

Morphological and Photometric Properties of Active and Non-Active Galaxies in the Green Valley

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Abstract

Context: The differences in properties of active and non-active galaxies in the green valley have been studied in the quest of finding the driving mechanism behind the evolutionary transition from the blue cloud to the red sequence galaxies.

Aims: Using COSMOS data, as one of the deepest surveys, and X-ray detected active galaxies, we studied their properties in the green valley, and established the differences in comparison with the non-active ones.

Methods: Green valley galaxies were selected using the U-B colour criteria of $0.8 \leq U - B \leq 1.2$. We then studied different properties between the two samples such as their morphologies, colours, stellar masses, photometric redshift distributions, and sizes, and performed a statistical comparative study.

Results: We found that in the green valley, active galaxies are dominated by earlier morphological types (elliptical and lenticular galaxies), are more massive, have higher photometric redshifts and redder colours than non-active galaxies.

Conclusions: Our findings suggest that the non-active galaxies in the green valley are different from the active ones, with active galaxies being more evolved.

Keywords: galaxies: active, galaxies: fundamental parameters, galaxies: structure, X-rays: galaxies

1. Introduction

Active galaxies are galaxies that have an Active Galactic Nucleus (AGN) in their centre, which shows a much higher than normal luminosity over a part or over all of the electromagnetic spectrum, especially in X-rays, infrared, and radio. The standard model of AGN suggests that the radiation is a result of accretion of mass by a supermassive black hole at the centre of its host galaxy. AGN are some of the most luminous observed sources, and therefore extremely important for studying the most distant galaxies and the universe in its

early stage.

Different questions that relate active and non-active galaxies still remain unanswered. Some of them include what is: (1) the effect of AGN on their host galaxy and vice-versa, (2) the origin of the accretion material, (3) the triggering mechanism that converts a normal galaxy into an active one, or (4) the duration of the active phase. A careful selection of samples of active and non-active galaxies, and studying of their properties under the same conditions, could lead to our better understanding on how one galaxy initiate its active phase.

Deep X-ray data provide some of the most complete and unbiased samples of AGN (Mushotzky, 2004; Brandt and Hasinger, 2005). On the other side, morphology and colours are two key parameters used to study the properties of AGN host galaxies, their connection with AGN, and their evolution. It is now well-known from previous studies of colour-magnitude relations that, in general, normal galaxies may be located in the 'red sequence', populated by massive, bulge-dominated galaxies with older, passively evolving stellar populations, or in the 'blue cloud', populated by blue, star-forming galaxies of small and intermediate masses (e.g., Baldry et al., 2004; Weiner et al., 2005; Cirasuolo et al., 2005; Schawinski et al., 2014). In most of the studies, X-ray detected AGN lie predominantly in the 'green valley' of the colour-magnitude diagrams, a transition region located between the red sequence and the blue cloud (e.g., Barger et al., 2003; Sánchez et al., 2004; Nandra et al., 2007; Georgakakis et al., 2008; Silverman et al., 2008; Treister et al., 2009; Pović et al., 2012). This has been considered as one of the pieces of evidence of a connection between AGN and galaxy evolution, suggesting that the AGN feedback mechanism may play an important role in quenching star formation, moving the galaxies from the blue cloud to the red-sequence (e.g., Springel et al., 2005; Schawinski et al., 2006; Hasinger, 2008).

However, the real conditions of sources in the green valley and the connection between the normal and active galaxies are still poorly known. In this work, we went deeper in analysing the green valley region, studying the morphological properties, sizes, stellar masses, and colours of its normal and X-ray detected active galaxies, trying to see what are the main similarities and differences between them. For this purpose we used the data from the Cosmic Evolution Survey (COSMOS), having the Hubble Space Telescope (HST) data available in the optical range, ideal for our morphological studies up to higher

redshifts ($z \leq 1$), and having also the X-ray data available for AGN selection.

