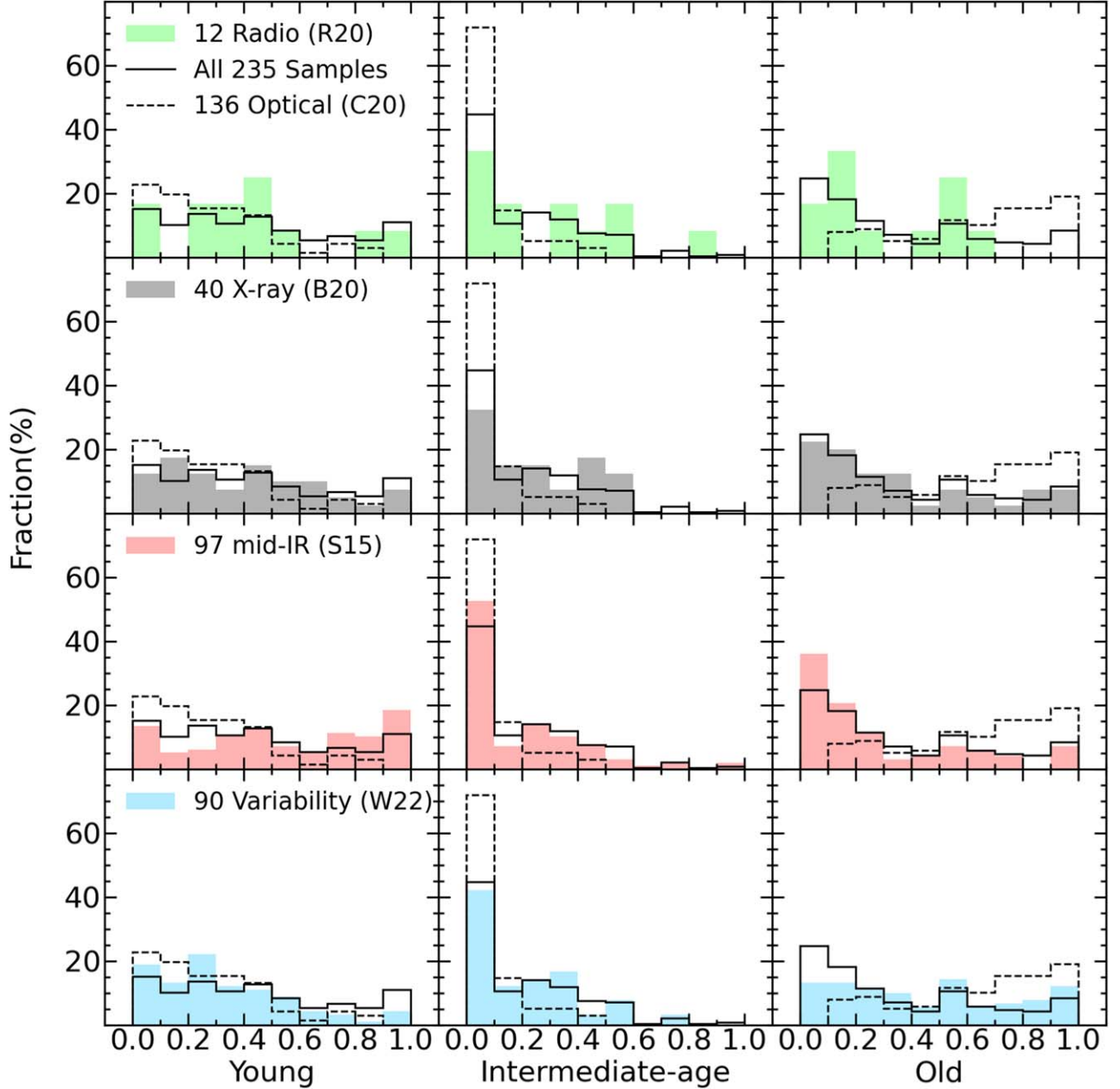


Figure 6. Fractional distributions of luminosity fractions of young ($t < 10^8$ yr), intermediate-age ($10^8 < t < 10^9$ yr), and old ($t > 10^9$ yr) stellar populations for different samples. In each panel, the black solid- and dashed-line histograms represent all of the 235 AGN-host dwarf galaxies and the optical sample, respectively.

selected by methods other than the BPT diagram to obtain a solid conclusion.

