Galaxy evolution in the local universe: studying the complete local-volume groups sample (CLoGS)

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Abstract. More than half of all galaxies within the local Universe are found in group environments. Therefore, galaxy groups are excellent laboratories for studying galaxy evolution. The Complete Local-Volume Groups Sample (CLoGS) is the first statistically complete galaxy group survey in the optical, X-ray and radio bands, consisting of 53 galaxy groups and 1427 member galaxies in total. The properties of the member galaxies, such as their star-formation rates ($SFR_{\rm FUV}$, $SFR_{\rm W3}$), stellar masses ($M_{*,\rm K}$), radio emission ($P_{1.4\,\rm GHz}$) and WISE colours (W1-W2 and W2-W3) have been determined. The relation between the properties of the group member galaxies and their X-ray environment has been examined. The trends we have found suggest that star-formation relates to each group's dynamical age, X-ray halo and radio emission from each group's brightest group elliptical (BGE). We have found that within the majority (over 80%) of the dynamically young and X-ray bright groups of the CLoGS High Richness subsample, the $SFR_{\rm W3}$ of the member galaxies tend to increase the closer they are to the BGEs of their respective groups. Furthermore, we have found that within X-ray bright groups, the $P_{1.4\,\rm GHz}$ of the member galaxies tend to increase the closer they are to the BGEs of their respective groups, while their $SFR_{\rm FUV}$ tends to decrease. As a continuation of this research, a detailed optical spectroscopic study of these BGEs using data obtained on SALT (Southern African Large Telescope) is currently underway. The determined statistical relations and latest spectroscopy results are presented here.

1. Introduction

Galaxies co-evolve in gravitationally bound structures such as groups. More than half, roughly 60%, of all galaxies in the local Universe are found within group environments [1]. By studying the properties of galaxies within nearby groups, galaxy evolution in the local Universe can be better understood. Typically, groups span $0.5\,Mpc$ across in diameter and contain less than 100 galaxies, each galaxy with a stellar mass between $\sim 10^{11}\,M_{\odot}$ and $\sim 10^{14}\,M_{\odot}$ [2]. However, there is not a single precise definition for the boundaries of a galaxy group.

CLoGS is the first statistically complete sample of galaxy groups in the local Universe (< 80 Mpc) observed in the radio, X-ray and optical bands [3]. CLoGS selects groups optically to avoid the X-ray detection bias for cool-core groups [4] and performs a follow-up X-ray study to determine which of these groups have extensive haloes to circumvent false detection. CLoGS consists of 1427 member galaxies distributed throughout 53 galaxy groups [3]. These groups are further divided into the high-richness (HRS) subsample and low-richness (LRS) subsample based on the richness parameter 'R' of these groups. 'R' is defined as the amount of optically bright galaxies with a luminosity of $\log(L_{\rm B}) \geq 10.2\,L_{\odot}$. The HRS subsample consists of groups with $4 \leq R \leq 8$ and the LRS subsample of groups with $R = 2$ or $R = 3$. In more detail, the HRS subsample consists of 26 groups with 766 member galaxies and the LRS subsample consists of 27 groups with 661 member galaxies in total.

The X-ray properties of the HRS subsample have been studied [3]. Additionally, the radio properties of the central radio galaxies of the HRS [5] and LRS subsamples [6] have been studied in detail. To relate the properties of the HRS subsample member galaxies with their group environment, the groups are divided into 6 categories. These categories are: X-ray bright, X-ray faint, dynamically young, dynamically old and with- or without radio jets. In terms of scale, X-ray bright groups have extensive X-ray haloes ($> 65\,kpc$) and X-ray faint groups have galaxy-like or point-like haloes [5]. The dynamical age of the groups is determined by their fraction of spiral (late-type) galaxies $f_{\rm sp}$. Groups with $f_{\rm sp} \geq 0.75$ are defined as dynamically young and groups with $f_{\rm sp} < 0.75$ as dynamically old [5]. The BGE of each group may or may not possess active galactic nuclei (AGN) with outflowing radio jets and the groups are categorised accordingly [6].