The outline of the paper is as follows: In section 2 we present the data used in this study. In section 3 we describe different parameters to be used in the analysis. In section 4 we define the sample of active and non-active galaxies in the green valley, and we perform statistical comparative analysis of their properties in order to detect whether the two samples have similar or distinct evolutionary tracks. Finally we discuss and summarise the results in section 6. Throughout the paper we assume a cosmology with $H_0=70$ km/s/Mpc, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Data

The general sample of galaxies was obtained from the COSMOS deep field survey. COSMOS is a 2 square degree equatorial field survey centred at RA (J2000) = 10:00:28.6 and DEC (J2000) = +02:12:21.0 (Scoville et al., 2007). It presents one of the largest and deepest data sets across the entire electromagnetic spectrum, providing the information of about 2 million sources with available high resolution ACS images up to a depth of IAB ≤ 28 (within 5σ), and 50% completeness for sources $0.5''$ in diameter at IAB = 26.0 (Koekemoer et al., 2007). It is a multiwavelength survey, observed with other telescopes, both space-based (e.g., Spitzer, GALEX, XMM and Chandra) and a number of large ground-based ones (e.g., Subaru, VLA, ESO-VLT, UKIRT, NOAO, and CFHT). It was initially designed to probe, among others, the evolution of galaxies, star formation processes, AGN phenomenology, and large-scale structure over the redshift range $0.5 \leq z \leq 3$.

In the optical, the ACS data were supplemented by observations from the Suprime-Cam on the 8.2 m Subaru Telescope on Mauna Kea to provide the B-, V-, r', i', and z'-band photometry. In addition, these data were complemented with further deep imaging in U and i bands from the 3.6 meter optical/infrared Canada-France-Hawaii Telescope (CFHT) in Hawaii and in K band from KPNO/CTIO, UH88, and UKIRT.

In X-rays, COSMOS was observed with XMM-Newton and Chandra telescopes. With XMM-Newton the average exposure time was ~ 25 ksec. X-ray source catalogue comprises 1390 different point-like X-ray sources detected over an area of ~ 2 deg² (Hasinger et al., 2007; Cappelluti et al., 2007). In this work we used a catalogue of optical counterparts provided by Brusa et al. (2007), with 695 X-ray sources

detected in the first 1.3 deg² of the COSMOS XMM-Newton survey, down to limiting fluxes of 10⁻¹⁵ and $\sim 5 \times 10^{-15}$ erg s⁻¹ cm⁻² in the 0.5 - 2.0 keV and 2.0 -10.0 keV bands, respectively. The Chandra COSMOS Survey, with a total exposure time of 1.8 Msec, observed the central 0.9 deg² of the COSMOS field down to limiting fluxes of 1.9×10^{-16} erg s⁻¹ cm⁻² and 7.3×10^{-16} erg s⁻¹ cm⁻² in the 0.5 - 2.0 keV and 2.0 - 10.0 keV bands, respectively, reaching four times fainter fluxes than XMM-COSMOS. In this work we use the catalogue of Civano et al. (2012) with 1761 X-ray point sources with optical counterparts.

2.1. Sample selection

Since morphological properties of active and non-active galaxies are crucial for our study, the catalogue where the morphological classification of galaxies is available is our starting point. For this purpose we used the catalogue of Tasca et al. (2011, see section 3 for more information), that provides the morphological classification for 237,912 galaxies with magnitudes $I \leq 23$. This catalogue is based on the Leauthaud et al. (2007) ACS photometric catalogue which covers a continuous area of 1.64 deg². To obtain a sample of active galaxies, we cross-matched the Tasca et al. (2011) catalogue with the X-ray ones with available optical counterparts (Civano et al., 2012; Brusa et al., 2007). Since Chandra data are deeper in comparison to XMM-Newton, as pointed above, we combined the two X-ray catalogues by maintaining the sources from Chandra and adding the missing ones detected with XMM-Newton. To select AGN we used the ratio between the X-ray flux on the hard band (2 - 10 ,keV) and optical I band:

$$\log F_X / F_O = \log F_X + F_O / 2.5 + 5.352,$$

and we selected as AGN all sources with $-1 \leq \log F_X / F_O \leq 1$, the condition tested in other works (Alexander et al., 2001; Bauer et al., 2004; Bundy et al., 2007; Trump et al., 2009). Finally, we selected in total a sample of 1,472 AGN sources.

