Galaxy evolution in clusters with the Square Kilometer Array

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Abstract

Galaxy clusters, the largest systems in the universe, result excellent laboratories for studying the properties of galaxies under similar environmental conditions. The general properties of the galactic population in clusters remarkably differ to their field counterparts. Consequently, the mechanisms responsible for the formation and evolution of the galaxies are believed to be closely tighten to the environmental conditions. In this chapter, we review the state-of-art of radio observations in galaxy clusters. We first mention the role that the neutral gas plays in tracing the properties of galaxies in high-density environments and highlight the impact that the SKA data will have in sampling deeper and wider samples. Secondly, we present our knowledge on the active galactic nuclei (AGN) mechanism in clusters and their impact on the brightest clusters galaxies (BCG). We then explore the power that the SKA data will have in sweeping a large range of redshift and host masses to study the relation of the AGN with the cluster host properties and to constrain the main evolutionary mechanism of BCGs. Finally, we investigate the presence of the diffuse emission in galaxy clusters and describe the impact on the characterization of their properties through a larger range of redshift than previous surveys that the SKA will achieve.

1 Introduction

Galaxy clusters are the largest structures gravitationally bound in the universe. Along with a large quantity of dark matter and very hot gas known as the intra-cluster medium (ICM), they contain several tens to thousands galaxies with tangential properties to the galaxies located in the field. Preliminary works (e.g. [51, 70, 31, 94]) discovered the so-called morphology-density relation, for which early-type galaxies are concentrated in the central part of the clusters and their density decreases with the cluster-centric distance. Reversely, the late-type galaxy fraction increases progressively as function of the distance to the center. Many works have later investigated the evolution of this relation with redshift and in different environments (e.g. [73, 87, 6]), a finding that holds at least up to redshift z$\sim$1 with the early-type galaxies becoming more spatially concentrated with redshift.

In addition to the different mix of morphological types, many differences have been detected in the properties of the spiral population itself: late-type galaxies inhabiting in clusters systematically differ from their field counterparts regarding their neutral gas content, star formation activity, molecular gas content, metallicity, cold dust content, kinematic perturbations, and radio continuum synchrotron emission (see [13] for a review on the effects of environment on late-type galaxies). The origin of these differences is still unknown and the debate about nature or nurture is still ongoing.

Using radio sources both associated to the ICM and to the Active Galactic Nuclei (AGN) [58] as cluster tracers, the SKA is expected to detect thousands of galaxy clusters up to redshift $\sim$0.6 and several hundreds at redshift z>1.5 (see Ascaso et al. in these proceedings). These cluster detections, in combination with other overlapping datasets such as X-ray, optical and infrared surveys and Cosmic Microwave Background (CMB) Planck maps, will provide a measurement of some of their overall properties such as masses, luminosities or temperatures. This cluster set will become several times superior to the previous radio surveys in terms of depth and redshift range. Therefore, it will constitute a unique sample to analyze the radio properties of the galaxies inhabiting there. Furthermore, it will play a crucial role in disentangling the main mechanisms involved in the formation and evolution of the Brightest Cluster Galaxies (BCGs), particularly at high redshift. The SKA then, will help unveiling unanswered questions and set constraints on the effect of the environment on the processes transforming galaxies.

The structure of the chapter is as follows. In §2, we focus on the detection of neutral hydrogen in cluster galaxies and highlights the advantages that the SKA will offer. §3 discusses the possibilities that the SKA will open for the study of AGN and the star formation of cluster galaxies. Finally, §4 reviews the diffuse emission in galaxy clusters and explores the improvement that will result in the understanding of the processes related with infra-red and radio emission thanks to the sensitivity and resolution of the SKA.

2 Neutral gas in galaxies in clusters with SKA

The content of neutral hydrogen, H I, in galaxies has been studied for a wide variety of galaxy samples. Here we focus on the studies regarding the galactic population in clusters, but a more general discussion on the topic can be found in Verdes-Montenegro et al. in these proceedings.