2. Method

2.1. Determining the properties of the CLoGS member galaxies

The fundamental galaxy properties that we examine in order to better understand how galaxy evolution works in nearby groups are stellar mass ($M_{*,\rm K}$), star-formation rates ($SFR_{\rm FUV}$ and $SFR_{\rm W3}$), radio power ($P_{1.4\,\rm GHz}$) and WISE colours (W1-W2 and W2-W3).

The stellar mass of a galaxy can be gauged from the luminosity of its evolved stellar population using stellar mass to luminosity (M/L) ratios. In particular the K-band ($2\ \mu m - 3\ \mu m$) is insensitive to dust and is dominated by infrared emission from the evolved stellar populations. For this purpose the 2MASS extended source catalog (XSC) which has data available for $\sim 60\%$ of the CLoGS member galaxies was chosen to estimate their stellar masses. The stellar masses were estimated with the following M/L ratio calibrated to the extended K-band (k_m_ext) of 2MASS [7]:

$$\log(\frac{M_{*,\rm K}}{L_{\rm K}}) = -0.206 + 0.135 \times E(B-V), \qquad (1)$$

where E(B-V) is the corresponding Galactic reddening of each galaxy.

The star-formation rate of a galaxy can be estimated from the luminosity of its young stellar population. The light from newly formed stars can either be measured indirectly from the dust reflecting light from them (dust-obscured star-formation) or directly from the stars themselves (unobscured star-formation).

The W3-band ($12\ \mu m$) from the AllWISE survey which observed all of the CLoGS member galaxies, is sensitive to dust-obscured star-formation [8] and was used to estimate their star-formation rates with the following relation [9]:

$$\log(SFR_{\rm W3}[M_{\odot}.yr^{-1}]) = 0.873(\pm 0.021) \times \log(\nu L_{\rm W3}[L_{\odot}]) - 7.62(\pm 0.18), \qquad (2)$$

where $\nu L_{\rm W3}$ is the normalised spectral luminosity of each galaxy in the W3-band.

The FUV-band (100 nm - 200 nm) from the GALEX survey, which observed $\sim$85% of the CLoGS member galaxies, is sensitive to unobscured star-formation [10] and was similarly used to estimate their star-formation rates with the following relation [10]:

$$SFR_{\rm FUV}[M_{\odot}.yr^{-1}] = 1.08 \times 10^{-28} L_{\rm FUV}[erg.s^{-1}.Hz^{-1}], \qquad (3)$$

where L_{FUV} is the luminosity of each galaxy in the FUV-band in cgs units.

To have an indication of each galaxy's degree of star-formation and AGN activity, the $P_{1.4\,\text{GHz}}$ of the CLoGS member galaxies were determined using data from the NRAO VLA Sky Survey (NVSS) [11], which observed all of the CLoGS member galaxies. The $1.4\,GHz$ band is sensitive to synchrotron radiation from electrons accelerated either by the observed galaxy's central black hole (possible AGN) or supernovae remnants [12]. To classify the CLoGS member galaxies by colour, the same classification method developed by Jarrett et al. [8] is used. This method relies on the W1 ($3.35\,\mu m$), W2 ($4.6\,\mu m$) and W3 ($12\,\mu m$) magnitude measurements of the AllWISE survey and divides galaxies into 4 possible colour regions based on the infrared properties of their bulges and discs (their W1-W2 and W2-W3 colours) [8].

The 4 possible WISE colour regions, as shown in Figure 1, are [8]:

- Spheroid-dominated (Spheroids): With $W2 - W3 < 1.5$ and $W1 - W2 < 0.8$. Galaxies in this colour region are identified by their prominent bulges and strong mid-infrared emission from its central evolved stellar population. These galaxies are typically spheroidal, although not necessarily.
- Star-formation dominated (Star forming discs): With $W2 - W3 > 3$ and $W1 - W2 < 0.8$. Galaxies in this colour region are significantly bright in $W3$ and have notable ongoing star-formation. These galaxies are typically discs, although not necessarily.
- Intermediate: With $1.5 \leq W2 - W3 \leq 3$ and $W1 - W2 < 0.8$.
- Infrared-AGN and extrema: With $W1 - W2 \geq 0.8$ A high W1 measurement may indicate AGN activity within the galaxy and such galaxies are classified accordingly.

