# A multi-band view on the evolution of group central galaxies

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**Abstract.** Nearby galaxy groups are the place in which non-secular processes have the greatest impact on galaxy formation and evolution. We examine, using multiple wavebands, the processes that play a significant role in galaxy evolution in the central brightest group early-type galaxies (BGEs) of an optically selected, statistically complete sample of 53 nearby groups (<80 Mpc; CLoGS sample). The CLoGS sample has been observed in radio 235/610 MHz (GMRT), CO (IRAM/APEX) and X-ray (Chandra and XMM-Newton) frequencies and also has a wealth of archival Far-UV and mid-infrared data. Characterizing the BGEs based on their X-ray group environment and radio properties we examine the relations between i) radio-AGN activity and X-ray intra-group gas and ii) between the molecular gas content, its morphology and the status of their star formation. We suggest that active star formation is promoted by the presence of cold gas in the form of disks whereas AGN radio jet activity mainly emanates from an X-ray bright Intra-group medium (IGrM), with AGN feedback in galaxy groups manifested either as a smooth continuous thermal regulation, or also as an extreme outburst that may affect the group gas dramatically.

## 1. Introduction

More than half of all galaxies reside in galaxy groups [1]. Groups are a diverse class, ranging from spiral-dominated systems rich in $HI$ and molecular gas, to more massive, evolved systems dominated by early-type galaxies, with little cold gas but often hosting an extended hot X-ray emitting intra-group medium (IGrM). The shallow potential wells of groups bring galaxies close together at low velocities, making interactions and mergers common, and making groups perhaps the most important environment for studies of galaxy evolution. The transition in gas properties, as groups increase in mass, is related to the evolution of the galaxy population, with some intermediate systems showing intergalactic structures of cold gas, or even a cold $HI$ IGrM [2].

X-ray bright groups are also a key environment for the study of Active Galactic Nuclei (AGN) feedback, having almost universally short central cooling times and low entropies [3]. Evidence of repeated cycles of AGN activity is relatively common, in the form of nested radio sources or multiple sets of X-ray cavities. While most group-central radio galaxies conform to the known relationship between the cooling luminosity of the IGrM and jet power (as measured from X-ray cavities, e.g., [4], there are cases where the AGN appears to be dramatically over-powered [5] and recent studies have shown that groups can host larger radio galaxies than clusters [6]. It is believed that these group-central AGN are fuelled by material cooled from the IGrM, often observed in clusters as H$\alpha$ and CO filaments (e.g., [7]). The amount of cooled material in X-ray bright groups is typically smaller than in clusters (e.g., [8]) perhaps indicating, in combination with the short cooling times, a more rapid cycling of the AGN.

At present, our understanding of the impact of the group environment on member galaxies is largely based on optical and $HI$ studies of low-mass compact groups, while studies of AGN feedback have focused on relatively small numbers of well-known, highly X-ray luminous galaxy groups. Selecting representative samples of groups is difficult, with both X-ray and optical selection having important flaws. The wide variety of data needed to trace star formation, different gas phases, and AGN activity is often only available in moderate redshift survey fields where detailed analysis of the groups is impossible. We use one of the few samples of nearby groups that is both representative and has the requisite supporting data at multiple frequencies (X-ray, CO, radio and archival mid-IR, FUV and K band) to investigate in detail the relative balance of different processes operating to transfer energy from the AGN and the IGrM, and the role of star formation in the cooling gas.

As AGN in galaxy groups dominate feedback in the Universe as a whole, the detailed study of the properties of cold gas and its link to star formation, will also have implications on our global understanding of structure formation and galaxy evolution.

## 2. The sample: CLoGS

The Complete Local-Volume Groups Sample (CLoGS, [3]) is a statistically complete, optically-selected set of 53 groups within 80 Mpc, with declinations >-30°. The groups cover a range of mass, richness and galaxy population, but all contain at least one large early-type galaxy, since the original goal of the sample was to investigate AGN feedback. The sample has an exceptionally rich supporting dataset: GMRT 235 and 610 MHz observations to trace continuum emission from AGN and star formation ([9],[5]); *XMM-Newton* and/or *Chandra* X-ray observations to provide information on their IGrM [3]; IRAM 30m or APEX CO mass measurements for the dominant galaxies ([10],[8]); and a wealth of optical imaging and spectroscopy, including (for subsets) MUSE IFU maps and long-slit spectra of the dominant galaxies, and wide-field H$\alpha$ imaging of the groups. In addition, due to its proximity CLoGS is ideal for the study of star formation using catalog data in the FUV (GALEX), and mid-infrared (WISE).