Since the pioneering observations of [30], the investigations on the H I content of cluster galaxies generally agree on the fact that on average, cluster spirals tend to have less neutral gas than their field counterparts. They also found evidence for correlations between the H I deficiency and the cluster-centric distance, with H I-poor disks typically situated close to the cluster cores and galaxies removed from those regions showing normal gas content (e.g., [43, 80]).

While the selection of reduced size samples has been reported to lead to biased results [1, 2, 72], plenty of these studies on galaxy clusters focused their attention on few nearby clusters, mainly Coma [15] and Virgo (e.g., [47, 19, 20, 81, 21, 86]), due to the current difficulty in obtaining deep H I observations. In particular, a very impressive example is the VIVA (VLA Imaging of Virgo in Atomic Gas [22]) survey, an imaging survey at $15''$ resolution of 53 late-type Virgo cluster galaxies located throughout the cluster, covering more than a factor of 20 in mass. Detailed imaging studies carried in all these nearby clusters show spirals with truncated gas disks, smaller than their undisturbed stellar disks, as well a trend of the extent of the H I disks with location in the cluster, being the most reduced those located near the core (e.g., [20, 2, 22]). Additionally, BUDHIES (Blind Ultra-Deep H I Environmental Survey of the Westerbork Synthesis Radio Telescope; [55, 56]) is a deep H I survey of galaxies in two clusters at z$\sim$0.19 and $\sim$0.21 and the large-scale structure around them. The survey aims at understanding where, how, and why star-forming spiral galaxies get transformed into passive early-type galaxies. The unique aspect of this study is that it has obtained measurements of the H I content of galaxies in different environments at intermediate redshift. This is the first time that optical properties and gas content are combined at a redshift where evolutionary effects begin to show, and in a volume large enough to sample all environments, ranging from voids to cluster cores. As part of this project, [54] found that the H I gas and the SF correlate with morphology and environment at z$\sim$0.2. Their results suggest that the H I gas gets removed and SF suppressed progressively, from the lowest mass galaxy groups to cluster-sized structures, as smaller structures get assembled into larger structures.

The measurements of H I content have been made extensive to other density regimes, showing that gas-depleted disks are not exclusive of cluster spirals: H I-deficiency has also been detected in Hickson Compact Groups (e.g. [90] and see Verdes-Montenegro in these proceedings), in X-ray bright groups (e.g., [78]), as well as in loose groups [77, 61]. In these less dense environments, in which the relative velocities of the galaxies are low, the tidal forces in close galaxy encounters can result in the removal of significant portion of a galaxy H I mass. Precisely, the efficiency of this mechanism in groups of galaxies has been used to favor the idea that galaxies suffer a pre-processing before entering the cluster environment (e.g., [37]). Several pieces of observations support this scenario, such as the compact group falling towards Abell 1367 [25], or of the Eridanus group [71].

All these observational results indicate that, at least in the densest regions of the cluster, gas-sweeping occurs. Since the 1970s, when the first models of tidal interactions between galaxies [85] and interactions of the inter-stellar medium (ISM) of galaxies with the dense ICM were proposed [45], theoretical models and numerical simulations have provided a wealthy variety of possible scenarios (see reviews by [46, 88, 13]). In general, the results of most of the aforementioned H I studies point towards ram pressure stripping (RPS) of the interstellar gas of galaxies by the hot ICM as the most plausible mechanism acting on the spiral galaxy population in today clusters. However, simple models of RPS are only partially consistent with galaxy data. For some galaxies, more than one mechanism appears to be necessary to explain the observations (e.g. [92]), whereas in other cases the results suggest that the effects of the ICM reach further than expected from simple ICM-ISM models (e.g. [28, 29, 65, 16]). Another mechanism that might affect cluster disks is galaxy harassment [68], proposed as a mechanisms to transform late-spirals into lenticulars (S0), and recently claimed to be responsible for the morphology of NGC 4254, as unveiled by the Arecibo Legacy Fast ALFA (ALFALFA, [44]) detection of this system [48].

We are currently limited when studying galaxies in clusters by two factors: they are scarcely detected in H I (high sensitivity and resolution is needed to detect cluster galaxies in H I, because they are gas-poorer than field galaxies) and the environment is not properly characterized in a quantitative manner. The SKA resolution and sensitivity will allow us to isolate the emission from galaxies in close proximity and therefore will help to mitigate confusion effects in dense environments over a large redshift range. This, in combination with optical redshift samples and observations of the ICM at other wavelengths (e.g., X-rays), will allow us to better quantify the effects of environment of galaxies.