Many works have reported a negative metallicity gradient, and this trend becomes flatter and even disappears for low-mass systems (Zheng et al. 2017; Belfiore et al. 2018; Cai et al. 2021). As illustrated in the bottom panel of Figure 7, we do not

see any obvious trend in $\langle Z_* \rangle_L$ within $1R_e$ for our whole sample, and the apparent decrease at larger radii is believed to be caused by the much fewer data points we used. Our result is generally consistent with the finding in Cai et al. (2021), who show that AGN-hosts and normal dwarfs have very flat radial profiles of $\langle Z_* \rangle_L$, with tiny gradients of -0.03 and -0.06

Table 3
Median Values and Dispersion of the Derived Stellar Population Properties With Pure Stellar Population Model

Sample	$\langle \log t_* \rangle_L$	$\langle \log t_* \rangle_M$	$\sigma_L(\log t_*)$	$\sigma_M(\log t_*)$	$\langle Z_* \rangle_L/Z_\odot$	$\langle Z_* \rangle_M/Z_\odot$
All	7.99 ± 0.80	9.74 ± 0.26	1.27 ± 0.23	0.55 ± 0.22	0.18 ± 0.06	0.19 ± 0.11
radio (R20)	7.83 ± 0.65	9.73 ± 0.14	1.38 ± 0.16	0.61 ± 0.23	0.17 ± 0.04	0.20 ± 0.06
X-ray (B20)	8.04 ± 0.66	9.78 ± 0.20	1.23 ± 0.18	0.60 ± 0.26	0.20 ± 0.07	0.20 ± 0.09
mid-IR (S15)	7.60 ± 0.98	9.72 ± 0.35	1.29 ± 0.26	0.62 ± 0.27	0.14 ± 0.06	0.15 ± 0.10
variability (W22)	8.32 ± 0.61	9.75 ± 0.21	1.26 ± 0.20	0.50 ± 0.17	0.20 ± 0.05	0.24 ± 0.11
$f_r < 20\%$ (S1)	8.12 ± 0.78	9.72 ± 0.26	1.26 ± 0.22	0.51 ± 0.19	0.19 ± 0.07	0.21 ± 0.14
$f_r \geq 20\%$ (S2)	7.69 ± 1.05	9.78 ± 0.21	1.32 ± 0.20	0.64 ± 0.24	0.17 ± 0.05	0.18 ± 0.08
$f_r < f_{r,\text{med}}$	8.19 ± 0.88	9.74 ± 0.25	1.26 ± 0.22	0.49 ± 0.19	0.18 ± 0.07	0.21 ± 0.14
$f_r \geq f_{r,\text{med}}$	7.88 ± 0.90	9.76 ± 0.25	1.29 ± 0.21	0.62 ± 0.23	0.17 ± 0.06	0.18 ± 0.09
S3	8.10 ± 0.87	9.78 ± 0.33	1.15 ± 0.27	0.51 ± 0.21	0.17 ± 0.08	0.17 ± 0.14
S4	7.96 ± 0.81	9.74 ± 0.24	1.29 ± 0.21	0.56 ± 0.21	0.18 ± 0.06	0.20 ± 0.10

