Comparison of star formation histories of AGN and non-AGN galaxies


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ABSTRACT

We used active galactic nuclei (AGNs) with X-ray luminosities, $L_{X,2-10\text{keV}} \sim 10^{42.5-44}\text{erg s}^{-1}$, from the COSMOS-Legacy survey that lie within the UltraVISTA region and cross-matched them with the LEGA-C catalogue. The latter provides measurements of the calcium break, D$_{4000}$, and H$_\alpha$ Balmer line that allow us to study the stellar populations of AGNs and compare them with a galaxy reference catalogue. Our samples consist of 69 AGNs and 2176 non-AGN systems, within $0.6 < z < 1.3$, that satisfy the same photometric selection criteria. We used the CIGALE code to better constrain the ages of the stellar populations. Furthermore, we find an increase of the estimated stellar masses by $\sim 2$ dex, in particular for systems with young stars ($D_{4000} < 1.5$), when the two indices are included in the SED fitting process. Our analysis shows that the inclusion of D$_{4000}$ and H$_\alpha$ allows CIGALE to better constrain the ages of the stellar populations. Furthermore, we find an increase of the estimated stellar masses by $\sim 2$ dex, in particular for systems with young stars ($D_{4000} < 1.5$), when the two indices are included in the SED fitting process. We then compare the D$_{4000}$ and H$_\alpha$ of AGNs with sources in the reference catalogue, accounting for the different stellar mass of the two populations. Our analysis reveals that low-to-moderate $L_X$ AGNs tend to reside in galaxies with older stellar populations and are less likely to have experienced a recent star formation burst compared to galaxies in the control sample. Finally, we compared the two populations as a function of their morphology (bulge-dominated, BD, versus non-BD) and compactness (mass-to-size ratio). A similar fraction of AGN and non-AGN systems are classified as non-BD ($\sim 70\%$). Our analysis shows that BD AGN tend to have younger stellar populations compared to BD non-AGN systems. On the other hand, non-BD AGNs have, on average, older stellar populations and are less likely to have experienced a burst compared to non-BD sources in the reference sample. Furthermore, AGNs tend to prefer more compact systems compared to non-AGNs.

Key words. galaxies: active – galaxies: star formation – X-rays: galaxies – galaxies: general – quasars: absorption lines – quasars: supermassive black holes

1. Introduction

It is widely accepted and well established that there is a correlation between the mass of a supermassive black hole (SMBH) and the properties of the galactic bulge (e.g., Magorrian 1998; Ferrarese & Merritt 2000). It is also known that black holes grow through accretion of cold gas onto their accretion discs. When this happens, the SMBH becomes active and the galaxy is called an active galactic nuclei (AGNs). The gas that triggers the SMBH originates either from the host galaxy or the extragalactic environment. Various mechanisms have been suggested to drive the gas over more than nine orders of magnitude, from kiloparsec to sub-parsec scales (e.g., Alexander & Hickox 2012). However, the cold gas does not only activate the SMBH, but it can also trigger the star formation of the galaxy. Furthermore, a number of studies have found that AGN activity and star formation peak at the same cosmic time ($z \sim 2$; e.g., Boyle & Terlevich 1998; Boyle et al. 2000; Sobral et al. 2013). These advocate for a connection between the BH activity and galaxy growth. However, the nature of this connection is still elusive.

Hydrodynamical simulations and semi-analytic models have shown that AGN feedback, in the form of, for example, jets, winds, and outflows, can affect the star formation of the host galaxy both ways (e.g., Zubovas et al. 2013). It can either quench the formation of stars (e.g., DeBuhr et al. 2012) or enhance it (e.g., Zinn et al. 2013). Results from observational studies that have compared the SFR of AGNs with that of star forming main sequence (SFMS) galaxies suggest that low-to-moderate X-ray luminosity AGNs ($L_{X,2-10\text{keV}} < 10^{44}\text{erg s}^{-1}$) present lower or consistent SFRs with those of SFMS galaxies, while the most luminous AGNs have enhanced SFRs compared to SFMS galaxies (e.g., Santini et al. 2012; Shimizu et al. 2015, 2017; Masoura et al. 2018; Florez et al. 2020; Mountrichas et al. 2021a, 2022a,b; Pouliasis et al. 2022). This suggests different
Recent advances in X-ray surveys have enabled the study of the age and metallicity of stellar populations of galaxies. These surveys have been used to examine the star formation histories (SFH) for AGN and SFMS galaxies, which differ in the timescales that the stars are formed and the mechanisms (e.g., mergers) that govern the star formation of each population. The Large Early Galaxy Astrophysics Census (LEGA-C) survey (van der Wel et al. 2016; Straatman et al. 2018) has collected high signal-to-noise-ratio, high-resolution spectra for ∼3500 galaxies that lie within 0.6 < z < 1.3. This allows the study of the ages and metallicities of the stellar populations of these galaxies as well as their stellar kinematics. Wu et al. (2018) used measurements provided in the LEGA-C catalogue for two age-sensitive absorption line indices, the equivalent width (EW) of the Hδ Balmer line (Worthey & Ottaviani 1997), and the calcium break (Ca ii) in older systems located between the young and old galaxy populations. Their analysis showed that for star forming regions of the galaxies included in the LEGA-C dataset, Dn4000 is small for young stellar populations and large for old, metal-rich galaxies. On the other hand, the EW of Hδ rises rapidly in the first few hundred million years after a burst of star formation, when O- and B-type stars dominate the spectrum, and then decreases when A-type stars fade (e.g., Kauffmann et al. 2003a; Wu et al. 2018). Based on the analysis of Wu et al. (2018), galaxies at z ∼ 0.8 present a bimodal Dn4000-Hδ distribution, implying a bimodal light-weighted age distribution.

Sobral et al. (2022) used the LEGA-C catalogue and the two indices (Dn4000, Hδ) to study the stellar populations of central and satellite galaxies. Their analysis showed that for star forming galaxies, Dn4000 and Hδ depend on stellar mass, M*, and are completely independent of the environment.

The two spectral indices have also been used to examine the stellar populations of AGNs. Kauffmann et al. (2003b) examined the stellar populations of ∼22,500 narrow line AGNs, at 0.02 < z < 0.3, selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000; Stoughton et al. 2002). They found that the host galaxies of low-luminosity AGNs (log I[OIII] < 7 L⊙) have stellar populations similar to normal early-types, while the high-luminosity AGNs have much younger stellar ages. A significant fraction of the more luminous AGNs have strong Hδ lines. They also examined a sample of broad line AGN and found no significant differences between broad and narrow-line AGNs.