The RPS has also been observed in other components of the interstellar medium such as the molecular gas. Indeed, several studies have reported no H_2 deficiency in galaxies associated to clusters, but a HI deficiency [59, 17, 12]. These results have been interpreted as a consequence of the larger concentration of the molecular gas towards the center of the galaxies and more recent works point towards the confirmation of molecular gas deficient galaxies in some nearby clusters [38, 39]. Additionally, it has been found that HI deficient Virgo galaxies show also truncated dust disks [26, 14], implying that RPS not only affects the neutral gas.

The HI deficiency is related to the star formation history (SFH) of galaxies in clusters, in the sense that HI deficient galaxies show truncated SFHs compared to non HI deficient galaxies [41]. This is explained by the fact that the star formation activity is regulated by the gaseous content of galaxies [42]. Supporting the link between the HI content of spiral galaxies and their star formation activity is the finding that many Virgo spirals show truncated Hα profiles [63] indicating that RPS is at the basis of this effect.

Historically, the SFH has been represented in a simple way, the exponentially decreasing parametrization being the most common one. This parametrization is able to explain present-day galaxies of all morphologies [60]. Some other more difficult parametrizations have also been explored in order to find a typical SFH of higher redshift galaxies. Unfortunately, the search for a typical SFH at higher redshifts has been unsuccessful and the relation might not be as simple as the local-universe one. To constrain the SFH of the galaxies, the ongoing star-formation needs to be measured, together with the mass of the stellar populations that has already been formed. Radio wavelengths offer the possibility of observing obscured and non-obscured star formation at the same time.

The SKA will be able to provide constraints on the SFH since the reionization epoch through a tiered survey strategy whereby enough volume is sampled at each cosmic epoch: an ultra-deep tier, a deep one and a wide one. As shown by [23], the deep SKA1 survey will be capable to recover the ∼85% of the star-forming galaxies detected by Euclid [64] up to $z = 3$ with ∼2000 hours. Furthermore, the ultra-deep tier SKA1-MID will detect the faintest star-forming populations to the highest redshifts (SFR $\sim 10 M_{\odot} yr^{-1}$ out to z∼4, and SFR$\sim 100 M_{\odot} yr^{-1}$ for z∼8). Finally, the SKA Wide Tier (1000-5000 deg^2 survey with $0.5''$ resolution with a 5σ detection limit of 5 μJy/beam) will relate the findings in the higher universe with those obtained locally. Since galaxies in clusters tend to populate the gas-poor regime, they are hardly detected in HI. A particularly powerful technique to study their properties with SKA will be the stacking of the HI spectra (e.g. [91, 32]). This technique will provide constraints thanks to the large statistics that will be available with SKA observations in combination with independent measurements of galaxy redshifts.

Likewise, the SKA will perform a breakthrough in the study of the relation between gas content and the star formation rate (SFR) of galaxies in clusters given its combined unprecedented sensibility and angular resolution. Thousands of galaxy clusters and groups will be mapped up to redshift $z = 1$ at least and even higher (see Ascaso et al. in these proceedings) with SKA2 facilities. Hence, a complete spatial coverage up to the infall regions ($r \approx 5R_{200}$) of the HI component will be ready to be fully exploited for a sample of clusters spanning a wide range in mass, from loose groups to Coma-like clusters, and different evolutionary states according to their substructure. This will result in a complete view of the effect of the local and global density on the gaseous component of galaxies. The resulting dataset will contribute to shed light on the role of the pre-processing of galaxies in small groups before entering the cluster environment.

Moreover, this study will benefit of the multiwavelength data available for different cluster samples in order to address other related topics like the relations between star formation and metallicity and the gas content of galaxies (via UV/IR spatially resolved imaging and integral field spectroscopy) in different environments. Combining SKA 21-cm with measurements and data in other wavelengths will be key in this respect. Optical and NIR imaging (e.g, J-PAS [7], LSST [53], Euclid), millimeters (e.g., ALMA [95]), Far Infrared (e.g. SPICA [84]) and X-ray (e.g. e-ROSITA[67]) imaging and spatially resolved optical spectroscopy will be available at the time SKA operates. These datasets will provide excellent follow-up samples to fully resolve the chemistry and dynamics of cluster galaxies: star-formation, metallicity, stellar population ages, angular momenta and stellar dispersions.

