White Paper: Radio Emission and Polarization Properties of Galaxy Clusters with VLASS

Tracy Clarke (NRL), Tony Mroczkowski (NRC Postdoc), Shea Brown (U. Iowa), Gianfranco Brunetti (INAF), Rossella Cassano (INAF), Daniele Dallacasa (INAF), Luigina Feretti (INAF), Simona Giacintucci (UMD), Gabriele Giovannini (Unibo), Federica Govoni (INAF), Maxim Markevitch (GSFC), Matteo Murgia (INAF), Lawrence Rudnick (UMN), Anna Scaife (Southampton), Valentina Vacca (INAF), Tiziana Venturi (INAF), Reinout van Weeren (CfA)

I. EXECUTIVE SUMMARY

We report here on a broad range of forefront science goals relating to the physics of galaxy clusters that could be addressed by the upcoming Very Large Array Sky Survey (VLASS). Based on these science goals and the complementarity VLASS will have with ongoing and completed surveys, we discuss observation strategies and provide recommendations for the bands and configurations with the most potential for scientific return for the subset of the galaxy cluster community interested in diffuse, non-thermal emission.

The VLASS could provide a major contribution in three key areas of the physics of galaxy clusters:

- The active galactic nucleus (AGN) population in galaxy clusters and the impact of AGN feedback on the intra-cluster medium (ICM). Extended radio galactic structures such as narrow and wide angle tails (NATs and WATs) trace ICM weather, while the radio emission associated with the cluster dominant galaxies is key in the study of the ICM/AGN feedback.

- The origin and evolution of diffuse cluster radio sources. Radio halos, minihalos and relics are direct signposts of the dynamical state of the ICM, and may probe the role of shocks and turbulence in the formation and evolution of large scale structures in the Universe.

- The origin and role of magnetic fields in the turbulent environs of the ICM and in large scale structures. Cluster magnetic fields are known to reach levels of several $\mu$Gauss, but their evolution and growth is not fully understood.

The evolution and interplay of baryons and magnetic fields in clusters, the galaxies within clusters, and large scale structure in general have been identified as key studies for this decade [75] [83]. Toward this end, we recommend VLASS wideband continuum survey strategies that attain high surface brightness sensitivity on scales from a few arcseconds and recover scales out to several arcminutes. The bands and configurations for large scale diffuse cluster emission include S Band (2–4 GHz) in VLA D (and possibly C) Configuration, L Band (1–2 GHz) in C Configuration, and P band (230–470 MHz) in B Configuration. Further, in order to probe cluster weather and feedback from AGN, as well as to subtract sources of contamination from the diffuse large scale emission, we recommend complementary observations in S Band, B Configuration.

II. INTRODUCTION: GALAXY CLUSTERS

Clusters of galaxies are the largest gravitationally bound systems in the Universe, and are dominated by dark matter (~80%). Only a tiny fraction of a cluster’s mass is in the form of stars in galaxies (~3–5%), while the rest (~15–17%) comprises the intra-cluster medium (ICM), which is diffuse hot ($10^7$–$10^8$ K) gas detected in X-ray observations by its thermal bremsstrahlung and highly-ionized line emission. A large improvement in the present knowledge of the astrophysics in galaxy clusters has been obtained in recent years from the study of the ICM through the combination of X-ray and radio observations.

Clusters form by hierarchical structure formation processes. In this scenario, smaller units (galaxies, groups and small clusters) formed first and merged under gravitational pull to larger and larger units in the course of time. Cluster mergers are the primary mechanism by which clusters and superclusters are assembled. Denser regions form a filamentary structure in the Universe, and clusters form at the intersections of these filaments. Major cluster mergers are among the most energetic events in the Universe [107]. During mergers, shocks are driven into the ICM, with the subsequent generation of turbulence. The merger activity appears to be continuing at the present time and, along with feedback from AGNs and star formation, explains the relative abundance of substructure and temperature gradients detected in clusters of galaxies by optical and X-ray observations.

Clusters can reach a relaxed, nearly virialized state characterized by a giant galaxy at the center and enhanced X-ray surface brightness peak in the core. The hot gas in the center has a high density, which implies short radiative cooling times; therefore energy losses due to X-ray emission are dramatic and produce a temperature drop towards the center. Relaxed clusters were then classified as “cooling flow” clusters [44]. This model was the subject of much debate, when XMM-Newton spectral results failed to confirm the lines and features expected as a product of a steady state cooling flow [92] [93]. The classical cooling flow model has finally been replaced by the “cool-core” paradigm where some heating source offsets the catastrophic cooling expected in the cooling flow model.

Galaxy clusters are spectacular systems in the radio band. Obvious radio sources are the individual galaxies, whose emission has been observed in recent decades with sensitive radio telescopes. It often extends well beyond the galaxy optical boundaries, and hence it is expected that the radio emitting regions interact with the ICM. This interaction is indeed observed in tailed radio galaxies, and radio sources filling X-ray cavities at the center of cool-core clusters [e.g. 47][85].