To select a sample of non-active galaxies we excluded all AGN selected sources from the initial Tasca et al. (2011) catalogue. We also excluded sources classified as stars in the Leauthaud et al. (2007) catalogue. In total we selected a sample of 22,154 non-active galaxies.

3. Description of available parameters

In this section we describe the parameters that we used to compare a sample of active and non-active galaxies in the green valley.

- Photometric redshifts.

We used two catalogues of photometric redshifts available in the COSMOS survey. For non-active galaxies we used Ilbert et al. (2009) catalogue, where the photometric redshifts were measured using the Le Phare code (Arnouts et al., 1999; Ilbert et al., 2006), based on χ^2 template-fitting procedure. They used the photometric information from 30 broad, intermediate, and narrowband filters from UV, optical, NIR and MIR bands, obtaining an accuracy of $\sigma \delta z / (1 + z) = 0.007$ for galaxies brighter than $i = 22.5$. For a sample of AGN we used the catalogue of Salvato et al. (2011), whose careful measurements were carried out for all Chandra and XMM-Newton detected X-ray sources, using again Le Phare code, including a set of AGN templates, and obtaining the accuracy of $\delta z / (1 + z) = 0.015$.

- Absolute magnitudes, rest-frame colours, and stellar masses.

We measured the K-corrections for both, active and non-active samples, by means of the IDL routine KCORRECT (Blanton and Roweis, 2007). We used the photometric information from 10 COSMOS optical and NIR filters and implemented their response files into the code, fitting the SEDs with about 500 available spectral templates (see Blanton and Roweis, 2007, for more information about the templates and SED fitting). We then obtained the K-corrections for all used photometric bands, absolute magnitudes, rest-frame colours, and luminosities of all green valley AGN and normal galaxies. Moreover, from the KCORRECT SED fits we obtained the stellar masses, using the Chabrier (2003) initial mass function.

- Morphological classification.

As already mentioned, morphological classification of galaxies was obtained from Tasca et al. (2011) catalogue. The catalogue is complete down to $i \leq 23.0$, and the morphological study was performed on HST/ACS images. Morphological types are estimated using three different automatic, non-parametric methods:

- Class_int: based on the concentration index, measuring a fraction of light contained in an inner 30% flux isophote, and asymmetry,

measuring the degree of symmetry of the galaxy (Abraham et al., 1996; Cassata et al., 2007; Tasca et al., 2011). Late-type galaxies (spirals and irregulars) have lower values of concentration, but higher values of asymmetry in comparison with the early-type galaxies.

- Class_linee: based on 5 morphological parameters, concentration and asymmetry in-dexes, as in previous case, and Gini index, smoothness (or clumpiness), and M_{20} moment of light. The Gini index is also a concentration parameter, presented as the cumulative distribution function of galaxy pixel values (Abraham et al., 2003). The smoothness, quantifies the degree of small scale structure (Conselice et al., 2000). Finally, M_{20} moment of light is the moment of the brightest 20% of the galaxy flux.
- Class_svm: based on 7 parameters and obtained through the galSVM code (Huertas-Company et al., 2008), adding the source ellipticity and the surface brightness in the classification in the comparison with the previous method.

In all three methods, galaxies were classified into three classes E/S0 ($class = 1$), spirals ($class = 2$), and irregulars ($class = 3$). We performed visual morphological identification of more than 300 galaxies to test each of the three methods and found that the deviation seems to be the lowest in the case of the class_int method. However in order to avoid the subjectivity using the visual methods, the 3 classifications found in the catalogue were used in our comparison (see the next section).