Recently, Georgantopoulos et al. (2022) compared the ages and galaxy properties of 55 X-ray unobscured or mildly obscured AGNs (NHI < 10^23 cm^-2) and 25 heavily obscured sources (NHI > 10^23 cm^-2) in the COSMOS field, at 0.6 < z < 1.0. They found that the majority of unobscured AGNs appear to live in younger galaxies in contrast to the obscured AGNs, which tend to reside in older systems located between the young and old galaxy populations.

In this work, we used low-to-moderate X-ray luminosity (LX < 10^24 erg s^-1) AGNs from the UltraVISTA region of the COSMOS-Legacy survey (Marchesi et al. 2016; Civano et al. 2016) and cross-correlated them with the LEGA-C catalogue. This enriches our sample with the Dn4000 and Hδ measurements included in the LEGA-C dataset. We also compiled a galaxy reference catalogue (control sample) that lies within the same area and redshift range as the AGNs (0.6 < z < 1.3) for which we also have the available Dn4000 and Hδ measurements from the LEGA-C catalogue. Then, we constructed the spectral energy distributions (SEDs) of both AGNs and sources in the reference galaxy catalogue using photometry from optical-to-far-infrared and fitted their SEDs using the CIGALE code (Boquien et al. 2019; Yang et al. 2020, 2022). The purpose of this exercise is to examine the effect of the inclusion of Dn4000 and Hδ in the SED fitting measurements. Specifically, we want to check whether the two spectral indices help CIGALE break the degeneracies of the SFH parameters, leading to more robust measurements of the galaxy properties. Then, we compare the Dn4000 and Hδ of AGNs with those of sources in the reference catalogue (Sects. 4.1–4.3). Moreover, we examine whether the morphology and compactness of the (host) galaxy affects this comparison by using the catalogue presented in Ni et al. (2021; Sect. 4.4). Throughout this work, we assume a flat ΛCDM cosmology with H0 = 70.4 km s^-1 Mpc^-1 and ΩM = 0.272 (Komatsu et al. 2011).

2. Data

2.1. The LEGA-C catalogue

The LEGA-C catalogue includes data obtained from the LEAGA-C survey (van der Wel et al. 2016; Straatman et al. 2018). In this work, we used the third and final data releases of the catalogue (van der Wel et al. 2021) that includes 4081 galaxy spectra, with 3741 unique objects that cover a redshift range from 0.6 to 1.3. The survey is based on a parent sample of spectroscopic and photometric galaxies from the UltraVISTA region (Muzzin et al. 2013) of the COSMOS field (Scoville 2007) and covers a footprint of 1.4255 square degrees. The key characteristic of the survey is that it is K-band selected. Specifically, the targeted sources are brighter than a redshift-dependent K-band limit (Kband = 20.7−7.5 log(1 + z)/1.8).

The catalogue includes high-resolution and signal-to-noise (S/N) spectra (R ∼ 3500, typical S/N ∼ 20 Å^-1) that have allowed the measurement of stellar velocity dispersions, stellar population properties, and absorption-line indices, as well as emission-line fluxes and EWs, among others. In this work, we made use of two stellar-age-sensitive tracers, the EW of Hδ absorption, and a Dn4000 index (e.g., Kauffmann et al. 2003c; Wu et al. 2018). A comparison of their values between X-ray-selected AGNs and a reference catalogue of galaxy (non-AGN) sources will allow us to draw conclusions about the star formation history of the two populations.

To measure the two indices, the stellar continuum is separated from the ionised gas emission, and the observed spectrum is modelled using the penalised pixel-fitting (pPXF) method by Cappellari & Emsellem (2004). Galaxy spectra are fit by a combination of stellar and gas emission templates. For sources included in our sample, the average uncertainties on Hδ and Dn4000 are 17% and 3%, respectively. This is true for the AGNs and sources in the galaxy reference catalogue (see next section). Detailed descriptions of the process are provided in Bezanson et al. (2018) and Wu et al. (2018). The definitions in Balogh et al. (1999) and Worthey & Ottaviani (1997) have been used for Dn4000 and Hδ, respectively.

2.2. X-ray AGNs and galaxy reference catalogues

The X-ray and galaxy reference catalogues used in this work are described in detail in Sect. 2 of Mountrichas et al. (2022b). Below, there is a brief description of the two datasets. First, we present the available photometry of the samples, and then we add the available information on the spectral indices and describe the properties of the final catalogues.

2.2.1. X-ray sample

The X-ray sample was extracted from the X-ray dataset described in Marchesi et al. (2016) and includes observations from the COSMOS-Legacy survey (Civano et al. 2016). The
latter is a 4.6 Ms Chandra programme that covers 2.2 deg$^2$
of the COSMOS field (Scoville 2007). The X-ray catalogue
includes 4016 sources. Marchesi et al. (2016) matched the
X-ray sources with optical and infrared counterparts using
the likelihood ratio technique (Sutherland & Saunders 1992).
Of the sources, 97% have an optical and IR counterpart
and a photometric redshift, and $\approx54\%$ have a spectroscopic
redshift. Only X-ray sources within both the COSMOS
and UltraVISTA (McCracken et al. 2012) regions were
used in our analysis. The reason for restricting the X-ray
dataset in the UltraVISTA region is that the LEGA-C cat-
ologue with which we cross-matched the X-ray sample
consists of galaxies in this region. This reduces the
number of AGNs to 1718 X-ray-detected sources with
$\log [L_{X,2-10\text{keV}}(\text{erg s}^{-1})] > 42$.