More puzzling are diffuse extended radio sources, which cannot be obviously ascribed to individual galaxies, but are instead associated with the ICM. This radio emission represents a striking feature of clusters, since it demonstrates that the thermal ICM plasma is mixed with non-thermal components. Diffuse sources are typically observationally identified...
as halos, relics, or minihalos according to their size, location in the cluster, polarization properties, and the dynamical state of the host cluster (merging or cool-core) \cite{46}. These systems all require the presence of large-scale magnetic fields and a population of relativistic electrons spread over 100's of kpc to Mpc scales throughout the cluster volume. Further demonstration of the existence of magnetic fields in the ICM is obtained by studies of the Faraday rotation of polarized radio galaxies lying in the background or embedded within the magnetized intra-cluster medium.

Non-thermal components are important for a comprehensive physical description of the intra-cluster medium in galaxy clusters \cite{24,108,113}, and play a major role in the evolution of large-scale structures in the Universe. The discovery of diffuse cluster radio emission presents an important step in the understanding of the physical processes in clusters of galaxies [see \cite{38} for a recent review]. Diffuse synchrotron sources are sensitive to the turbulence and shock structures of large-scale environments and provide essential complements to studies at other wavelengths as well as unique physics not probed by any other wavelength regime. Studies in the radio domain will fill essential gaps in both cluster astrophysics and in the growth of structure in the Universe, especially where the signatures of shocks and turbulence, or even the thermal plasma itself, may be otherwise undetectable.

In the following sections of this white paper, we make the case for the key scientific focus areas for a VLASS survey sensitive to extended non-thermal emission from clusters (§III). We provide a brief overview of relevant multi-wavelength data sets important for cluster studies in §III.F, and discuss available and upcoming radio surveys in the context of their importance for clusters and integration to the VLASS in §III.G. Section IV provides the specifics of the survey configuration possibilities and their applicability to cluster science, and it highlights our recommended survey strategies for maximizing scientific return for cluster astrophysics.

III. EXTENDED NON-THERMAL EMISSION FROM GALAXY CLUSTERS

A. AGN and the Environment: Lifecycle and Feedback

Radio emission from individual cluster galaxies provides invaluable information on the formation and evolution of the hosting structures, mainly along three main branches: (i) AGN activity and AGN/ICM feedback in the central cluster regions; (ii) distorted wide angle tail (WAT) and narrow angle tail (NAT) radio galaxies as probes of the cluster dynamical state and cluster weather, as well as signposts of high-z clusters; (iii) the role of cluster dynamics on the radio emission of individual galaxies through the radio luminosity function.

1. AGN Feedback

Some galaxy clusters known as cool core clusters display highly peaked X-ray emission and are generally hosts to cluster-center radio galaxies (CCRGs). The probability of hosting a CCRG increases from 45% for non-cool cores to 67% for weak cool core and up to 100% for strong cool core clusters \cite{87}. These powerful active galactic nuclei (AGN) are currently considered one of the favored sources of energy input into the ICM to offset radiative cooling which, left unopposed, would eventually develop into a runaway cooling flow \cite{43}. AGN-induced feedback is also considered a key component in shaping the luminosity function of the host galaxy \cite{38}, it may set the upper limit to host galaxy masses, and it is expected to contribute to pre-heating of the ICM \cite{41}.

Deep X-ray observations toward cool-core systems discovered X-ray cavities filled with synchrotron plasma visible at GHz frequencies. The most well-studied AGN cavity systems are Perseus \cite{45}, Abell 2052 (\cite{11}; see Figure 1), Hydra A \cite{128}, Virgo A \cite{39}, and NGC 5813 \cite{101}. These observations clearly indicate that the radio galaxy is significantly impacting the ICM, inflating cavities in the thermal gas and driving weak shocks and sound waves through the ICM. These bubbles are expected to detach and buoyantly rise through the ICM after the central AGN activity decreases. In addition to the energy injection, these rising bubbles provide a means of seeding the ICM with magnetic fields and relativistic particles.

X-ray observations are only able to easily detect small cavities near the plane of the sky at relatively small distances from the cluster core. Larger cavities at large distances from the core, where the ICM is more diffuse, as well as those at small angles from the line of sight do not provide sufficient contrast for detection in even moderately deep X-ray observations \cite{45}. On the other hand, radio observations of CCRGs provide methods to place observational limits on the energy injected into the ICM by AGN feedback by tracing the complete kinetic feedback history of the ICM over multiple AGN outburst cycles. As a matter of fact, a number of central galaxies in clusters and groups are characterised by extended (10–100 kpc) diffuse and faint aged synchrotron emission, best detectable at frequencies of few hundred MHz, with an active radio nucleus, whose spectrum clearly shows ongoing activity. Despite the many uncertainties, the study of the radio spectrum in the aged and active components provides reliable information on the cycles of activity of CCRGs, and the total energy output delivered into the cluster ICM throughout the cluster lifetime (e.g. \cite{52}).