- Sizes.

To quantify the sizes of galaxies we used two different measurements. We extracted the half light radius from Tasca et al. (2011) catalogue. Moreover, we run SExtractor (Bertin and Arnouts, 1996) to obtain the flux radius for different amounts of light, from 5% up to 100%.

4. Analysis and Results

4.1. Selection of green valley galaxies

There have been many ways of defining the green valley galaxies, all being based on the bimodal distribution of galaxies when using different colours, e.g. U-B (Nandra et al., 2007), U-V (Moresco et al., 2010), NUV-r (Wyder et al., 2007), or NUV-r+ (Pan et al., 2013). In this work, green valley galaxies were selected using the U - B rest-frame colour, and criteria: $0.8 \leq U - B \leq 1.2$, as showed in Figure 1, where all galaxies

with $i \leq 23$ from the Leauthaud et al. (2007) catalogue are represented. The final sample of green valley galaxies contains 317 AGN and 13,877 normal galaxies, as showed in Table 1.

	Initial sample	Green valley $0.8 \leq U - B \leq 1.2$ and $i \leq 23$
AGN	1472	317
Normal galaxies	22154	13877

Table 1: Population of active and non-active galaxies in the initial sample and after the green valley selection.

4.2. Properties of green valley active and non-active galaxies

In this section we compared different properties described in section 3 between the samples of AGN and normal galaxies.

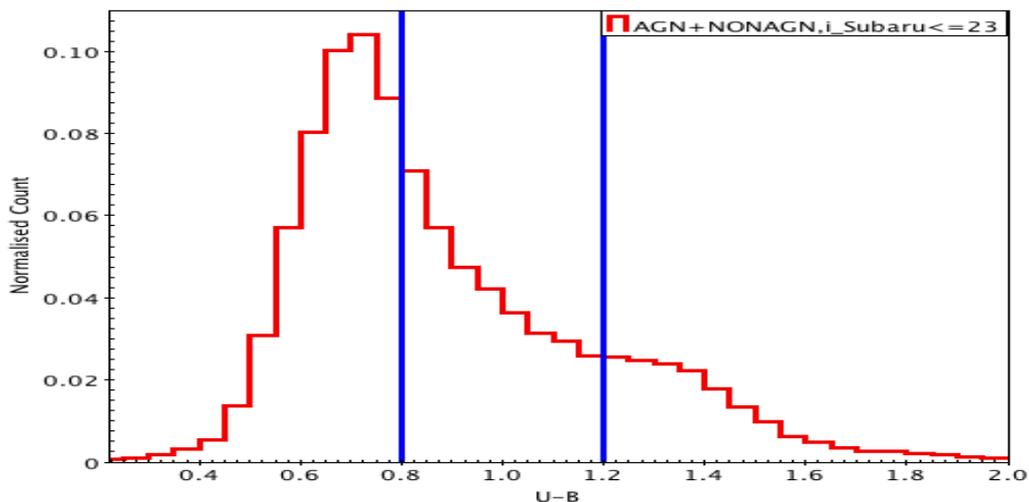


Figure 1: Normalised distribution of U-B colour of the total sample of COSMOS galaxies. Green valley is marked with blue vertical lines.

- Morphological properties.

We compared the morphologies of active and non-active galaxies. Figure 2 shows these comparisons for the three different classification methods, as described above. In general, in all three methods, early-types (E/S0) are dominated by AGN, while late-type galaxies (both spirals and irregulars) are dominated by non-active galaxies. Depending on the classification method used, 40 - 60% of AGN and 20 - 35% of non-active galaxies reside in early-types.