A subsidiary goal of this work is to examine the effect of
the inclusion of the two spectral lines (H$\beta$, D$_n$4000) in the
measurements of the star formation history (SFH) parameters
and (host) galaxy properties estimated by SED fits (see next
section). To construct the SEDs, the X-ray catalogue is cross-
matched with the COSMOS photometric catalogue produced
by the Herschel Extragalactic Legacy Project (HELP) collabor-
ation (Shirley et al. 2019, 2021). HELP includes data from
23 of the premier extragalactic survey fields imaged by the
Herschel Space Observatory that form HELP. The catalogue pro-
vides homogeneous and calibrated multi-wavelength data. The
cross-match with the HELP catalogue is done using a 1$''$
radius and the optical coordinates of the counterpart of each X-ray
source. To obtain reliable measurements through the SED fit-
ting process, we require all our X-ray AGNs to have been
detected in the following photometric bands: $u,g,r,i,z,J,H,K_s$,
IRAC1,IRAC2 and MIPS24, MIPS16 or 12 for the $[3.6]$, $[4.5]$, and $24\mu$m photometric bands of Spitzer
(Mountrichas et al. 2022a). This photometric criterion reduces
the X-ray sample to 1627 AGNs. All these sources have measured
fluxes in the Herschel PACS photometric bands and $\sim80\%$
also have SPIRE bands. Mountrichas et al. (2022b) examined the
effect of the lack of far-IR photometry on SFR measurements
by applying SED fitting with and without far-IR photometry on
sources in the COSMOS field (see their Sect. 3.2.2). Based on
their results, the mean difference, $\mu$, of the SFR calculations is
0.01 and the dispersion, $\sigma$, is 0.25. Similar numbers are found for
sources in the galaxy reference catalogue (see below; $\mu = 0.05$
and $\sigma = 0.16$).

2.2.2. Galaxy reference catalogue
In our analysis, we compare the H$\beta$ and D$_n$4000 of X-ray AGNs
with that of non-AGN galaxies. The galaxy reference catalogue
is provided by the HELP collaboration. About 500 000 sources
are in the UltraVISTA region and approximately 230 000 meet
the photometric criteria applied to the X-ray dataset. About 50% of
the sources in the galaxy reference catalogue also have available
measurements in the far-IR (Herschel).

2.2.3. Final LEGA-C samples
We cross-matched the X-ray and galaxy reference cata-
ologue described above with the LEGA-C dataset using a
1$''$ radius and the optical coordinates provided in each catalogue.
134 X-ray AGNs and 3105 sources in the reference catalogue
have counterparts in the LEGA-C sample. We exclude sources
with FLAG_SPEC $= 2$, which indicates that the photometry-
based flux calibration showed significant imperfections, com-
promising the measurement of absorption and emission indices
(Sect. 4.2 in van der Wel et al. 2021). We further excluded sources
with FLAG_MORPH $= 1$ or 2. This flag is used to indicate
cases where the light coming from the slit is not from a
single galaxy with a regular morphology. Finally, we only used
line indices for galaxies that have a measured stellar velocity dis-
persion. These criteria reduce the number of X-ray AGN to 134
and the number of galaxies to 12 200, within $0.6 < z < 1.3$.

The redshift distributions of the two catalogues are presented
in Fig. 1. The two populations present similar distributions.
Moreover, the vast majority of the sources (91% of AGNs and
93% of sources in the reference catalogue) are within $0.6 < z < 1.0$. The small redshift range probed by the samples allows us to
assume that there is no (significant) redshift evolution that could
affect our results. Figure 2 shows the X-ray luminosity distribu-
tion of the AGNs. The vast majority of X-ray sources ($\sim95\%$
) have low-to-moderate luminosities ($L_{X,2-10\text{keV}} \leq 10^{44}\text{ erg s}^{-1}$).

Of the 94 AGNs, 69 (75%) have available measurements for the
D$_n$4000 index and 83 (85%) have a measurement of the

![Fig. 1. Redshift distributions of sources in the galaxy reference cata-
ologue (blue shaded histogram) and of X-ray AGNs (red line). The two
populations present similar distributions.](image1)

![Fig. 2. X-ray luminosity distributions in the 2–10 keV band of the X-ray
AGNs used in our analysis. The vast majority of sources have low-to-
moderate X-ray luminosities ($L_{X,2-10\text{keV}} \leq 10^{44}\text{ erg s}^{-1}$).](image2)
Table 1. Models and values for their free parameters used by X-CIGALE for the SED fitting.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model/values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of the main population e-folding time</td>
<td>3000, 4000, 5000, 5500, 6000 Myr, 50, 100, 200, 500, 700 Myr</td>
</tr>
<tr>
<td>Burst stellar mass fraction</td>
<td>0.0, 0.001, 0.003, 0.005, 0.01, 0.02, 0.1</td>
</tr>
<tr>
<td>Initial mass function</td>
<td>Charbonnier (2003)</td>
</tr>
<tr>
<td>Metallicity</td>
<td>0.02 (Solar)</td>
</tr>
<tr>
<td>Dust attenuation law</td>
<td>Charlot &amp; Fall (2000) law</td>
</tr>
<tr>
<td>V-band attenuation $A_V$</td>
<td>0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.5, 2, 2.5, 3, 3.5, 4</td>
</tr>
<tr>
<td>$\alpha$ slope in $dM_{dust} \propto U^{-\alpha}dU$</td>
<td>2.0</td>
</tr>
<tr>
<td>AGN module: SKIRTOR</td>
<td></td>
</tr>
<tr>
<td>Torus optical depth at 9.7 microns $\tau_{9.7}$</td>
<td>3.0, 7.0</td>
</tr>
<tr>
<td>Torus density radial parameter $p$ ($\rho \propto r^{-p}e^{-q</td>
<td>\cos(q)</td>
</tr>
<tr>
<td>Torus density angular parameter $q$ ($\rho \propto r^{-p}e^{-q</td>
<td>\cos(q)</td>
</tr>
<tr>
<td>Angle between the equatorial plan and edge of the torus</td>
<td>40°</td>
</tr>
<tr>
<td>Ratio of the maximum to minimum radii of the torus</td>
<td>20</td>
</tr>
<tr>
<td>Viewing angle</td>
<td>30° ($\text{type 1}$), 70° ($\text{type 2}$)</td>
</tr>
<tr>
<td>AGN fraction</td>
<td>$0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.99$</td>
</tr>
<tr>
<td>Extinction law of polar dust</td>
<td>SMC</td>
</tr>
<tr>
<td>$E(B-V)$ of polar dust</td>
<td>0.0, 0.2, 0.4</td>
</tr>
<tr>
<td>Temperature of polar dust (K)</td>
<td>100</td>
</tr>
<tr>
<td>Emissivity of polar dust</td>
<td>1.6</td>
</tr>
<tr>
<td>X-ray module</td>
<td></td>
</tr>
<tr>
<td>AGN photon index $\Gamma$</td>
<td>1.4</td>
</tr>
<tr>
<td>Maximum deviation from the $\alpha_{\text{ox}} \sim L_{2500\AA}$ relation</td>
<td>0.2</td>
</tr>
<tr>
<td>Total number of models</td>
<td>24 948 000 ($3 118 500$ per redshift)</td>
</tr>
</tbody>
</table>

Notes. For the definition of the various parameters, see Sect. 3.

