MeerKAT's view on galaxy clusters: Diffuse radio emission in MeerKAT Galaxy Cluster Legacy Survey

K Kolokythas,[1] T Venturi,[2] I Loubser[1] and K Knowles[3,4,5]

[1]Centre for Space Research, North-West University, Potchefstroom 2520, South Africa
[2]INAF, Istituto di Radioastronomia di Bologna, via Gobetti 101, 40129 Bologna, Italy
[3]Astrophysics Research Centre, University of KwaZulu-Natal, Durban 4041, South Africa
[4]Centre for Radio Astronomy Techniques and Technologies, Department of Physics and Electronics, Rhodes University, PO Box 94, Makhanda 6140, South Africa
[5]South African Radio Astronomy Observatory, 2 Fir Street, Observatory 7925, South Africa

Abstract.

Galaxy clusters are the largest gravitationally-bound structures in the Universe, with their baryonic mass being distributed between the constituent galaxies and the ionized plasma of their intracluster medium (ICM). As such, radio observations of galaxy clusters are powerful tools for the detection of diffuse cluster-scale synchrotron emission, which carries information about the cluster formation history. Observations using Square Kilometre Array precursor and pathfinder instruments are nowadays opening up a new window on diffuse cluster sources and challenge our simple classification scheme (radio halos, mini-halos, and radio relics), making clear the need for an update of our current knowledge. Towards this direction the MeerKAT telescope carried out a program of long-track observations of galaxy clusters in L- band which became the MeerKATs Galaxy Cluster Legacy Survey (MGCLS), consisting of ∼1000 hours, observing 115 galaxy clusters at 1.28 GHz spread out over the Southern sky. A brief overview of the MGCLS is presented here, focusing on the diffuse radio emission detected in galaxy clusters showing some first results and statistics that reveal both the much-improved radio products compared to previous observations, as well as new discoveries that open up new areas of investigation in cluster formation and evolution.

1. Introduction

One of the most important aspects in the observations of galaxy clusters is the search for diffuse cluster-scale radio synchrotron emission. The detection of such structures plays a key role as it can reveal information regarding the evolution and the formation history of a cluster (for an observational detailed review see e.g., [1], and for a theoretical one see [2]). A great variety of low surface brightness and steep radio spectra ($\alpha < -1.0$) diffuse radio morphologies has been detected to date in clusters, however, historically, there are three dominant classes that almost every detected diffuse cluster radio emission falls into: *a) radio halos, b) radio mini-halos, and c) radio relics.*

As *radio halos* are called the diffuse sources that are typically correlated with the morphology of the X-ray emitting intracluster medium (ICM). The main mechanism that gives rise to these structures that span to scales of >500 kpc (up to few Mpc scales), is particle reacceleration as a result of massive cluster mergers, with radio halos exhibiting observed correlations between the radio source's power and its host cluster mass as well as with its thermal properties (e.g., [3],[4],[5]).

Radio mini-halos on the other hand, are smaller structures than radio halos with their projected sizes spanning between few tens to few hundreds of kpc situated in the central area of dynamically relaxed, cool-core clusters ([6]) and most of the times are found to be confined within cold fronts that are observed at the cluster core. A radio active brightest cluster galaxy (BCG) is always present at mini-halo clusters that is contributing, at minimum, part of the seed electrons necessary to generate the observed diffuse emission (e.g., [7]). As is the case in radio halos, particle reacceleration induced by gas sloshing is most likely the driving mechanism for the production of radio mini-halos (e.g.,[8],[9]).

Radio relics are the last class where elongated kpc to Mpc-scale structures are included that are usually observed at the outskirts of merging galaxy clusters. One of the main observed properties of radio relics is that they present a high degree of polarization (e.g., [10]) which denotes that their origin is closely related to the presence of merger-induced shocks in the ICM. For this reason, numerous clusters exhibit relics at opposite directions in the periphery of a cluster, also known as double radio relics (e.g., Abell 3667; [11]) either with the detection of a radio halo inbetween them or not (see [12],[13]). In this class is also included a sub-class of revived fossil emission from radio active galactic nuclei (AGN) in the region of the cluster known as radio phoenices ([1]).

Due to their detecteable surface brightness from current radio telescopes, the number of detected radio halos and relics in merging clusters has been continuously rising to date, over a broad range of cluster masses ([14]) and a wide range of redshifts ([15]). However, the detection of radio mini-halos, still remains at low numbers as a result of current radio observational constraints. Recently, the number of detected radio sources with very steep-spectrum filaments has been significantly rising (e.g., Abell 2034; [16]), introducing a necessity to further investigate the link between radio galaxies and the particle reservoir they deposit into the ICM, but also in general, the mechanism of cluster merger events (see e.g., [17]).