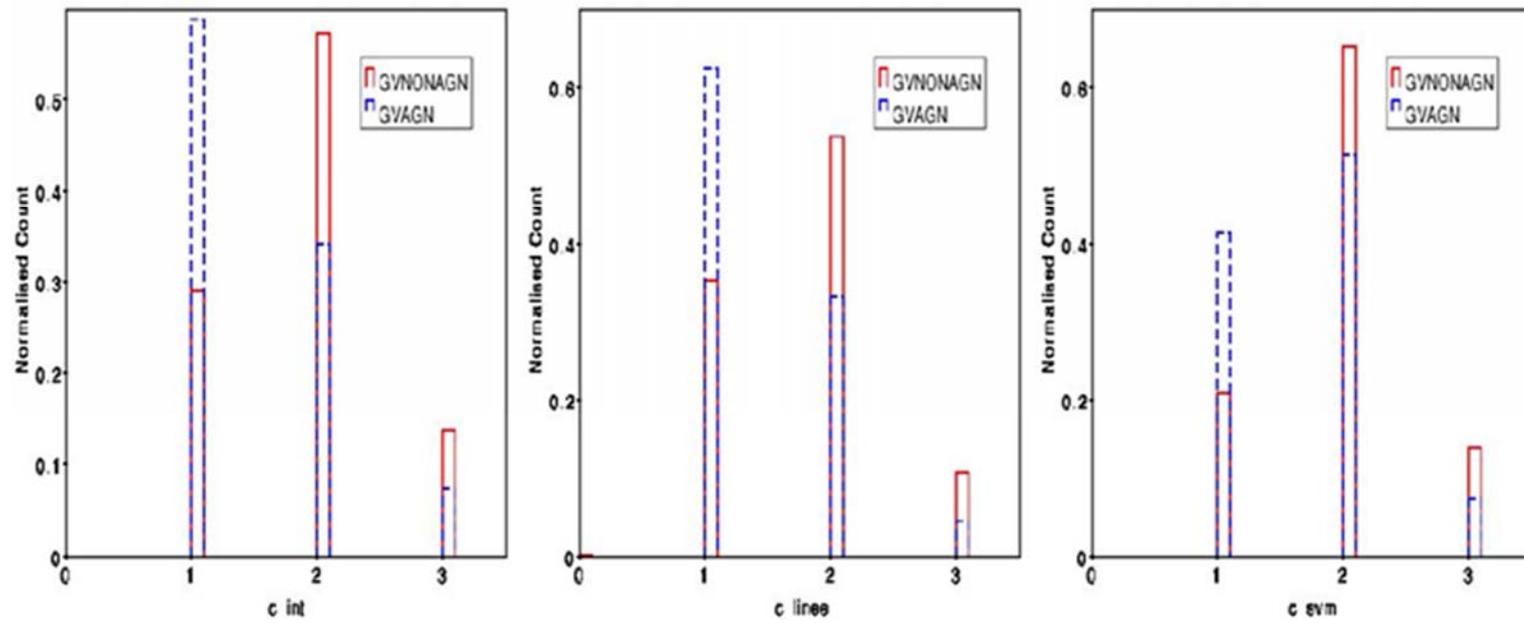


Figure 2: Normalised distributions of morphological types classified by int (left), linee (middle), and galSVM (right) methods (see Sec. 3) of a sample of active (dashed blue line) and non-active (solid red line) galaxies in the green valley.

- Colour distribution.

Figure 3 shows the normalised distribution of U - B rest-frame colour and comparison between the active and non-active galaxies. The two distributions are significantly different, where redder colours show to be dominated by AGN hosts. 49% and 36% of active and non-active galaxies have $U - B > 1.0$, respectively.