EW of the H$\alpha$ absorption line. All AGNs with available D$_{n}$4000 also have available measurements for H$\alpha$. Therefore, 69/94 AGNs have measurements for both indices. The corresponding numbers for the galaxy sample are as follows: $\approx$82% of galaxies have a measurement of H$\alpha$ and $\approx$75% have a measurement for D$_{n}$4000. Approximately 75% (2176) of the sources in the reference catalogue have available measurements for both indices.

3. Impact of absorption lines on the SED fitting measurements

Star formation history parameters suffer from large degeneracies and are difficult to accurately constrain with any SED fitting algorithm (e.g., Ciesla et al. 2016; Chisholm et al. 2019). In this section, we examine if the inclusion of the H$\alpha$ and D$_{n}$4000 indices in the SED fitting process affects the reliability with which the algorithm estimates the SFH parameters, if it improves their calculations, and whether it affects the measurements of the (host) galaxy properties.

For this exercise, we use the CIGALE SED fitting algorithm (Boquien et al. 2019; Yang et al. 2020, 2022). CIGALE allows the inclusion of the X-ray flux in the fitting process and has the ability to also account for the extinction of the UV and optical emission in the poles of AGNs (Yang et al. 2020; Mountrichas et al. 2021b,a; Buat et al. 2021). CIGALE is able to combine both photometric data and spectral indices in the same fit.

Table 1 presents the templates and the values for the free parameters used in the fitting process. The galaxy component is modelled using a delayed SFH model with a function form $SFR \propto \alpha \times t \times \exp(-t/\tau)$. A star formation burst is included (Ciesla et al. 2017; Maler et al. 2018; Buat et al. 2019) as a constant ongoing period of star formation of 50 Myr. Stellar emission is modelled using the single stellar population templates of Bruzual & Charlot (2003) and is attenuated following the Charlot & Fall (2000) attenuation law. The emission of the dust heated by stars is modelled based on Dale et al. (2014), without any AGN contribution. The AGN emission is included using the SKIRTOR models of Stalevski et al. (2012, 2016).

We have extended CIGALE to compute the H$\alpha$ absorption line EW. To do so, we define three wavelength windows. We used the windows at the shortest and longest wavelengths to measure the continuum level of the absorption line. The EW is then computed by subtracting the mean level from the central window and integrating the spectrum. We fitted EWs to the observations similarly to broadband fluxes, passing the rest-frame EWs and the corresponding uncertainties to the input file in nm, along with fluxes in mJy.

3.1. Effect on galaxy properties

In this section, we examine the effect that the inclusion of the two indices in the SED fitting process has on the calculation of the SFH parameters and on the (host) galaxy properties. First,
we examine whether the parameter space used in the SED fitting, described in the previous section (see also Table 1) sufficiently covers the data space of the H\textsubscript{\alpha} and D\textsubscript{4000} indices. For this purpose, we used the models built by CIGALE prior to the fitting process. CIGALE creates models using the templates and parameter space and determines the full list of parameters for each model to be computed. Then, the spectrum is computed for each model, as well as its physical properties and passbands (for more details, see Sect. 4.2 in Boquien et al. 2019). In Fig. 3, we plot the EW of H\textsubscript{\alpha} against D\textsubscript{4000} for the models and the AGNs and sources in the reference catalogue. The data present lower H\textsubscript{\alpha} values compared to those produced by the models; however, taking into account the statistical uncertainties of the data values, we conclude that the parameter space we used for the SED fitting covers the data space well.

Figures 4 and 5 present the distributions of the three free SFH parameters (Table 1), with and without including the H\textsubscript{\alpha} absorption line and the D\textsubscript{4000} index in the SED fitting, for the sources in the galaxy reference catalogue and AGNs, respectively. The top panels in the two figures present the distributions of the stellar age in million years. When the two indices are not included in the fitting process, the distributions highly peak at the lowest stellar age value allowed by the parametric grid (see Table 1). This is at odds with the redshift distribution of the galaxies, presented in Fig. 1. Based on the redshift distributions, most of the sources in our sample lie at low(er) redshift (0.6–0.8) and thus we expect to have old(er) stellar populations. When the two indices are included in the fitting process, the distribution of stellar ages appears flatter and in better agreement with the redshift distribution. Figure 6 compares the mass-weighted stellar ages calculated by CIGALE, with and without using H\textsubscript{\alpha} and D\textsubscript{4000} in the fitting process. Again, the inclusion of the two indices in the SED fitting provides additional constraints on the stellar population and allows CIGALE to calculate, on average, more meaningful stellar ages, as the mass-weighted stellar age distributions are flatter and similar to the distribution of the age of the Universe.

The middle panels of Figs. 4 and 5 present the distributions of the e-folding time of the main stellar population in million years. When the SED fitting is done without using the information from H\textsubscript{\alpha} and D\textsubscript{4000}, for the majority of the galaxies the e-folding time has values of ≥500 Myr. The opposite trend is observed when H\textsubscript{\alpha} and D\textsubscript{4000} are included in the fitting process. In this case, most of the galaxies have short e-folding times (<200 Myr). Bottom panel: mass fraction of the late burst population. Inclusion of the two indices does not significantly affect the calculated values of this parameter.
trend is observed when Hδ and D_4000 are included in the fitting process. In this case, most of the galaxies have short e-folding times (<200 Myr).

The bottom panels of Figs. 4 and 5 present the mass fraction of the late burst population. In this case, inclusion of the two indices does not significantly affect the calculated values of this parameter. This could be due to the (fixed) value of the age of the burst (see Table 1), which is too short (50 Myr) to be detected by the H_δ line. Therefore, the inclusion of this line in the fitting process does not provide an additional constraint for the calculation of the mass fraction of the late stellar burst. If we leave the age of the burst as a free parameter, mock analysis shows that the parameter cannot be reliably constrained by the algorithm.