3 AGN in clusters and BCGs with SKA

Faint radio sources in clusters are currently an unexplored population that can become crucial to set constraints on the main scenarios explaining the evolution of galaxies in clusters. In particular, AGNs seems to play a fundamental role on the control of star formation of galaxies [18, 33, 49]. AGNs can be divided in two types depending on their accretion mode: a) quasar-like AGN or radiative mode AGN with high accretion rates (≥ 0.1 per cent of the Eddington rate) and, b) radiatively inefficient or jet-mode AGN, with low accretion rates and radio jets carrying the bulk of their energetic output. The feedback of jet-mode AGN is suggested as the main mechanism that can maintain massive galaxies (mainly found in clusters [31], e.g. the BCGs, see below) "red and dead" (see [9] and Perucho et al. in these proceedings). This radio-mode feedback evolves in time increasing up to a redshift 0.5 and decreasing at higher redshifts [10]. Galaxies in clusters are less likely to harbor a radiative-mode AGN and more likely to harbor a jet-mode one [75]. The most probable explanation is the presence and physical properties of the supply of gas that feeds the activity [76]. In this way, AGNs can shape the properties of the gas of the cluster and vice versa.

By contrast, while the AGN is generally believed to suppress the star-formation activity in galaxies, several observational [11, 69, 62, 27, 52, 5, 82] studies claim that AGN might also induce star formation. This result has also been supported by theoretical [79] and simulation [40] works claiming that the energy released from the jets can indeed trigger star-formation by allowing the collapse of over-dense clouds. This might be a crucial issue for the early universe, where the density of the gas was much higher in galaxies and when AGN activity was much more prevalent.

The SKA will go deep enough (e.g. the SKA1 is expected to detect about 500 million radio sources at a limiting noise level of 2 μJy rms [74]) to distinguish between the different populations of AGN and star forming galaxies at high distances. This will allow to trace the evolution of the radio-mode feedback up to high redshifts, quantifying its role across the history of the universe. It will also show enough resolution ($\sim 0.2'' - \sim 1''$) to decompose local galaxies into its compact individual radio sources, and will help to clarify the feedback processes that can trigger or quench the star formation. Indeed, with only <0.5 arcsec angular resolution continuum imaging capability, the SKA will study the individual components within a distance of <100 Mpc in the local universe [57]. Besides, its wide coverage will provide the necessary reference frame to compare the physical processes that drive the evolution of galaxies in clusters with those found in other environments.

In addition to the AGNs, the BCGs, the most luminous galaxies of the cluster lying usually on the centre of the cluster potential well, are interesting objects that will enormously benefit from the SKA potential. The BCGs have been explored in large samples drawn from optical and X-ray cluster samples. Two main mechanisms have been proposed to explain their evolution since $z \sim 1$: major/minor mergers (e.g. [8, 93, 66, 4]) or adiabatic expansion through AGN/quasar feedback (e.g. [34, 24, 83, 3]). According to numerical simulations predicting the latter mechanism (e.g. [50]), a galaxy would lose a fraction of its central mass, therefore producing an increase of its size but keeping a similar surface brightness profile. The observational data available at present do not allow to rotundly give an answer of the preference of one scenario versus the other. However, this scenario will change with the arrival of SKA. Since SKA will be able to map very faint radio-galaxies up to z=1 at least, these radio sources will be easily correlated with the already-identified BCGs in next-generation optical and X-ray samples (e.g. Euclid, J-PAS, LSST, eROSITA) overlapping with the SKA area. The correlation of the optical/X-ray properties of the host cluster (e.g. the presence of cooling-flows) with the type of radio-source identified in the BCG within a wide range of redshift and halo masses will definitively provide a new window on the type of mechanism that has helped forming the BCGs, particularly at $z \sim 1$, range where striking differences with their local counterparts start being appreciated (e.g [4]).