It should be noted this method does not strictly determine the morphology of the galaxies, for such a task visual inspection would be required. This method merely states what the most likely morphology of each galaxy would be based on their WISE colours, star-formation activity and AGN activity. The galaxies are further divided into 3 star-formation types based on their far-ultraviolet (FUV) and infrared (IR) colours provided by GALEX and AllWISE, as similarly done by Gil de Paz et al. [13]. The 3 star-formation types are [13]:

- Dust-obscured star-forming (IR bright), with colours: $FUV - K_{\text{s}} > 8.8$ and $W3 - W4 > 2$.
- Star-forming (FUV bright) with colour: $FUV - K_{\text{s}} \leq 8.8$.
- Non-star-forming, with colours: $FUV - K_{\text{s}} > 8.8$ and $W3 - W4 \leq 2$.

2.2. Relating the HRS member galaxies to their group environment

To study the galaxy evolution of the CLoGS group sample, we examine the properties of the HRS member galaxies with respect to their group environment. To achieve this, we study the most prevalent type of the CLoGS member galaxies: those within the WISE colour region: $W2 - W3 > 3$ and $W1 - W2 < 0.8$. We note how their properties change with distance from the brightest group ellipticals (BGEs) of their groups. Here we only consider galaxies within R_{500} of each group, where $R_{500} = 500\rho_{\text{c}}$ (ρ_{c}: critical density of the Universe), which is a rough estimation of each group's size. We simply inspect and note whether the properties of the member galaxies $P_{1.4\,\text{GHz}}$, SFR_{FUV}, SFR_{W3} and $M_{*,\text{K}}$ increase or decrease towards the centres of the groups, where each group's BGE is roughly located.

3. Results

Only the results for the HRS subsample are shown. The results for the LRS subsample are qualitatively the same with a slightly different WISE colour distribution. The stellar masses and star-formation rates of the LRS subsample galaxies are of the same order of magnitude.

3.1. The properties of the CLoGS HRS member galaxies

The WISE colour distribution of the 766 HRS member galaxies are shown Figure 1. Figure 1 shows the 4 different WISE colour regions as defined in Section 2. The member galaxies are shown in terms of their star-formation types (FUV and IR colours) as described in Section 2.