Figure 7 shows an example of an SED for an AGN, when the spectral indices are included in the fitting process (top panel) and when they are not included (bottom panel). This figure illustrates the effect that the inclusion of the H_δ and D_4000 measurements has on the various emission components. When the two indices are not included in the fit, CIGALE measurements for D_4000 and the EW of H_δ are 1.58 and 0.16 Å, respectively. The corresponding values from the LEGA-C catalogue are 1.63 and 0.03 Å. When we fit the sources including the two indices, CIGALE’s calculations for D_4000 and H_δ are 1.69 and 0.05 Å, respectively. The mass-weighted stellar age is 4512 Myr and 3087 Myr, for the runs with and without the indices, respectively. The redshift of the source is 0.86 (age of the Universe is ~6500 Myr).

Next, we examine the effect that the inclusion of H_δ and D_4000 indices in the SED fitting may have on the calculation of the galaxy properties and specifically on the stellar mass, M_*, and star formation rate, SFR.

The top panel of Fig. 8 presents a comparison of the SFR measurements of CIGALE with and without the two indices in the SED fitting, for sources in the reference catalogue. Based on our results, the inclusion of H_δ and D_4000 does not significantly affect the SFR calculations. This is expected, since the burst stellar mass fraction values are not affected by the inclusion of the two indices (bottom panel of Fig. 4). However, in the case of stellar mass measurements (bottom panel of Fig. 8), we observe a systematic increase (by ~0.2 dex) of the M_* values when H_δ and D_4000 are included in the fitting process. This is more evident for systems that host young stellar populations (D_4000 < 1.5). Similar trends are observed for the AGN population (Fig. 9).

In the LEGA-C catalogue there are measurements available for more lines. In a future paper, we will explore the effect of adding more spectroscopic information alongside the photometric data and in relation to the photometric coverage.

3.2. Reliability of H_δ and D_4000 calculations from CIGALE

In this section, we examine how accurately CIGALE can recover the H_δ and D_4000 indices. For that purpose, we used the 69 AGNs and the 2,176 sources from the galaxy reference catalogue that have measurements available for both indices in the LEGA-C catalogue and ran CIGALE without including the two indices in the fitting process. We then compared CIGALE’s calculations for H_δ and D_4000 with those from the LEGA-C catalogue.

Figure 10 compares the D_4000 measurements of CIGALE to the data values, for the AGNs (top panel) and the galaxies in the reference catalogue (bottom panel). The index is not included as input in the fitting process. For both populations, the algorithm successfully recovers the value of D_4000. As discussed earlier, this could be due to the extended wavelength coverage of the dataset. The dashed lines in the two panels present the best linear fits. In the case of AGNs, the fit is given by the following expression: D_4000[CIGALE] = 0.7903 × D_4000[dataset] + 0.3236. For the reference sample a similar best linear fit is found: D_4000[CIGALE] = 0.7567 × D_4000[dataset] + 0.3230.

In Fig. 11, we present the comparison of CIGALE’s measurements with the data values for H_δ. In this case, we notice that, both for AGNs and galaxies, the algorithm tends to overestimate the true values, in particular for EWs higher than ~0.1 nm. This shows that CIGALE cannot predict H_δ using the available photometric coverage. Thus, the inclusion of the line brings additional information to the fitting process and helps the algorithm to break the degeneracies among the SFH parameters to converge to a solution that would not be necessarily selected.
Figure 6. Comparison of mass-weighted stellar ages (in million years) calculated by CIGALE, with (blue shaded contours) and without (black line contours) using H\textalpha{} and D\textalpha{}4000 in the fitting process, for sources in the reference catalogue (left panel) and AGNs (right panel). The addition of the two indices in the SED fitting provides additional constraints on the stellar population and allows CIGALE to calculate, on average, more meaningful stellar ages, in the sense that the distributions of the mass-weighted stellar age are flatter and better resemble the distribution of the age of the Universe, as compared to the highly peaked (at low values) and mass-weighted stellar age distributions without the spectral indices.

otherwise. In the analysis presented in the next sections, we used the $M_*$ of the AGNs and sources in the reference catalogue estimated by the CIGALE runs that include the two spectral indices in the SED fitting process.

4. Comparison of H\textalpha{} and D\alpha{}4000 between AGN and non-AGN systems

In this section, we compare the values of the H\textalpha{} and D\alpha{}4000 indices between the AGNs and sources in the reference catalogue. First, we use the full datasets for both populations, as described in Sects. 2 and 3.2. Then, we restrict the comparison to star forming systems by excluding quiescent (Q) sources. Finally, we split AGNs and galaxies based on their morphology and compactness.

4.1. Comparison between the full AGN and reference catalogues

Previous studies that compared the SFRs of X-ray AGNs with those of star forming galaxies found that low-to-intermediate X-ray luminosity AGNs, as those used in this study, have an SFR that is lower than or consistent with that of main-sequence star forming galaxies (e.g., Hatcher et al. 2021; Mountrichas et al. 2022a,b). H\textalpha{} and D\alpha{}4000 indices have been used in the literature to trace recent (a few hundred million years) star formation bursts in galaxies and as proxies of the age of stellar populations (e.g., Worthey & Ottaviani 1997; Kauffmann et al. 2003c; Wu et al. 2018; Sobral et al. 2022). Thus, in this section we compare the two indices between X-ray AGNs and sources in the reference galaxy catalogue.

To facilitate a fair comparison, we need to account for the redshift and stellar mass of the sources in the AGN and reference catalogues. As presented in Fig. 1, AGNs and galaxies span a narrow redshift range, and most importantly they have very similar redshift distributions. Figure 12 presents the stellar mass distributions of AGNs and sources in the galaxy reference sample. We also plot the $M_*$ distribution of the AGN sample used in Mountrichas et al. (2022b; see next section). As expected, AGNs tend to reside in more massive galaxies (e.g., Yang et al. 2017, 2018). To account for this difference, a weight is assigned to each source. This weight is calculated by measuring the joint stellar mass distributions of the two populations (i.e. we add the number of AGNs and galaxies in each $M_*$ bin, in bins of 0.1 dex) and then normalise the $M_*$ distributions by the total number of sources in each bin (e.g., Mountrichas et al. 2019, 2021b; Masoura et al. 2021; Buat et al. 2021). We made use of these weights in all distributions presented in the remainder of this work.