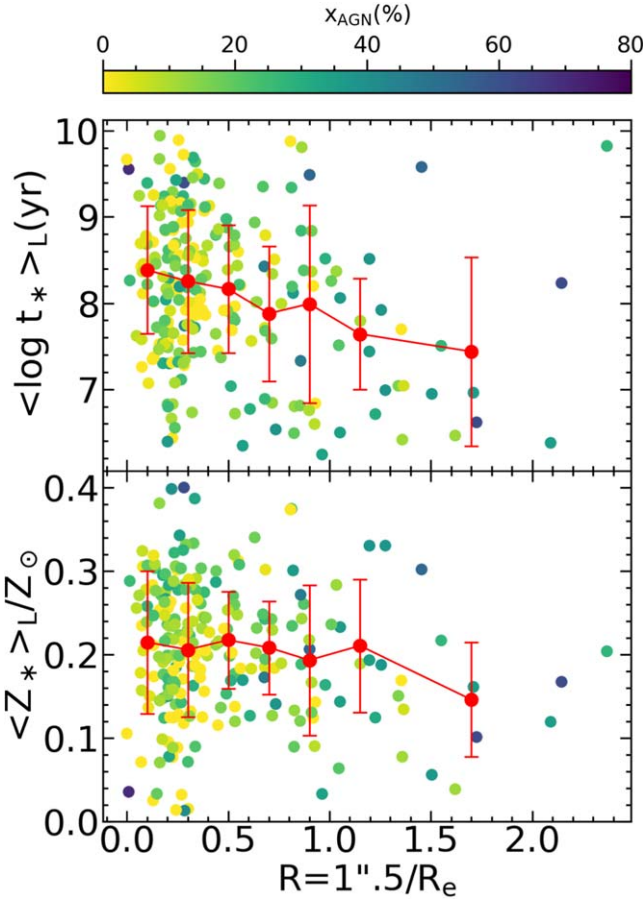


Figure 7. Distributions of $\langle \log t_* \rangle_L$ (top) and $\langle Z_* \rangle_L$ (bottom) as a function of the normalized radius $R = 1'' .5/R_e$ for all of the 235 AGN-host dwarf galaxies, colored with x_{AGN} . The error bars in the y-axis show the dispersion of the mean value in each R bin.

dex/ R_e , respectively, for the inner region of $1R_e$. These results further confirm that AGNs have no strong impact on the chemical evolution of their host galaxies.

3.3. Stellar Population Properties from the Pure Stellar Population Model

As shown in Section 3.1, the optical emission lines may be dominated by the host galaxy for our sample objects, and thus the AGN should only have a minor contribution to the spectral light. Considering this fact, we also carried out SSP synthesis without an AGN component (i.e., the pure stellar population model). In addition, this process can help us to estimate to what extent an FC component would affect our synthesis results. In Table 3 we list the derived properties of the SSPs for different (sub) samples.

Comparing the values listed in Table 2 with those in Table 3, we find that, in general, the mass (light)-weighted age from the pure stellar population model would be older (younger) by ~ 0.1 (~ 0.2) dex, and the mass (light)-weighted stellar metallicity would be reduced by a factor of 10%–20% (10%–25%). These results can be seen more clearly in Figure 8, which plots the fractional distribution of $\Delta t = \langle \log t_* \rangle_{\text{noAGN}} - \langle \log t_* \rangle_{\text{AGN}}$, the difference of stellar ages between the pure stellar population and AGN-included models, for different samples. Figure 8 demonstrates that only a small fraction of galaxies have $\Delta t > 0.5$ dex, and each sample has a comparable dispersion in Δt . For the whole sample, both Δt_M (filled gray histogram) and Δt_L (filled pink histogram) peak around 0.0, and a Gaussian function can generally fit the distribution (except for the small fraction of galaxies showing large Δt), which gives $(\mu, \sigma)_{\Delta t_M} = (0.02, 0.13)$ dex and $(\mu, \sigma)_{\Delta t_L} = (0.10, 0.19)$ dex.

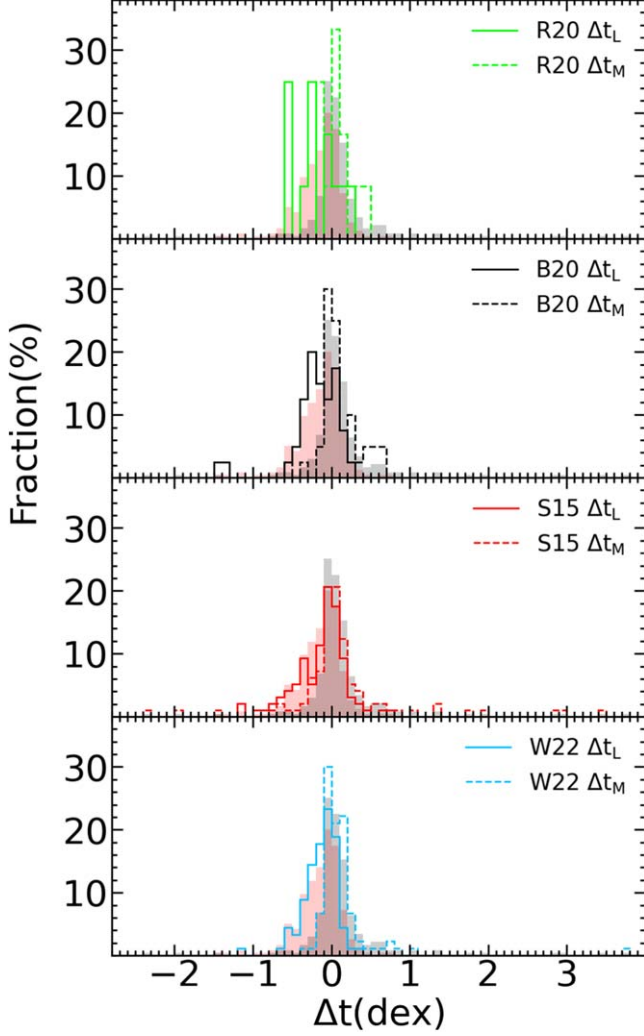


Figure 8. Fractional distributions of the difference between the light-weighted (Δt_L ; solid line) and mass-weighted (Δt_M ; dashed line) ages from the two fitting models (with/without a PL component). Line colors signify different samples, the same as in Figure 1. Filled histograms represent distributions of whole samples in terms of light-weighted (pink) and mass-weighted (gray).