Another benefit of CLoGS proximity, is that it provides also the opportunity to study in detail the AGN outburst properties and energetics of individual strong radio jet sources (e.g., NGC 4261, [11]) as well as the examination of galaxy interactions and their important role in the development of a galaxy group and its formation history (see e.g., NGC 5903, [12] and NGC 1550, [13]).

## 3. Results from multiple bands

### *3.1. X-rays, radio-AGN and gas content in group dominant galaxies*

X-ray observations reveal that more than half (55%) of the CLoGS groups are X-ray luminous, presenting a full scale X-ray halo; their hot gas halo extends >65 kpc (26/53; [3], O'Sullivan 2022 in prep), with the remaining systems having only limited or no hot intra-group medium being generally spiral rich. The X-ray bright groups were misidentifed as single galaxies or not detected at all in the Rosat All Sky Survey prior to our observations, which implies that about 30% of the X-ray bright groups in the local universe might still be not known. On the other hand, using GMRT radio observations at 235/610 MHz and archival VLA data, the radio-AGN population of the central CLoGS group dominant galaxies appears at a high detection rate (87%; 46/53) with the dominant galaxies presenting a wide range in radio power ($10^{20} - 10^{25}$ W Hz$^{-1}$) and projected size (~3 kpc to 2 Mpc). Roughly half of the radio detected dominant galaxies (53%) present point-like radio emission, followed by 19% having jets with non-detections at 13%. The mean spectral index $\alpha_{235}^{610}$ is ~0.68 with only 3.8% of the radio sources presenting ultra-steep spectra (>2.5). Radio morphology is seen to correlate with the dynamical youth of the groups as radio point sources are more common in the dominant galaxies of spiral-rich systems whereas jet sources show no preference of their close environment ([9],[5]) and can emanate from a range (2-50 $\times 10^8 M_\odot$) of black hole masses.

Adding to the picture examination of the cold gas content in CLoGS groups' dominant galaxies, a relatively high detection rate is found for CO (∼40%). However the galaxies are found to present short depletion times, suggesting that group-central galaxies must replenish their molecular gas reservoirs on timescales of ∼100 Myr. The majority of the dominant galaxies present signs of AGN (instead of star formation) dominance with at least half of them containing HI as well as molecular gas ([10],[8]).

### *3.2. AGN feedback in group dominant galaxies*
Combining radio and X-ray observations shows that 11/26 (∼42%) of X-ray bright groups host jet systems with the radio non-detections appearing in groups which either possess a galaxy scale X-ray halo or not one at all (X-ray faint groups). This suggests that gas cooling availability is more likely to feed the central engine and give rise to radio jet sources, in contrast to X-ray faint systems. The jet occurence in X-ray bright groups implies an AGN duty cycle >1/3 with these central jet sources seen in systems that possess cool cores with short central cooling times ($t_{cool}$ <7.7 Gyr; [3]) and low entropies in their cores (jet activity hasn't increased significantly the entropy in their central region).

Examining the balance in CLoGS groups between heating from AGN jet systems and cooling from X-rays (cooling X-ray luminosity), it is found that AGN feedback in galaxy groups can manifest as expected, as a smooth near-continuous thermal regulation without excessive cooling, but in addition we have identified two systems (NGC 193 and NGC 4261) whose exceptionally powerful AGN outbursts are delivering 100× more power into the intra-group medium than is being lost by radiative cooling. Therefore, AGN feedback in galaxy groups can also manifest as an extreme outburst which could potentially shut down cooling in the group for much longer periods of time [9].

### *3.3. Star formation in galaxy groups*
With all relevant information from multi-band wavelengths at hand for CLoGS groups (Far-UV, and mid-infrared), we examine the star formation (star-formation rate -SFR-, specific star-formation rate, stellar mass) and central AGN properties (e.g., radio power) of the dominant early-type galaxies in relation to their gas content and the large-scale environment they reside in. FUV magnitudes were drawn from the *Galaxy Evolution Explorer* (*GALEX*; [14]) GR6 data release[1] with mid-infrared ones retrieved from the *WISE* mission catalog [15] at 3.4 $\mu$m (W1), 4.6 $\mu$m (W2), 12 $\mu$m (W3) and 22 $\mu$m (W4) with an angular resolution of 6.1″, 6.4″, 6.5″ and 12″ respectively. The near-infrared $K_s$-band magnitudes were taken from the Two Micron All-Sky Survey (2MASS; [16]).