Figure 13 presents H\textalpha{} versus D\alpha{}4000 for AGNs and sources in the reference catalogue. Sources located in the upper left corner of the H\textalpha{}-D\alpha{}4000 space (high H\textalpha{} and low D\alpha{}4000 values) have predominantly young stellar populations, whereas sources located in the bottom right panel have old stellar populations. We note that the two populations have H\textalpha{} and D\alpha{}4000 with similar uncertainties (see Sect. 2.1). We find that $\sim$10% of the AGNs are located in the bottom left corner of the H\textalpha{}-D\alpha{}4000 space, which suggests that although these systems have not undergone a (recent) star formation burst, their stellar population is young. CIGALE’s measurements also corroborate this ($f_{\text{burst}} < 0.002$ and mean stellar age $\sim$3200 Myr). An examination of the optical spectra of these AGNs does not show the presence of broad emission lines that could contaminate the two indices. We also plot the weighted distributions, that is taking into account the different stellar mass distributions of the two populations. The distribution of D\alpha{}4000 for sources in the reference catalogue appears double peaked, with one peak at D\alpha{}4000 $\sim$ 1.2 and a second peak at D\alpha{}4000 $\sim$ 1.8. On the other hand, AGNs present a peak at D\alpha{}4000 $\sim$ 1.4 and a long tail that extends out to D\alpha{}4000 $\sim$ 1.8. Based on the SED fitting calculations presented in the previous section, we estimate the stellar ages

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that correspond to these $D_n4000$ values. $D_n4000 \sim 1.2$ roughly corresponds to 3200 Myr, while $D_n4000 \sim 1.8$ corresponds to $\sim 4700$ Myr. For the AGNs, $D_n4000 \sim 1.4$ corresponds to $\sim 3800$ Myr. A Kolmogorov-Smirnov (KS) test gives a $p$-value of 0.014. This means that the two populations have different $D_n$ values at a statistically significant level that is marginally higher than 2$\sigma$ ($2\sigma$, which corresponds to a $p$-value of 0.05, is the minimum threshold to consider two quantities as different; e.g., Zou et al. 2019). KS tests are more suitable in finding shifts in probability distributions and present the highest sensitivity around the median value. However, they are less sensitive to the differences at the tails of the distributions, which seem to exist in our case. For that reason, we also applied a Kuiper test, which is better at finding spreads that affect the tails of the distributions. The latter gives $p$-value $= 0.002$, which means the two populations have different $D_n$4000 distributions at a statistically significant level of $\sim 3\sigma$. Regarding the distributions of $H_\alpha$, we notice that AGNs present a peak at $H_\alpha \sim 3$ (stellar ages $\sim 4.0$ Gyr), whereas sources in the reference catalogue have a flatter distribution. A KS test gives a $p$-value $= 0.0027$, and a Kuiper test yields a $p$-value $= 8.59 \times 10^{-9}$, indicating a statistically significant difference in the $H_\alpha$ values of AGN and non-AGN systems. Hernán-Caballero et al. (2014) used 53 X-ray-selected AGNs at $0.34 < z < 1.07$ from the Survey for High-$z$ Absorption Red and Dead Sources (SHARDS) and found a significant excess of AGN host galaxies with $D_n4000 \sim 1.4$. Our results are in agreement with theirs.

Overall, based on our analysis, low-to-moderate luminosity AGNs tend to have intermediate $D_n4000$ values, whereas sources in the galaxy reference catalogue prefer low and high $D_n4000$. Moreover, a significant fraction of AGNs (27/69 $\approx 40\%$) have $H_\alpha \sim 3$, while non-AGN systems present a flat $H_\alpha$ distribution. These differences are statistically significant, as indicated by the Kuiper tests.

4.2. Spectral indices and position on the main sequence

In this section, we classify the X-ray AGNs and galaxies in the reference catalogue into star forming (SF), starburst (SB), and quiescent (Q) systems. We also examine how they are distributed in the $H_\alpha$-$D_n4000$ space.

Mountrichas et al. (2022a,b) classified galaxies as quiescent using their sSFR. Specifically, to identify such systems, they
used the location of the second lower peak presented in the sSFR (sSFR = \( \frac{\dot{M}_{\text{SFR}}}{M_{\odot}} \)) distributions (Sect. 3.5 of Mountrichas et al. 2022b). We note that in Mountrichas et al. (2022b), the SFR and \( M_* \) of the sources were calculated using CIGALE with the same templates and parameter values as those used in this study. Using this criterion, we find 42 (~60%) AGNs hosted by Q systems in our sample. A similar fraction of Q is found among galaxies in the reference catalogue (~50%). SB systems are identified as those galaxies that have sSFRs 0.6 dex higher than the mean value of the Mountrichas et al. (2022b) sample at the redshift range of our dataset (e.g., Rodighiero et al. 2015). ~8% and ~10% of the AGN and galaxies in the reference catalogue, respectively, are SBs. The remainder of the sources that are not Q or SBs are considered SF.

The fraction of Q systems appears high compared to the ~25% found in Mountrichas et al. (2022b) at a similar redshift range (see their Table 2). Figure 12 presents the \( M_* \) distribution of the X-ray AGNs used in Mountrichas et al. (2022b). We notice that our X-ray sources, which are a subset of the sources used in Mountrichas et al. (2022b), include the most massive systems of those among the Mountrichas et al. (2022b) sample. This is expected taking into account the selection function of the LEGA-C survey (see Fig. A.1 in van der Wel et al. 2021). This also explains the high fraction of quiescent sources among galaxies in the reference catalogue (~50%) are identified as quiescent.

In Fig. 14, we plot the distribution of the three (host) galaxy classifications in the \( H_\alpha - D_4000 \) space. Quiescent galaxies from the reference catalogue are well separated from the SF and SB non-AGN systems. SB galaxies present the lowest \( D_4000 \) and the highest \( H_\alpha \) values. In the case of AGNs, SB systems are located in a similar locus with the SB non-AGN galaxies. This is also true for the SF AGNs that reside in the same \( H_\alpha - D_4000 \) space with the SF galaxies from the reference sample. In the case of Q AGNs, there is a small fraction (~5%) that presents high \( H_\alpha \) and low \( D_4000 \); that is, they are located in the \( H_\alpha - D_4000 \) space occupied by SB systems. A similar fraction of Q AGNs are also in the \( H_\alpha - D_4000 \) area where SF galaxies are found. However, the vast majority (>80%) of Q AGNs are in the bottom right corner of the plot, where systems with old stellar populations are located.