We also note that for a few sources Δt_M (Δt_L) can be as large as 3.8 (1.5) dex. These galaxies might have a large contribution from the AGN. To further check the AGN effect on our results, we plot Δt as a function of the corresponding stellar age obtained from the AGN-included model, color-coded by x_{AGN} , as shown in Figure 9. Indeed, 16 out of 24 sources with $\Delta t_M > 0.5$ dex have $x_{\text{AGN}} > 20\%$, while a larger fraction (21/26) of sources with $|\Delta t_L| > 0.5$ dex show $x_{\text{AGN}} > 20\%$. Furthermore, nine out of 13 galaxies with $\Delta t_M < -0.3$ dex have $x_{\text{AGN}} > 15\%$, which is unexpected theoretically. Combining this with the fact that there also exist 39 sources (the “S3” sample in Tables 2 and 3) having $x_{\text{AGN}} = 0$, the dusty starburst-FC degeneracy, which would lead to a mistake of a dusty

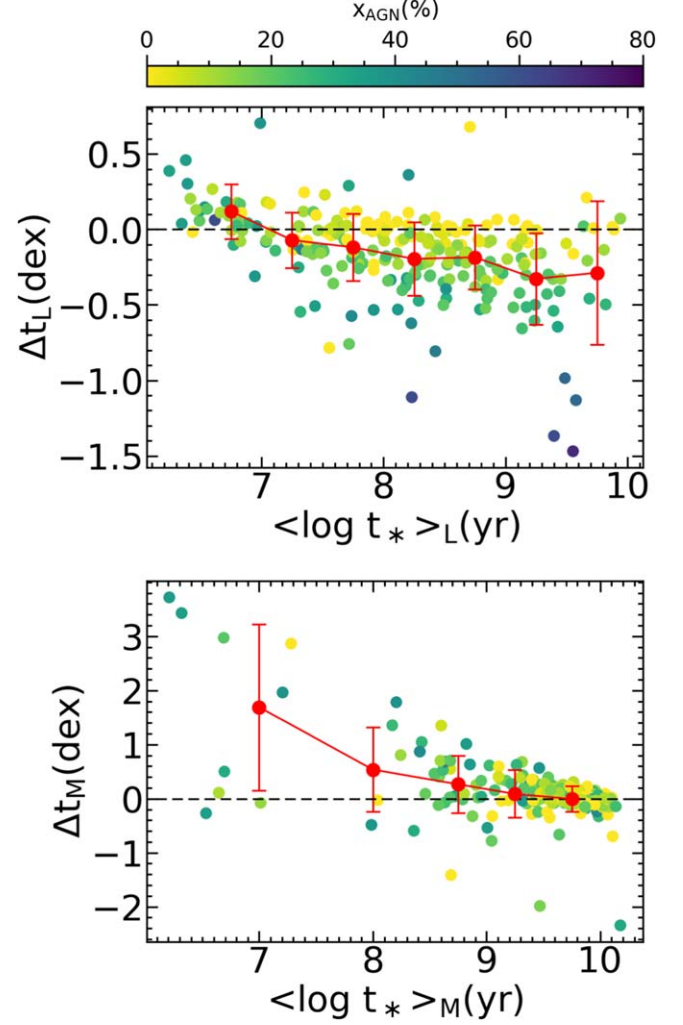


Figure 9. Difference between the mean stellar ages from the two fitting models as a function of $\langle \log t_* \rangle_L$ (top) and $\langle \log t_* \rangle_M$ (bottom). Samples colored by x_{AGN} , and red solid circles with error bars show the median value and dispersion of each $\langle \log t_* \rangle$ bin.

starburst being misidentified as an AGN FC and vice versa (Cid Fernandes et al. 2004), has affected the results for about 20% of our sample galaxies.

