Galaxy Evolution and Feedback across Different Environments
Proceedings IAU Symposium No. 359, 2020
T. Storchi-Bergmann, W. Forman, R. Overzier & R. Riffel, eds.
doi:10.1017/S1743921320001507

AGN feedback and galaxy evolution in nearby galaxy groups using CLoGS

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Abstract. Much of the evolution of galaxies takes place in groups where feedback has the greatest impact on galaxy formation and evolution. We summarize results from studies of the central brightest group early-type galaxies (BGEs) of an optically selected, statistically complete sample of 53 nearby groups (<80 Mpc; CLoGS sample), observed in radio 235/610 MHz (GMRT), CO (IRAM/APEX) and X-ray (Chandra and XMM-Newton) frequencies. We characterize the radio-AGN population of the BGEs, their group X-ray environment and examine the jet energetics impact on the intra-group gas. We discuss the relation between the radio properties of the BGEs and their group X-ray environment along with the relation between the molecular gas content and the star formation that BGEs present. We conclude that AGN feedback in groups can appear as relatively gentle near-continuous thermal regulation, but also as extreme AGN activity which could potentially shut down cooling for longer periods.

Keywords. AGN feedback, galaxy groups, galaxy evolution, jets

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1. Scientific background

Galaxy groups are gravitationally bound systems in which the majority of galaxies and stars in the Universe reside (Eke *et al.* 2006). They contain >50% of all galaxies and are not simply scaled-down galaxy clusters (e.g., Ponman, Cannon & Navarro 1999), but possess shallow gravitational potentials and low velocity dispersions, which are conducive to the galaxy mergers and tidal interactions that drive rapid galaxy evolution (e.g., Alonso *et al.* 2012). As such, galaxy groups are the most important laboratories for the study of galaxy formation and evolution, where the crucial effects of baryon physics, such as cooling, galactic winds, and AGN feedback, are most evident.

The nature of the feedback is one of the most important unresolved questions in extragalactic astronomy (see McNamara & Nulsen 2007). While the required mechanical power from AGN activity needed to produce X-ray cavities has been argued as sufficient to balance gas cooling, in some systems star formation continues in the central galaxy. The mechanism of transfer of energy between the AGN and the intra-group medium (IGM) is poorly understood, and requires a combination of multi-wavelength data, including radio, CO and high-quality X-rays to provide insight into the processes involved. Towards this end, we defined the Complete Local-Volume Groups Sample (CLoGS), a statistically complete, optically-selected set of 53 groups within 80 Mpc creating the first truly representative survey of groups in the local Universe (see O'Sullivan *et al.* 2017 for more details on the sample). CLoGS is ideal for understanding the balance between hot and cold gas, AGN activity and star formation in groups, and therefore the evolution of galaxies as a whole, as nearby groups provide the best angular resolution for a detailed study.

† KK acknowledges support from the Grants for IAU Symposia and Regional IAU Meetings

2. A multi-wavelength view of galaxy evolution with CLoGS

X-ray observations from *XMM* and *Chandra* reveal that almost half (49%) of CLoGS groups present a full scale X-ray halo; hot gas extending >65 kpc (26/53; O'Sullivan *et al.* 2017, 2020 in prep). More than half of these X-ray bright groups (14/26) are unknown or misidentifed as single galaxies prior to our observations, which implies that 30% of the X-ray bright groups in the local universe might still be unknown. Examining in detail the radio-AGN population of the central BGEs using GMRT observations at 235/610 MHz and archival VLA data, a high radio detection rate of 87% (46/53) is found, with the BGEs presenting a wide range in radio power (10^{20}–10^{25} W/Hz) and projected size ($\sim$3 kpc to 2 Mpc). Of the radio detected BGEs, 53% present point-like radio emission, followed by 19% having jets with non-detections at 13%. We find that radio morphology correlates 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 (Kolokythas *et al.* 2018, 2019).

Combining radio and X-rays reveals that 11/26 ($\sim$42%) of X-ray bright groups host jet systems with the radio non-detections appearing in X-ray faint groups. 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; O'Sullivan *et al.* 2017) and low entropies in their central region (jet activity hasn't increased dramatically the entropy in their cores). Examining the balance between heating from AGN and cooling from X-rays we conclude that AGN feedback can manifest in groups as smooth near-continuous thermal regulation, but also as extreme outbursts which could potentially shut down cooling for long periods of time (Kolokythas *et al.* 2018).

Examinination of the cold gas content of the CLoGS groups' dominant galaxies using the IRAM 30m and APEX telescopes shows a high detection rate for CO ($\sim$40%), but a short depletion time indicating that group-central galaxies must replenish their molecular gas reservoirs on timescales $\sim$100 Myr. The majority of the BGEs are found to be AGN (instead of star formation) dominated with at least half of them containing HI as well as molecular gas (O'Sullivan *et al.* 2015, 2018a).

Lastly, due to its proximity, CLoGS provides also the opportunity to study in detail the AGN outburst properties and energetics of individual strong radio jet sources (e.g., NGC 4261, Kolokythas *et al.* 2015) 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, O'Sullivan *et al.* 2018b and NGC 1550, Kolokythas *et al.* 2020).

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