Therefore, with the advent of radioastronomy and the operation of new era radiotelescopes (such as the LOFAR, JVLA and the MeerKAT) a unique opportunity arises in the study of galaxy clusters from MHz to GHz fequencies opening up new areas of investigation in cluster formation and evolution.

2. The MGCLS sample and data

The first step towards the SKA era, was made in 2018 with the comissioning of the L-band of the MeerKAT radio telescope. Between June 2018 and June 2019 using the full MeerKAT radio-telescope array, (minimum of 59 antennas per observation) utilising the L-band receiver (900−1670 MHz) in the 4K mode (4096 channels) and an integration time of 8 seconds, 115 clusters were observed. This is the MeerKAT Galaxy Cluster Legacy Survey (MGCLS). MGCLS is a sample of 115 galaxy clusters with a mean redshift of ∼0.14 (only four clusters have $z > 0.4$) that spans over a large area in the Southern sky between declination -80° and ∼0°. A detailed description of the sample, the observations, and its data are presented at the MGCLS survey paper in [18].

For the MGCLS sample no specific selection criteria were applied, either in mass, redshift or luminosity, which makes MGCLS an inhomogeneous sample consisting of clusters that were drawn either from a group of 'radio-selected' clusters or a group of 'X-ray-selected' ones. The radio sub-sample consists of 41 clusters with known diffuse cluster radio emission from earlier studies (e.g., [6],[19],[20]). Due to this selection, this sub-sample contains only high mass clusters and is strongly biased towards clusters with radio halos and relics. On the other hand, the rest of the clusters (74 clusters or 65% of the MGCLS sample), are the X-ray sub-sample, that was selected from the MCXC catalog ([21]), in an effort to balance cluster selection and avoid any prior biases towards or against cluster radio properties.

All MGCLS datasets were calibrated and imaged with the basic procedure described in [22] using the Obit package 2 ([23]). The images were corrected for the primary beam at each frequency, as described in [22], both at the full resolution of the image ($\sim 7.5 - 8''$), and at a convolved $15''$ one in order to aid the recovering of low surface brightness features. The very good short baseline spacing of MeerKAT (29 m minimum baseline length) is key for the detection of diffuse radio structures, and allows the full recovery of up to $10'$ extended emission in angular scales (more details on the data and their analysis see [18].

3. First results from the MGCLS diffuse radio emission catalog

The galaxy clusters that have been observed in the MGCLS provide only a glimpse of the many diffuse cluster emission discoveries that are most likely to be made in the Square Kilometre Array era. We provide here an overview and some first results from the detected diffuse radio emission sources. For a detailed description of all clusters with detected diffuse radio sources and a full analysis of their properties see the MGCLS diffuse emission catalog paper (Kolokythas et al. 2023 in prep.)

For each of the diffuse sources, the emission classification in [18] was based on a combination of the full 7″ and 15″ resolution MeerKAT data products with candidate structures being classed those which presented either a marginal detection or an uncertain feature and as 'unknown' those whose the diffuse source wouldn't fit into any of the current classes.

We used a similar strategy as in [18] for the calculation of the flux densities of the diffuse radio sources by estimating the total flux density of a radio structure using the 15″ resolution image and then extracted the contribution of background point radio sources within this region using the full 7″ resolution image. The physical projected sizes were calculated based on the 15″ resolution image.

3.1. Statistical analysis

We find that more than half (∼54%; 62/115) of the observed MGCLS clusters in this Legacy Survey present some kind of diffuse cluster emission, with the total number of diffuse cluster structures or candidates detected being 99 as several clusters are found to host more than one. 57% (56/99) of these structures are noted as new ([18]). Examining the MGCLS sample in more detail, we find that 34% of these new structures are discovered in the radio selected sample (19/56) whereas the majority (66%; 37/56) of the newly detected radio structures are seen in the X-ray selected sample. This suggests that X-ray selected cluster samples are more likely to 'reveal' new radio structures that have been missed by earlier surveys/studies. However we also note that a significant amount of new faint radio structures has also been confirmed/found in the radio selected sample due to the much improved surface brightness sensitivity of the MGCLS at 1.28 GHz.

Our diffuse cluster emission detections can be summarised as follows: 3 new mini-halos and 7 new mini-halo candidates, 25 halo detections and 6 candidates (of which 13 are new), 28 relics and 18 relic candidates (of which 26 are new), 2 new phoenix candidates, one known revived fossil plasma, and 9 diffuse sources with ambiguous or unknown classifications, 6 of which are new. This shows that (including the candidates -c-) only ∼9% (10/115) of the observed clusters present a radio mini-halo whereas the occuring rate for radio halos in clusters is much higher at 27% with the rate of clusters that exhibit at least one relic being 25% (29/115) (as some clusters present more than one relics). Having a look only at the detected radio structures, we see that radio relics are the most commonly detected diffuse structures in MGCLS at 47% (46/99) followed by halos at 32% (31/99) and mini-halos at 11% (10/99). 10% (9/99) of the detected structures is ambiguous/unknown with only 3% (2/99) being candidate Phoenices and just 2% listed as revived fossil plasma (1/99).