Cardoso et al. (2017) constructed synthetic galaxy spectra representing a wide range of galactic SFHs, including different PL contributions from AGNs, and performed a quantitative examination of the impact of the FC of an AGN on the estimation of physical properties of galaxies. The authors show that, at the empirical AGN detection threshold of $x_{\text{AGN}} \simeq 0.26$, the exclusion of a PL component from spectral fitting can lead to an overestimation by up to ~ 4 dex in $\langle \log t_* \rangle_M$ for the youngest ($t_M \lesssim 10^6$ yr) objects, and to an overestimation (underestimation) by up to ~ 0.8 dex in $\langle \log t_* \rangle_L$ for $t_L \lesssim 10^7$ yr ($t_L > 10^7$ yr). Furthermore, these biases become more severe

with increasing x_{AGN} and are independent of the adopted SFH. As demonstrated in Figure 9, our results agree very well with the findings in Cardoso et al. (2017). We can see that Δt is related to the corresponding mean stellar age, and Δt_L (top panel) is more sensitive to x_{AGN} than Δt_M (bottom panel). In particular, the transition of Δt_L for our sample galaxies occurs at $\langle \log t_{\star} \rangle_L \sim 7$, the same as that in Cardoso et al. (2017). Therefore, the uncertainties in the mean stellar ages are generally in the range of 0.2–0.3 dex, and there should be a tiny/mild effect on the stellar population results for the vast majority of our sample galaxies if we exclude the PL component from the model library, since x_{AGN} has a mean value of 0.16 for our whole sample. However, the large difference between these two models for some sources emphasizes the importance of the PL component in stellar population synthesis for AGN-hosts, and a careful evaluation is required when the host galaxy spectrum is severely affected by an AGN.

3.4. Connection Between AGN Activities and SFHs

As one of the strongest optical lines in most galaxies, the [O III] $\lambda 5007$ emission is sensitive to hardness and intensity of the radiation field, and thus its luminosity ($L_{[\text{O III}]}$) can be used as a good tracer of the strength of AGN activities (Kauffmann et al. 2003). For the optical sample, C20 find a mild (anti-) correlation between x_Y ($\langle \log t_{\star} \rangle_L$) and $L_{[\text{O III}]}$, especially when $L_{[\text{O III}]} > 10^{39} \text{ erg s}^{-1}$, suggesting some physical connections between the nuclear star formation and AGN activities. Since the current sample is selected with multiple methods, and is about 1.5 times larger than that used in C20, we perform a similar analysis to C20 in the following, to further explore whether such correlation still holds for a more representative sample of AGN-host dwarfs.

To obtain an extinction-free luminosity of the [O III] line, we first estimate the intrinsic nebula extinction, $A_{V,\text{neb}}$, by utilizing the Balmer decrement as in Zhao et al. (2011) and C20. For the nine Seyfert/Composite sources (see Figure 3), we adopt an intrinsic ratio of $I_{\text{H}\alpha}/I_{\text{H}\beta} = 3.1$, appropriate for AGNs (e.g., Gaskell & Ferland 1984; Osterbrock & Ferland 2006), for an electron temperature of 10^4 K and an electron density of 100 cm^{-3} . For the remaining sources located in the star-forming region in the BPT diagram, we take $I_{\text{H}\alpha}/I_{\text{H}\beta} = 2.86$, suitable for H II galaxies (Brocklehurst 1971). For those objects with an observed Balmer decrement smaller than the intrinsic value, we assign their $A_{V,\text{neb}} = 0$. Then we correct the observed [O III] flux using the obtained $A_{V,\text{neb}}$ and the Cardelli et al. (1989) reddening law. We find that $\sim 73\%$ of our sample galaxies are weak AGNs having $L_{[\text{O III}]} < 10^7 L_{\odot}$ (Kauffmann et al. 2003).

Most of our sources are located in the star-forming region, though the BPT diagram might not be usable in classifying dwarf galaxies as discussed in Section 3.1, and thereby it is