4.3. Exclusion of quiescent systems

In Mountrichas et al. (2022a,b), the lower SFR of AGN compared to non-AGN systems was found after excluding quiescent systems from their datasets. To examine whether our results from the comparison of the two indices (\( H_\alpha, \ D_4000 \)) for the two
populations corroborate their findings, we excluded sources that are identified as quiescent from our samples (see previous section).

Figure 15 presents $H\delta$ versus $D_n4000$ for AGNs and sources in the reference catalogue, after excluding quiescent systems from both datasets. We notice that for both populations the vast majority of sources (100% of AGNs and 98% of sources in the reference galaxy catalogue) with high $D_n4000$ values ($D_n4000 > 1.6$, which corresponds to about $\sim 4.2$ Gyr) have been excluded. There are many AGN ($\sim 33\%$) compared to non-AGN systems ($\sim 7\%$) located within the parameter space defined within $1.2 < D_n4000 < 1.5$ and $H\delta < 3$, which is where sources with old stellar populations are located. Regarding the $D_n4000$ index, both populations peak at similar values ($D_n4000 \sim 1.3$), but sources in the reference catalogue present a wider distribution, as they extend to lower ($D_n4000 < 1.2$) and higher ($D_n4000 > 1.55$) values compared to the AGNs ($p$-value $= 0.008$ from Kuiper test). In the case of the $H\delta$ distributions, the exclusion of quiescent systems results in the exclusion of the majority of sources with $H\delta < 2$. However, there is still a significant fraction of AGNs with $H\delta \sim 2$−4. On the other side of the distribution, $\sim 20\%$ of the galaxies have $H\delta > 6$, whereas the corresponding fraction of AGNs is $\sim 5\%$. Although, these differences do not appear to be statistically significant ($p$-value $= 0.08$, $< 2\sigma$, based on Kuiper test), they suggest that AGNs that reside in star forming (non-quiescent) galaxies tend to have lower $H\delta$ values on average compared to their non-AGN star forming counterparts.

We also identified and excluded sources as quiescent using their $D_n4000$ and $H\delta$ values. Specifically, we classified systems that have $D_n4000 > 1.55$ and/or $EW(H\delta) < 2$ Å (Wu et al. 2018) as quiescent. This analysis is presented in Appendix A. The results and conclusions are similar to those presented above.

Based on our analysis, when quiescent systems are excluded, low-to-moderate-luminosity AGNs tend to live in systems with older stellar populations and are less likely to have experienced a recent burst of their star formation compared to their
For both populations, the vast majority of sources with high Dn using the sSFR distributions of the sources (see text for more details). Same format as in Fig. 13, but excluding quiescent systems Fig. 15.

Fig. 14. Location of SB, SF, and Q AGN (circles) and galaxies in the reference catalogue (contours) in the Hδ-Dn4000 space. The distribution of Hδ and Dn4000 for the AGN population is also presented.

non-AGN counterparts. The results are not sensitive to the method applied to select quiescent systems. This could explain the results presented in Mountrichas et al. (2022a,b), where they found that low-to-moderate-luminosity (non-quiescent) AGNs have slightly (by ~20%) lower SFRs compared to SF galaxies.

Hδ values (Dn4000 > 1.6) has been excluded. In the case of the Hδ distributions, the exclusion of quiescent systems results in the exclusion of the majority of sources with Hδ < 2. However, there is still a significant fraction of AGNs with Hδ ~ 2–4. On the other side of the distribution, ~20% of the galaxies have Hδ > 6, whereas the corresponding fraction of AGNs is ~5%.

Fig. 15. Same format as in Fig. 13, but excluding quiescent systems using the sSFR distributions of the sources (see text for more details). For both populations, the vast majority of sources with high Dn4000 values (Dn4000 > 1.6) has been excluded. In the case of the Hδ distributions, the exclusion of quiescent systems results in the exclusion of the majority of sources with Hδ < 2. However, there is still a significant fraction of AGNs with Hδ ~ 2–4. On the other side of the distribution, ~20% of the galaxies have Hδ > 6, whereas the corresponding fraction of AGNs is ~5%.

4.4. The role of (host-)galaxy shape

Yang et al. (2019) used a sample from the five CANDELS fields Grogin et al. 2011; Koekemoer et al. 2011 and found that the SMBH accretion rate (BHAR) correlates more strongly with SFRs than with M∗, for bulge-dominated (BD) systems. The term BD refers to galaxies that only display a significant spheroidal component, without obvious disc-like or irregular components (for more details, see Sect. 2.3 in Yang et al. 2019). Ni et al. (2021) used sources from the COSMOS field and found that for star forming BD and non-BD systems, BHAR correlates more with Σ1 than with SFR or M∗, where Σ1 measures the mass-to-size ratio in the central 1 kpc of galaxies and is used as a proxy of a galaxy compactness.

In this section, we use the catalogue presented in Ni et al. (2021) and cross-correlate it with our AGN and galaxy reference catalogues to add information about the morphology and compactness of our systems. The morphological classification was done using a deep-learning-based method to separate sources into BD and non-BD galaxies (for more information, see Appendix C in Ni et al. 2021). Σ1 has been measured by fitting sources with a single-component Sérsic profile and assuming a constant M∗-to-light ratio throughout the galaxy (for a detailed description, see Sect. 2.2 in Ni et al. 2021). We note that type 1 sources have been removed from the Ni et al. (2021) catalogue, since they can potentially affect host galaxy morphological measurements (see their Sect. 2.4).

From the 69 AGNs and 2176 sources in the reference catalogue used in our analysis above, 57 and 1782, respectively, are included in the Ni et al. (2021) dataset. Out of the 57 AGNs, 16 (28%) are classified as BD, and a similar fraction is found among galaxies in the reference catalogue (459 sources ~ 25%).
AGNs and galaxies. An immediate difference to notice is that AGNs do not have $\Sigma_1$ values lower than 9.0, whereas sources in the reference catalogue go down to 7.5. This implies that AGNs reside in more compact systems compared to non-AGNs. Both populations present an increase of $D_n4000$ and a decrease of $H_\delta$ with $\Sigma_1$, at $\Sigma_1 > 9.5$. Interestingly, this $\Sigma_1$ value is similar to the median $\Sigma_1$ values of the two samples (9.8 for the AGNs and 9.6 for the galaxies). For both populations, we find that the vast majority (95%) of BD systems have $\Sigma_1 > 9.5$.