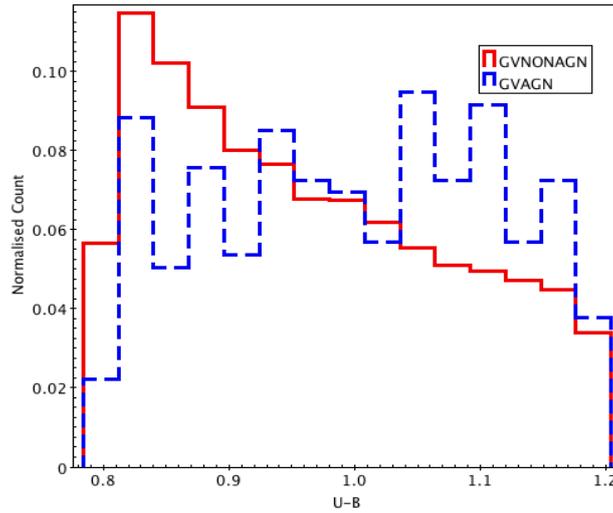


Figure 3: Normalised distributions of U - B rest-frame color of active and non-active galaxies in the green valley. For line descriptions see Fig. 2.

- Photometric redshift distribution

Figure 4 shows the normalised distribution of photometric redshifts for the two samples. Although, the total covered range of photometric ≤ 1.2 , respectively. Galaxies hosted by AGN show higher redshifts with the mean z of 0.82, while the mean z of normal galaxies is 0.59.

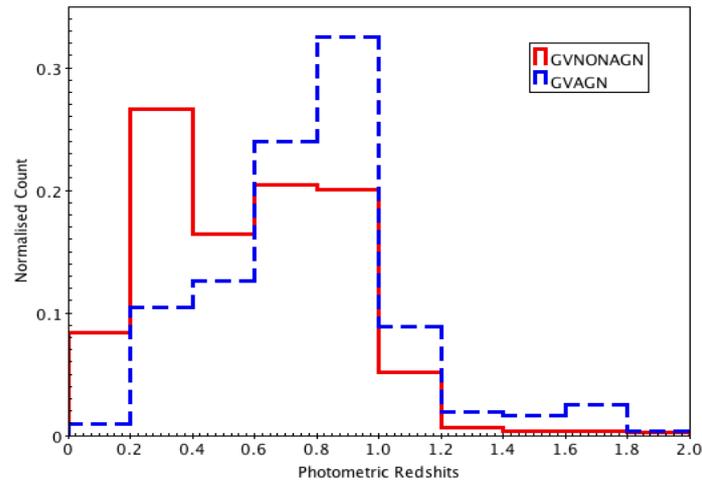


Figure 4: Normalised distributions of photometric redshifts in the green valley. For line descriptions see Fig. 2.

- Stellar masses.

We found significantly different stellar mass distributions of active and non-active green valley galaxies. Figure 5 shows the normalised and normalised cumulative distributions of both samples. AGN hosted galaxies show higher masses than non-active ones, with the mean masses of $3.39 \times 10^{10} M_{\odot}$ and $1.17 \times 10^{10} M_{\odot}$, respectively. The amount of AGN and normal galaxies with masses above $5 \times 10^{10} M_{\odot}$ are 74% and 34%, respectively.