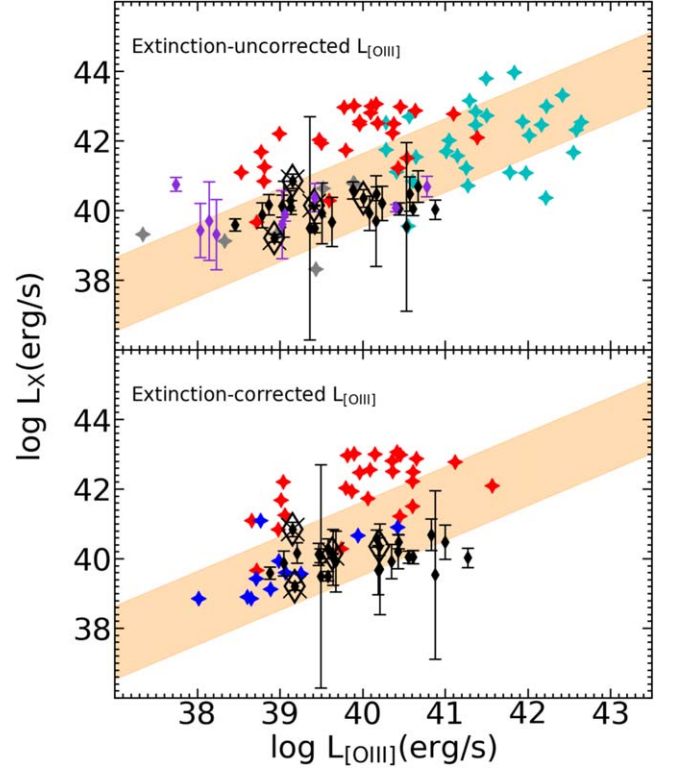


Figure 10. The observed X-ray luminosity L_X plotted against the extinction-uncorrected (top panel) and extinction-corrected (bottom panel) [O III] luminosity $L_{[\text{O III}]}$. Diamonds represent the 35 sources in the X-ray ($L_X = L_{2-12 \text{ keV}}$) sample, with the black (violet) points included (excluded) in Figure 3. Colored stars are non-Compton-thick type-2 AGNs (cyan: Heckman et al. 2005; red: Gu et al. 2006; and blue: Panessa et al. 2006) and optical variability-selected low-mass AGNs (gray: Messick et al. 2023) with $L_X = L_{2-10 \text{ keV}}$. The color-filled region shows the mean $L_X/L_{[\text{O III}]}$ with $\pm 1\sigma$ dispersion from Heckman et al. (2005). Crosses and larger symbols are the same as in Figure 3.

worth investigating the origin of the [O III] emission for our sample galaxies. To this end, we check whether the relation between the X-ray luminosity (L_X) and $L_{[\text{O III}]}$ for our sample galaxies, as shown in Figure 10, follows the trend established by more massive objects, such as type-2 Seyferts, in which the X-ray luminosity is believed to be dominated by the AGN. It can be seen from the figure that our X-ray sample has a similar $L_X/L_{[\text{O III}]}$ ratio to those AGNs in Heckman et al. (2005) and Panessa et al. (2006). However, the overall $L_X/L_{[\text{O III}]}$ ratio of the Seyfert 2 AGNs from Gu et al. (2006) is about an order of magnitude larger than the other samples. Though the X-ray sample shows nuclear X-ray activity indicative of an AGN, it seems difficult to rule out the possibility that the host galaxy may heavily contaminate the [O III] luminosity based only on the observed $L_X/L_{[\text{O III}]}$ ratios. However, we note that for star-forming blue compact dwarf galaxies, no correlation between $L_{[\text{O III}]}$ and $\langle \log t_{\star} \rangle_L$ (or x_Y) is found in C20.

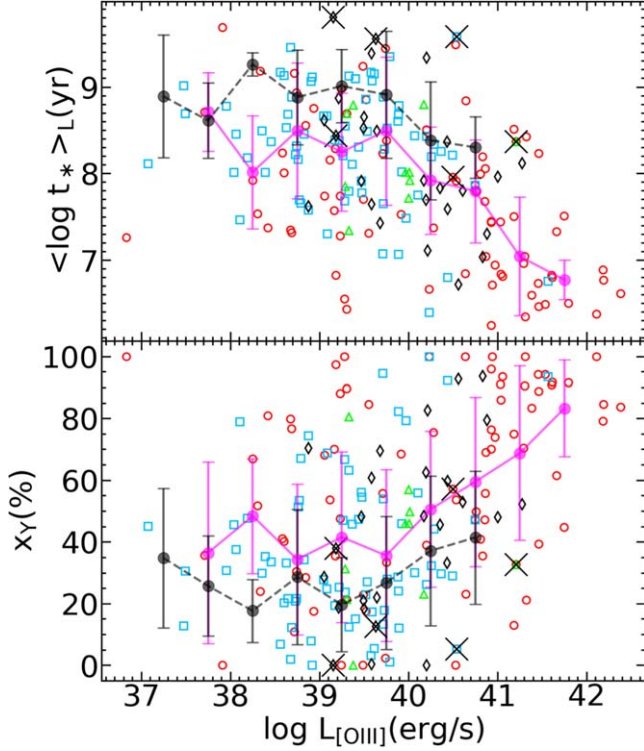


Figure 11. Extinction-corrected $L_{[\text{O III}]}$ vs. $\langle \log t_* \rangle_L$ (top panel) and x_Y (bottom panel). Magenta solid and black dashed lines show the median (mean for x_Y) trends for our and the optical samples, respectively. Colors and symbols are the same as in Figure 3.