4 Diffuse emission in galaxy clusters with SKA

Clusters mergers produce cluster-wide shock waves that can be detected as faint elongated structures at their borders [35, 89]. These structures are the signature of large scale magnetic fields interacting with the ICM. Several theories have been proposed to explain the origin of these magnetic fields (see Battaner et al. in these proceedings). There are also radio halos linked to the X-ray emission of the ICM which are usually found around radio-loud BCGs and are probably related to AGN feedback processes. We can also find radio relics associated to the old jet emission of radio- galaxies in the cluster. Their morphology and physical properties can trace the formation and evolution of the cluster. The morphology of these relics is shaped by the interaction with the ICM tracing their relative movement, on the other hand, the spectral index of the source is related to the age of the synchrotron emission of the jet. Finally, there are AGN radio relics, whose emission is boosted by the adiabatic compression of merger shock waves, known as radio phoenixes (see Ascaso et al. in these proceedings). Fig. 1 reproduces a simulation of a galaxy cluster at $z = 0.5$ (see [36] for a wider explanation) where a diffuse radio halo can be seen together with several tailed radio galaxies and point sources. All these faint radio sources can be used to trace the formation and evolution of clusters.

The wide spectral coverage of SKA, from 50 MHz to 13.8 GHz, will allow us to determine the age of the synchrotron emission of the jets that can be used to constrain the AGN duty cycle. The sensitivity of SKA-LOW to low surface brightness radio emission will allow the detection of faint extended radio sources. It is expected to detect ∼2600 radio haloes up to z ∼0.6, almost an order of magnitude more than with current state-of-the-art instruments [74]. The SKA all-sky survey at band 2 with a noise level of $2\mu Jy$ and a resolution of 2 arcsecs will provide more than two orders of magnitude increase in the number of radio sources currently known, including radio relics in clusters. The sensitivity of SKA to low surface brightness radio emission combined with its resolution make it an ideal instrument to study these faint radio sources, which trace the evolution of the cluster, at high distances.

Radio continuum emission is widely used as a dust-unbiased tracer for measuring the recent massive star formation activity in galaxies. The observed tight relation between infra-red and radio emission is used to convert the radio flux density into a star formation rate measurement. However, as discussed in [13], such an indirect tracer should be used with caution for cluster galaxies because the involved quantities might not be reliable indicators of the star formation activity due to dust removal or magnetic field compression. In that respect, the sensitivity and resolution of future SKA observations will allow us to gain a better understanding on the underlying processes that give rise to the infra-red and radio emission relation itself and the origin of the differences for galaxies inhabiting clusters.

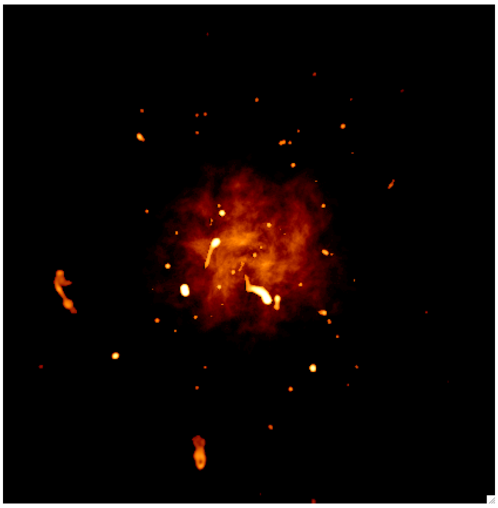

Figure 1: The population of radio sources of a local cluster (A2255) is simulated and then redshifted. In addition to the central halo, the disruption of the shape of extended radio jets due to the interaction with the ICM is clearly visible. SKA1 will observe at relatively high resolution the diffuse emission of clusters like this at high redshifts. Source: [36]

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In summary, the future SKA facilities will provide a great advantage in a variety of topics related with the main formation and evolutionary mechanisms happening in galaxy clusters. These data, with unprecedented quality in radio, will explore an uncharted range of redshift and clusters masses which, will immediately shape the evolution of the radio properties of galaxies in clusters and their relations with the environment.

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