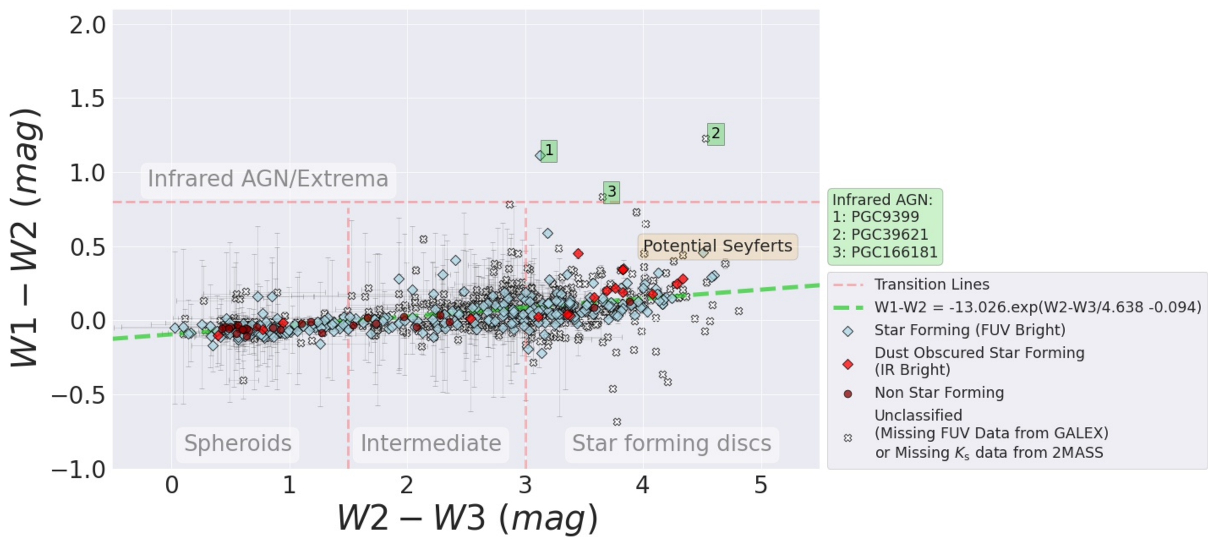

Figure 1. The $W1 - W2$ and $W2 - W3$ colours of the member galaxies are fitted with an exponential function which shows the general trend in star-formation. Galaxies which deviate from this trend are classified as potential Seyfert galaxies (or other). The star-formation types of the galaxies with missing data from GALEX or 2MASS are left as unclassified. The infrared AGN are numbered and their Principal Galaxies Catalog (PGC) names shown.

The W3-star-formation rates and K-band estimated stellar masses of the 766 HRS subsample member galaxies are shown in Figure 2. The members are once again categorised according to their WISE colour region and their star-formation type as discussed in Section 2.

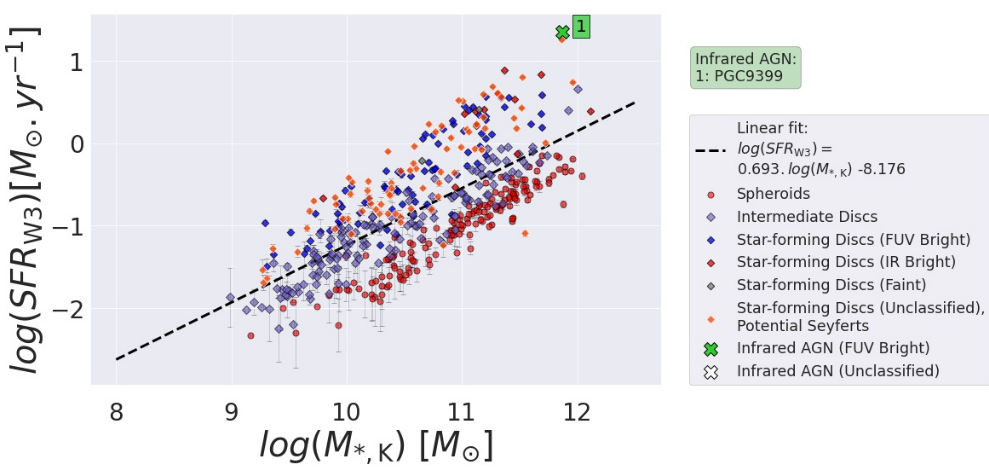

Figure 2. It can clearly be seen that the star-formation rates (SFRs) increase with stellar mass and change with WISE colour region. In ascending order, the SFRs of the member galaxies change in terms of their WISE colour regions as: spheroid-dominated, intermediate, star-formation dominated and Infrared-AGN.

3.2. Relationship between the HRS member galaxy properties and their group environment
The property trends of the HRS member galaxies, with $W2 - W3 > 3$ and $W1 - W2 < 0.8$ are shown in Table 1. Only galaxies within R_{500} of each group are selected as discussed in Section 2.2. The groups are divided by category as discussed in Section 1. These trends were determined by treating each group individually, with each member galaxy a data point (further binned to every 0.25 kpc). Linear regression lines were fitted to determine if the member galaxies within each group had an an increase or a decrease in each property the closer they were to the BGEs of their respective groups. However these trends are not necessarily linear, other functions may be more accurate. A larger sample of member galaxies within each group would be required to fit these.

Table 1. ↑ indicates an increase in the property and ↓ indicates a decrease. For example, the first cell reads: Within 80% of the X-ray bright groups (4 out of the 5 groups), the member galaxies had an increase in $P_{1.4\,\mathrm{GHz}}$ the closer they were to their group's BGE.