Table 4
Spearman Correlation Coefficients

Sample	Number	$L_{[\text{O III}]} - \langle \log t_* \rangle_L$		$L_{[\text{O III}]} - x_Y$	
		ρ	p -value	ρ	p -value
radio	10	0.30	4.0E-01	0.16	6.5E-01
X-ray	26	-0.49	1.1E-02	0.46	1.8E-02
mid-IR	79	-0.50	2.9E-06	0.36	1.3E-03
variability	70	-0.18	1.3E-01	0.10	3.9E-01
All	181	-0.45	3.4E-10	0.37	2.4E-07
$L_{[\text{O III}]} > 10^{39}$	139	-0.47	6.7E-09	0.41	3.8E-07
optical	136	-0.20	1.8E-02	0.19	2.6E-02
$L_{[\text{O III}]} > 10^{39}$	91	-0.41	6.4E-05	0.42	2.8E-05

Bearing the above caveat in mind, we plot the extinction-corrected $L_{[\text{O III}]}$ against the light-weighted stellar age (upper panel) and fractional contribution of the young population (bottom panel) in Figure 11, and list the Spearman correlation coefficients (ρ) and p -values in Table 4, for various (including the optical) samples. We can see that the current sample extends to a much (about one order of magnitude) higher $L_{[\text{O III}]}$ compared with the optical sample studied in C20, but they show a similar trend (with an offset in the y-axis). As indicated

by the Spearman correlation coefficients, there exists a mild (anti-)correlation between $L_{[\text{O III}]}$ and x_Y ($\langle \log t_* \rangle_L$) for the X-ray, mid-IR, $L_{[\text{O III}]} > 10^{39} \text{ erg s}^{-1}$ and whole samples, further suggesting a connection between AGN and star-forming activities.

Meanwhile, no correlation is found for the radio sample, which should be due to the fact that there is a large scatter in the relation and the sample size is very small. Like the optical one, there is no correlation for the variability sample too, because it generally has the lowest $L_{[\text{O III}]}$ and most of the sample galaxies are located within the flat part of the trend, as illustrated in Figure 11. To reach a solid conclusion regarding the correlation between AGN activity and SFH, a large sample selected with various methods and IFU data (such as MaNGA) is needed to reduce the influence of the host galaxy on the $[\text{O III}]$ luminosity.

3.5. Extinction

For the stellar visual extinction $A_{V,*}$, it is returned by STARLIGHT, modeled as due to a foreground dust screen using the continuum spectrum. To estimate the internal extinction suffered by nebular lines, we adopt Equation (5) in Zhao et al. (2011), namely

$$A_{V,\text{neb}} = 7.93 \times \log \left(\frac{F_{\text{H}\alpha}/F_{\text{H}\beta}}{I_{\text{H}\alpha}/I_{\text{H}\beta}} \right),$$

where $F_{\text{H}\alpha}/F_{\text{H}\beta}$ and $I_{\text{H}\alpha}/I_{\text{H}\beta}$ are the observed and intrinsic Balmer decrements, respectively. Here we have assumed that the intrinsic Balmer line ratios are equal to Case B recombination, and used the Calzetti et al. (1994) reddening law. As mentioned in Section 3.4, two different $I_{\text{H}\alpha}/I_{\text{H}\beta}$ ratios are adopted respectively for sources located in the AGN/composite ($I_{\text{H}\alpha}/I_{\text{H}\beta} = 3.1$) and star forming ($I_{\text{H}\alpha}/I_{\text{H}\beta} = 2.86$) regions in the BPT diagram.

To measure $A_{V,\text{neb}}$ of a galaxy, we require that both $\text{H}\alpha$ and $\text{H}\beta$ have $\text{S/N} > 3$. For the radio, X-ray, mid-IR, variability and whole sample, the median values of $\log(F_{\text{H}\alpha}/F_{\text{H}\beta})$ are 0.55 ± 0.07 , 0.54 ± 0.05 , 0.51 ± 0.05 , 0.56 ± 0.06 and 0.54 ± 0.07 , respectively, corresponding to median $A_{V,\text{neb}}$ of 0.74 ± 0.57 , 0.59 ± 0.32 , 0.45 ± 0.36 , 0.90 ± 0.43 and 0.66 ± 0.48 mag. Except for the variability sample, other samples show smaller nebular extinction than the optical sample ($A_{V,\text{neb}} = 0.9$; Cai et al. 2020), but are comparable to the star-forming galaxies with similar stellar masses presented in Garn & Best (2010).