The detected MGCLS diffuse radio structures vary significantly in size, flux density, spectral index and radio power, indicating the variety of their properties. We find that the projected sizes in the MGCLS sample range from as small as ∼80 kpc (Abell 2751; cRelic) to as big as ∼2.3 Mpc (Abell 3667; Relic). The estimated flux densities at 1.28 GHz range between as faint as ∼0.4 mJy (c radio mini-halo) and as strong as ∼400 mJy (A3667; Relic), with the radio power ($P_{1.28GHz}$) of the detected structures spanning from $\sim 10^{22}$ W Hz^{-1} to greater than 10^{25} W Hz^{-1}. Examining the in-band radio spectral index distribution between 900 and 1400 MHz we find structures that have regions with relatively flat spectral index ($\alpha_{908}^{1656} \sim -0.50$) with radio relics exhibiting as steep spectra indices as -3.5[1].

4. Conclusions

The first results from the detected diffuse radio emission sources in MGCLS galaxy clusters provide a glimpse of the many diffuse cluster emission discoveries that are most likely to be made in the Square Kilometre Array era that open up new areas of investigation in cluster formation and evolution. One such example is the very faint (low luminosity) radio relic candidates detected by exploiting the excellent surface brightness sensitivity of the MGCLS with another example being the ambiguous diffuse structures in several clusters that do not belong into any of the typical existing classes, a finding which urges the need for new dynamical, particle acceleration, or field amplification processes in the ICM.

[1] The radio spectral index α is defined as $S_\nu \propto \nu^\alpha$, where S_ν is the flux density at frequency ν

5. Acknowledgments

This work is based on the research supported by the National Research Foundation of South Africa (KK & SIL: Grant number 120850). Opinions, findings and conclusions or recommendations expressed in this publication is that of the author(s), and that the NRF accepts no liability whatsoever in this regard. MGCLS data products were provided by the South African Radio Astronomy Observatory and the MGCLS team and were derived from observations with the MeerKAT radio telescope. The MeerKAT telescope is operated by the South African Radio Astronomy Observatory, which is a facility of the National Research Foundation, an agency of the Department of Science and Innovation.

References

[1] van Weeren R J, de Gasperin F, Akamatsu H, et al 2019 *Space Sci. Rev.* **215** 16
[2] Brunetti G and Jones T W 2014 *Int. J. Mod. Phys. D* **23** 1430007
[3] Brunetti G, Setti G, Feretti L and Giovannini G 2001 *MNRAS* **320** 365
[4] Kale R, Venturi T, Giacintucci S, et al 2015 *A&A* **579** A92
[5] Cuciti V, Cassano R, Brunetti G, et al 2021a *A&A* **647** A51
[6] Giacintucci S, Markevitch M, Cassano R, et al 2017 *ApJ* **841** 71
[7] Richard-Laferrire A, Hlavacek-Larrondo J, Nemmen R S et al 2020 *MNRAS* **499** 2934
[8] ZuHone J A, Markevitch M and Lee D 2011 *ApJ* **743** 16
[9] ZuHone J A, Markevitch M, Brunetti G and Giacintucci S 2013 *ApJ* **762** 78
[10] van Weeren R J, Rttgering H J A, Brggen M and Hoeft M 2010 *Science* **330** 347
[11] Rottgering H J A, Wieringa M H, Hunstead R W and Ekers R D 1997 *MNRAS* **290** 577
[12] Bonafede A, Brggen M, van Weeren R et al 2012 *MNRAS* **426** 40
[13] Lindner R R, Baker A J, Hughes J P et al 2014 *ApJ* **786** 49
[14] Cuciti V, Cassano R, Brunetti G et al 2021b *A&A* **647** A50
[15] Di Gennaro G, van Weeren R J, Brunetti G et al 2021 *Nature Astronomy* **5** 268
[16] Shimwell T W, Luckin J, Brggen M et al 2016 *MNRAS* **459** 277
[17] de Gasperin F, Intema H T, Shimwell T W et al 2017 *Sci. Adv.* **3** e1701634
[18] Knowles K, Cotton W D, Rudnick L, Camilo F et al 2022 *A&A* **657**, A56
[19] Kale R, Wik D R, Giacintucci S et al 2017 *MNRAS* **472** 940
[20] Parekh V, Dwarakanath K S, Kale R and Intema H 2017 *MNRAS* **464** 2752
[21] Piffaretti R, Arnaud M, Pratt G W, Pointecouteau E and Melin J B 2011 *A&A* **534** A109
[22] Mauch T, Cotton W, Condon J et al 2020 *ApJ* **888** 61
[23] Cotton W D 2008 *PASP* **120** 439