Group Category	$P_{1.4\,\mathrm{GHz}}$	SFR_{FUV}	SFR_{W3}	$M_{*,\mathrm{K}}$
X-ray Bright (5 groups)	↑ (80%)	↑ (40%) ↓ (40%)	↑ (80%)	↑ (80%)
X-ray Faint (1 group)	-	-	-	-
With Jet (6 groups)	↑ (66.7%)	↓ (66.7%)	↑ (83.3%)	↑ (83.3%)
Without Jet (0 groups)	-	-	-	-
Dynamically Young (3 groups)	↑ (66.7%)	↓ (66.7%)	↑ (100%)	↑ (100%)
Dynamically Old (3 groups)	↑ (66.7%)	↓ (66.7%)	↑ (66.7%)	↑ (66.7%)
All (6 groups)	↑ (66.7%)	↓ (66.7%)	↑ (83.3%)	↑ (83.3%)

3.3. Current work: spectroscopy of the CLoGS brightest group ellipticals (BGEs)
We have already analysed long-slit spectra for 32 BGEs from the Hobby-Eberly Telescope [15]. At present, the BGEs observable from the Southern Hemisphere have been observed with the Southern African Large Telescope (SALT) and an in-depth optical spectroscopic study of these galaxies is in progress. We are studying the spatially resolved stellar kinematics of these galaxies by analysing their spectra, such as Figure 3. Furthermore, we are studying the stellar populations of these galaxies and deriving their star-formation histories.

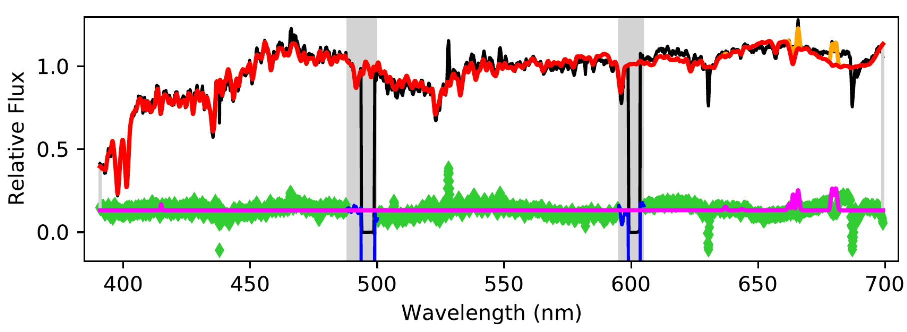

Figure 3. The observed SALT spectrum for NGC7377 is shown in black. The masked chipgaps of SALT is shown in grey and blue. The fitted spectrum, generated with the penalised pixel fitting method (pPXF) of Cappellari [14], is shown in red. The baseline fit is shown in pink. The deviations between the data and model spectra is shown in green and the identified spectral lines are shown in orange.

Clear $H\alpha$ (656 nm), $[SII]$ (6716 nm and 6731 nm), $[OI]$ (6300 nm) and $[NII]$ (6583 nm) emission can be seen on the spectrum of NGC7377, as shown in Figure 3. Similar spectra were observed and fitted for all the CLoGS BGEs, with minor differences in shape and emission lines.

4. Concluding Remarks

Within each group, the member galaxies with $W2 - W3 > 3$ and $W1 - W2 < 0.8$ in the CLoGS HRS subsample have several of their properties related to their distance from the BGEs of their respective groups. Within the majority (over 80%) of the dynamically young and X-ray bright groups, the $SFR_{\rm W3}$ of the member galaxies tend to increase the closer they are to the BGEs of their respective groups. Furthermore, within 80% (4 out of 5) of the X-ray bright groups, the $P_{1.4\,\rm GHz}$ of these member galaxies tend to increase the closer they are to the BGEs of their respective groups, whilst their SFR_{FUV} tends to decrease. This increase in $P_{1.4\,\rm GHz}$ and decrease in $SFR_{\rm FUV}$ is found to be more frequent in X-ray bright groups than in any other group category. However, a larger and more statistically significant number of groups need to be observed to verify these trends. Additionally, more member galaxies need to be observed within each group to determine the exact function of these trends, which may be linear or otherwise. The CLoGS BGEs are currently being studied more closely using optical spectroscopy obtained on SALT. These results will provide more clues to galaxy evolution in groups in the local Universe.

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