*3.3.1. Results from SFR Diagnostics* We find that the FUV star-formation rate ($SFR_{FUV}$) in CLoGS group dominant galaxies is low ($0.01 - 0.4$ $M_\odot$ $yr^{-1}$). Using the [FUV - $K_s$] < 8.8 mag criterion from the study of [17] to distinguish between actively star-forming and quiescent galaxies, we find that only 6/47 (∼13%) of the dominant galaxies are currently in some form star-forming (namely NGC 252, NGC 924, NGC 940, NGC 1106, NGC 7252 and ESO507-25). All of the six FUV bright systems share some common characteristics between them: they are lenticular (S0 morphological type), cold gas rich, present low-powered radio sources ($P_{1.4GHz}$ <$10^{23}$ W $Hz^{-1}$) and occupy X-ray faint groups. This suggests that, as expected, the majority of the group dominant galaxies (87%; 41/47) are FUV faint (passive) with no significant star-forming activity in agreement also with previous studies ([17],[18]).

The state of the dominant galaxies is also determined based on the mid-infrared diagnostics by [19] and [20]. Examination of the mid-infrared activity of the CLoGS dominant galaxies also reveals that the majority of the systems (87%; 46/53) occupy the spheroid region (W2 − W3 < 1.5 mag) having little star-formation with only one system (NGC 4956) having a very 'warm' W1 − W2 color, thus characterized as mid-IR bright AGN and with only one system having the reddest (W2 − W3 > 3 mag) color in the sample (NGC 7252) and characterized as actively star-forming disk. Five systems are classified as mid-infrared intermediate disks, namely NGC 252, NGC 940, NGC 1106, NGC 1779, and NGC 7377 with 3/5 of them being also classed as actively star-forming based on [FUV - $K_s$] color, having the same characteristics as the FUV bright ones.

[1] https://galex.stsci.edu/GR6https://galex.stsci.edu/GR6

*3.3.2. Radio power in relation to $SFR_{FUV}$ and stellar mass* Examining the relation between radio power and $SFR_{FUV}$ with stellar mass for the CLoGS group dominant galaxies, we find a lack of correlation denoting that the relation between AGN feedback and star formation is dependent on a variety of factors and can hint to multiple governing related processes. We suggest that this favors predominantly a combination of i) an external origin of gas (e.g., mergers) for some systems and ii) a stellar mass loss or cooling from the inter-stellar medium or halo for some other CLoGS dominant galaxies instead of a single origin of gas supply for the CLoGS sample that fuels the AGN and/or star formation related only with the host galaxy itself.

*3.3.3. Specific star-formation rate and gas content* The majority of the CLoGS group dominant galaxies exhibit low specific star-formation rates (sSFRs; $\sim 10^{-13}$ $yr^{-1}$) with the six FUV bright active star-forming galaxies presenting an order of magnitude higher sSFRs than the rest of the sample. Adding to the picture information on the cold gas morphology for the FUV bright systems, we find that 4/6 have gas disks suggesting that not only the presence of cold gas, but also its dynamical state plays an important role. In addition, the fact that all of these dominant galaxies are found in X-ray faint groups denotes that the cold gas is not likely originating from the cooling of gas from a hot intra-group medium, but most probably has been acquired through gas-rich mergers/tidal interactions.

On the other hand, we find that passive systems with lower sSFR values can either have AGN feedback at work in powerful radio systems suppressing or keeping star formation at low rates, or, in the case of low-radio power systems their gas deposit is not sufficient to fuel any significant star formation or a powerful AGN which is inherent to their environmental properties or linked to their groups evolutionary status/history. Examining the large scale environment of passive systems we find that radio powerful AGN reside in X-ray bright groups showing the connection between IGrM cooling and jet-mode feedback, with X-ray bright systems overall presenting a range of SFRs, but lower than the SFRs seen in the active star-forming systems -with the exception of NGC 315. This suggests that gas mass availability promotes fueling of star formation in actively star-forming systems, with the presence of a cooling IGrM on the other hand, being capable of promoting more powerful AGN, but not the fastest SFR, with mergers/interactions being important factors for both star formation fueling and AGN.

## 4. Conclusions

We conclude that evolution in the nearby group dominant galaxies of the CLoGS sample is driven not merely by a single process for all systems, but by a combination of secular processes and mergers/interactions, regulated also by the environment in which they reside. In the near future, observations with MeerKATs unprecedented sensitivity at L-band will allow us to examine in more detail the neutral hydrogen content of nearby galaxy groups, as well as to complement the continuum radio emission from AGN and star-forming galaxies.

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