Calzetti et al. (1994) find that the extinction derived from the Balmer emission line is about twice as much as that from the continuum (see also Charlot & Fall 2000). For our sources with positive $A_{V,\text{neb}}$ and $A_{V,*}$, the median values of $A_{V,\text{neb}}/A_{V,*}$ are 1.60 ± 1.15 (radio), 1.74 ± 1.14 (X-ray), 1.59 ± 1.42 (mid-IR), 1.84 ± 1.02 (variability), and 1.72 ± 1.25 (whole sample), which are 10%–20% smaller than the value found for nearby

star-forming galaxies (Calzetti et al. 2000). Our results seem consistent with the finding in Woo et al. (2024), who study the model uncertainties of STARLIGHT and show that the stellar extinction tends to be overestimated when $S/N \lesssim 15$ (see their Figure 12). At $S/N = 10$, $\Delta E(B - V)$ is about 0.02 dex (Woo et al. 2024), resulting in an overestimation of $A_{V,*} \sim 5\%$, which is a bit smaller than our value of 10%–20%.

Therefore, we further check other possible reasons causing the above discrepancy, and find that an obvious difference exists in $A_{V,neb}/A_{V,*}$ between the two subsamples S3 ($x_{AGN} = 0$; 22 sources) and S4 ($x_{AGN} > 0$; 139 sources), with median $A_{V,neb}/A_{V,*}$ ratios of 1.35 and 1.76, respectively. This result implies that the stellar extinction for the S3 subsample could be overestimated to some degree, which can be naturally explained by the degeneracy between AGN FC and dusty starburst, in the sense that STARLIGHT would have treated the AGN FC as a dusty starburst. To check to what extent the age-extinction and/or AGN FC-dusty starburst degeneracy would affect our fitting results, we re-run STARLIGHT using the same parameters except limiting $A_{V,*}$ to the value of $A_{V,neb}$ for 23 sources with $A_{V,*}/A_{V,neb} > 1.5$. We find that the mean stellar age increases by a mean value of $\Delta \langle \log t_* \rangle_L = 0.30 \pm 0.18$ ($\Delta \langle \log t_* \rangle_M = 0.45 \pm 0.72$) dex.

4. Summary

In this paper, we present detailed results of our stellar population synthesis for a sample of 235 AGN-host dwarf galaxies selected by different methods from radio, X-ray, mid-IR, and variability using the STARLIGHT code and fiber spectra from SDSS DR8. Our main results can be summarized as follows:

1. Among our four samples, the mid-IR (variability) sample is the youngest (oldest) with median value of the light-weighted mean stellar age of $10^{7.74}$ ($10^{8.44}$) yr, and 57.7% (23.3%) of the sample sources having $\langle \log t_* \rangle_L < 8$. Our sample galaxies are ~ 0.7 dex younger than the optically selected AGN-host dwarfs, but they have similar distributions in $\sigma_L(\log t_*)$, suggesting complex and diverse SFHs in all of the AGN-host dwarf systems, irrespective of the selection method.

2. AGNs are unlikely to strongly influence the chemical evolution of their host dwarf galaxies, as evidenced by them showing a similar metallicity-mass relation and a flat radial profile of $\langle Z_* \rangle_L$ within $1R_e$ compared to normal dwarfs.

3. For our whole sample, there is a negative gradient of $\langle \log t_* \rangle_L$, indicative of inside-out and/or suppression of star formation in the central region. Only $\sim 9.5\%$ of the sources with stellar mass of $10^9 - 3 \times 10^9 M_\odot$ have $\mu_Y > 5\%$, far less than the fraction of 25%–40% in literature for normal dwarf galaxies, suggesting that AGNs in dwarfs seem to suppress the current star formation of the host galaxies.

4. We compare the difference between the pure stellar population model and AGN-included model, and find that our results agree very well with the previous findings in literature.

The mass (light)-weighted age from the pure stellar population model would be older (younger) by ~ 0.1 (~ 0.2) dex, and the mass (light)-weighted stellar metallicity would be reduced by a factor of 10%–20% (10%–25%).

5. Like the optical sample, there exists a mild (anti-) correlation between $L_{[O III]}$ and x_Y ($\langle \log t_* \rangle_L$) for the X-ray, mid-IR, $L_{[O III]} > 10^{39}$ erg s $^{-1}$ and whole samples, further suggesting there are some connections between the AGN and star-forming activities.

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