Based on our results, the morphology of a galaxy seems to affect the stellar population of non-AGN systems more compared to AGNs, since galaxies that host AGNs appear to have stellar populations with similar ages and are equally likely to have experienced a recent burst, regardless of their morphological type. BD AGNs tend to have younger stellar populations compared to BD non-AGN systems. On the other hand, non-BD AGNs have, on average, older stellar populations compared to non-BD sources in the reference catalogue. Finally, AGNs prefer more compact systems compared to non-AGNs, based on the mass-to-size ratio.

5. Summary and conclusions

We used 69 low-to-moderate $L_X$ ($L_{X,2-10keV} \sim 10^{42.5-44}$ erg s$^{-1}$) X-ray AGNs from the UltraVISTA region of the COSMOS-Legacy field that are also included in the LEGA-C catalogue. The latter provides measurements on absorption-line indices, among others. We also constructed a galaxy reference catalogue that consists of 2176 sources. The two populations have the same photometric coverage and lie within $0.6 < z < 1.3$. We made use of two spectral indices provided by the LEGA-C catalogue, namely the $D_n4000$ and the $H_\delta$, that are sensitive to stellar ages. $D_n4000$ increases monotonically with time, while the peak strength of $H_\delta$ depends on whether the SFR varies rapidly or changes smoothly.

The purpose of this work is to examine if the inclusion of the two indices provides additional constraints on the SED fitting process and thus affects the (host) galaxy properties. Moreover, we compare the values of the two indices between AGN and non-AGN systems (reference catalogue) to extract information regarding their stellar populations.

To examine if the inclusion of $D_n4000$ and $H_\delta$ affects the SFH parameters and important (host) galaxy properties (SFR, $M_*$), we used the CIGALE SED fitting code. Our analysis revealed that adding the two indices to the fitting process allows CIGALE to better constrain the stellar ages and the e-folding time of the stellar population. We also found an increase of the $M_*$ measurements by $\sim$0.2 dex that is more evident for systems that host young stellar populations ($D_n4000 < 1.5$). The results are similar for AGNs and sources in the reference catalogue. We found that these changes should mostly be attributed to the addition of the $H_\delta$ line rather than the $D_n4000$ index. The stability we found on global SFH parameters (SFR, $M_*$) is attributed to the very good photometric coverage of our sample. In a future work, we will examine the effect of adding more spectroscopic information in the SED fitting and in relation to the photometric coverage.

We then compared the $D_n4000$ and $H_\delta$ for AGNs and sources in the reference catalogue. The two populations have similar redshift distributions; therefore, for the comparison we accounted only for their different $M_*$, which we did by assigning weights to the sources in the two datasets. Our analysis reveals that AGNs tend to reside in systems with intermediate stellar ages ($D_n4000 \sim 1.4$), whereas sources in the reference catalogue...
presented a double-peaked $D_n4000$ distribution. The latter also has a flat $H_\alpha$ distribution, while an AGN peaks at $H_\beta \sim 3\,\AA$. These differences are statistically significant ($p$-values = 0.002 and $8.59 \times 10^{-9}$, for $D_n4000$ and $H_\beta$, respectively).

When we excluded quiescent systems from both populations, we found that the low-to-moderate X-ray AGNs used in our analysis tend to live in systems with older stellar populations (higher $D_n4000$ values) and are less likely to have experienced a recent burst (lower $H_\alpha$ values) compared to galaxies in the reference catalogue. This is in agreement with the results presented in Mountrichas et al. (2022a,b), where they found that AGNs with similar luminosities to those used in this work have lower SFRs compared to SF galaxies.

We also compared the two indices for AGNs and galaxies with different morphologies (BD and non-BD), as well as based on their mass-to-size ratio ($\Sigma$) with di (similar luminosities to those used in this work have lower SFRs). Di, on the other hand, non-BD AGNs have, on average, older stellar populations (lower $D_n4000$ values) compared to non-BD sources in the reference catalogue. Based on our analysis, the morphology of a galaxy seems to affect the stellar populations of non-AGN systems more than those of AGNs, since galaxies that host AGNs appear to have stellar populations with similar ages and are almost equally likely to have experienced a recent burst, regardless of their morphological type. Furthermore, AGNs prefer more compact systems compared to non-AGNs, based on the mass-to-size ratio.

Our work shows that low-to-moderate X-ray luminosity AGNs and non-AGN galaxies are systems that, on average, have different stellar ages and different likelihoods of having undergone a recent SF. Different trends are also found for the two populations based on the shape of the (host) galaxy.

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References

Appendix A: Exclusion of quiescent systems based on their $D_{n4000}$ and $H_{\delta}$ values

Wu et al. (2018) used galaxies from the LEGA-C dataset and examined their stellar ages and SFH histories using $D_{n4000}$ and $H_{\delta}$. In their analysis, they identified quiescent systems utilising the two indices. Specifically, they classify systems that have $D_{n4000} > 1.55$ and/or $EW(H_{\delta}) < 2$ Å as quiescent. We applied their criteria to our AGNs and reference catalogue to check whether the results presented above are sensitive to the choice of selecting quiescent systems. Based on these criteria, there are 51 non-quiescent AGNs in the X-ray sample and 1401 non-quiescent sources in the galaxy reference catalogue. We then compare the $D_{n4000}$ and $H_{\delta}$ distributions of the two populations in Fig. A.1. The results and conclusions are similar to those presented in Sect. 4.3, where we identify quiescent systems based on their sSFRs. Specifically, non-quiescent AGNs present a large tail that extends to high $D_{n4000}$ values compared to non-quiescent systems in the reference catalogue (top panel of Fig. A.1). The $H_{\delta}$ distributions of the two populations also appear different (bottom panel of Fig. A.1), with AGNs peaking at $H_{\delta} = 2–3$ Å and sources in the reference catalogue at $H_{\delta} = 5–6$ Å.

Fig. A.1. Comparison of the distributions of $D_{n4000}$ and $H_{\delta}$ (in Å) for galaxies in the reference catalogue and AGN, when excluding systems as quiescent systems based on $D_{n4000}$ and $H_{\delta}$ (see text for more details). Sources in the reference catalogue tend to have younger stellar population (smaller $D_{n4000}$) and are more likely to have undergone a recent star formation burst (higher $H_{\delta}$), compared to AGN.