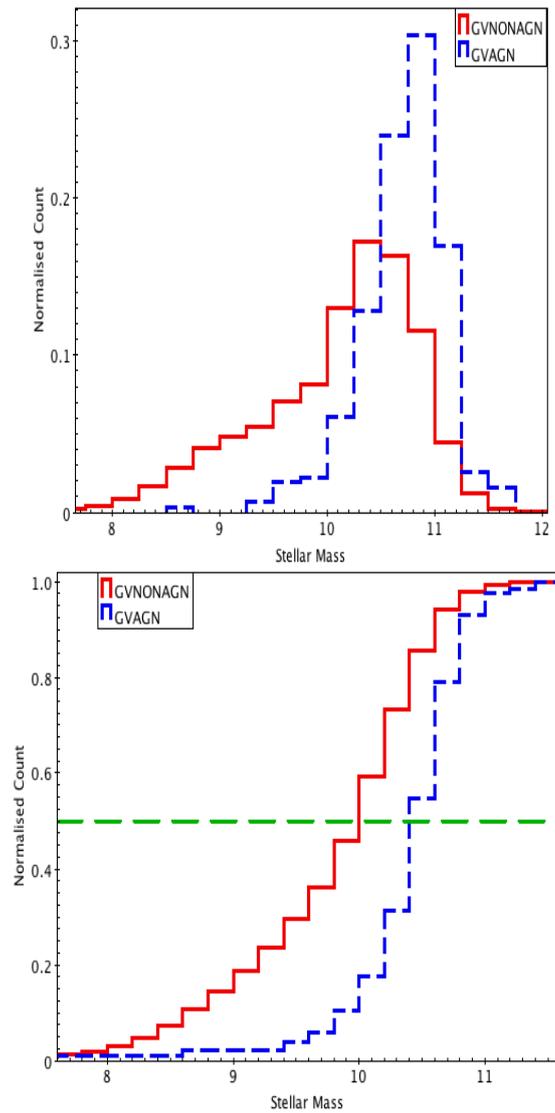


Figure 5: Normalised (left) and normalised cumulative (right) distributions of stellar masses in the Green Valley. For line descriptions see Fig. 2. The horizontal dashed, green line sets the distribution at 50%.

- Sizes.

We compared the sizes at 50% and 90% of flux of the two samples of galaxies, as described above, without finding significant differences. Figure 6 shows these comparisons. When comparing the mean values of the distributions they are consistent inside 1σ .

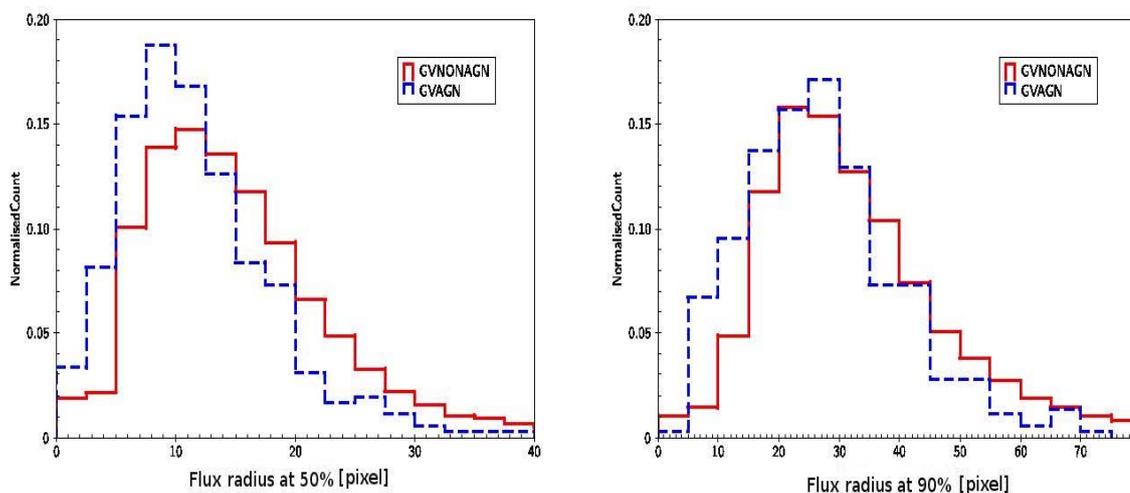


Figure 6: Normalised distributions of flux radius at 50% (left) and 90% (right) of the flux. For line descriptions see Fig. 2.

5. Summary

In this work we compared different properties of active and non-active galaxies that are located in the green valley of the colour-magnitude diagram. Our comparisons suggest that active galaxies seem to be more evolved than the normal ones, being hosted by earlier morphological types, showing redder colours, higher photometric redshifts, and higher stellar masses. Results obtained are consistent with those obtained in the previous studies suggesting that X-ray detected AGN in the green valley may present the transitional population of galaxies between the normal blue cloud and red sequence galaxies.

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