FIG. 1: AGN feedback in Abell 2052 (z = 0.035), from \cite{11}. 

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WAT and NAT radio galaxies are the most spectacular examples of radio emission from elliptical galaxies (see Figure 2). Their shape is the signature of galaxy cluster membership, and is explained as due to the combination of motion of the host galaxy within the cluster and intra-cluster bulk motion. Spectral studies along the tails provide estimates of the age of the radio plasma, which in turn can be used to infer the galaxy velocity within the cluster, and information on the dynamical state of the cluster. Due to their unique association with dense environments, WATs and NATs can be used to easily identify high-z galaxy clusters. Note that high-z clusters require significant observational efforts for detection in the X-ray and optical bands, while they are fairly accessible with high resolution (arcsecond scale) radio observations.

In this way, wide radio surveys that discover WATs and NATs nicely complement the ongoing surveys that exploit the redshift-independent surface brightness of the Sunyaev-Zel’dovich (SZ) effect, which is now being used to locate previously unknown clusters at high-z (see [111]).

Radio galaxy bending, forming WATs, NATs, or even distorted FRII radio galaxies, is sensitive to the pressure gradients and the relative motions through the ICM. While simple swept-back radio structures could be due to galaxy motions, more complicated morphologies require ‘weather’ in the cluster, as expected by the ongoing accretion of material along filaments. This weather is normally undetectable in X-ray or SZ observations, and is only visible in those regimes when there is a significant contact discontinuity (i.e. a shock or cold front). However, radio galaxy distortions can easily pick out the transonic or even subsonic motions that persist even when the cluster may appear relaxed in the X-rays. Such studies will require large samples to eliminate structures that could simply be due to cluster motion, and to look for the correlations between weather indicators and evolutionary state as indicated from X-ray or SZ images. We also highlight here the strong complementarity of these observations with X-ray observations with ASTRO-H, and with Athena+ in about 15 years, that are aimed at the measure of turbulent motions from the study of metal lines in the X-ray spectra of galaxy clusters.

One critical discontinuity that has so far eluded detection is the accretion shock for massive clusters likely exists at several Mpc from the cluster center, outside the virial radius, but the thermal gas is currently too diffuse to be detectable directly in X-ray observations. Radio galaxies have the potential, however, to statistically map out this critical transition region, because a galaxy’s infall through the shock region will be relatively unaffected, while the tails will be disrupted as they interact with the shocked ICM. Rudnick and students (2013, in preparation) have used the bending classifications of FIRST sources by Wing and Blanton [127] to examine the prevalence of bending as a function of distance from the cluster center. While a cluster-associated population of WATs/NATs can be statistically detected out to at least 10 Mpc, the numbers are so far only high enough to detect tail disruption within the inner ~ 1 Mpc. With larger samples enabled by probing > 1.5× deeper than FIRST and recovering the larger scales appropriate to WATs/NATs (see Table I), this pioneering work may be extended to larger cluster radii, with the potential of identifying the otherwise invisible accretion shock.

3. AGN–ICM Connection and Scaling

A longstanding question in our understanding of the trigger of nuclear radio activity in AGN is whether the environment plays a role, and how. The radio luminosity function for galaxies in different environments is the primary statistical tool for investigation in this area. The wealth of data available from public archives in the X-ray and optical bands now allows us to address the role of cluster dynamics (i.e. merger versus relaxed systems) on the AGN activity. This research has been impossible until recently, and has been limited mainly by the statistical information in available radio survey data.

A new L or S band survey of intermediate depth (~70–90 μJy/bm) would considerably increase this statistical information. An improved sensitivity of a factor of 5–7× over NRAO VLA Sky Survey (NVSS; [37]) would bring the radio power limit down to ~ 10^{20} W Hz^{-1} in the local Universe (i.e. z = 0.02), thus allowing exploration of the faint end of the radio luminosity function and separation of the AGN and starburst contribution. At higher redshifts (e.g. z = 0.2–0.5), the radio power limit would be of the order of ~ 10^{23} W Hz^{-1}, still within the FRI range. This will allow the study of both evolutionary and environmental effects in the population of low and high luminosity radio galaxies (FRI and FRII).

B. Dynamically Complex Clusters: Halos and Relics

In about 70 clusters, diffuse, Mpc-scale radio emission has been found, implying the presence of relativistic particles and magnetic fields. These giant halos and relics are only found in dynamically disturbed clusters that show clear evidence for undergoing one or multiple merger events (see Figure 3). Halos and relics generally have steep synchrotron spectra (α ≤ −1, where flux density S_ν ∝ ν^α), large physical extents (~1–1.5 Mpc), and 1.4 GHz radio powers in the range of 10^{23–26} W Hz^{-1} [see 48 for a recent review]. An important aspect of the study of halos and relics concerns the origin of the relativistic particles and magnetic fields. The lifetime of the synchrotron radiating electrons is much shorter than the
FIG. 3: The merging cluster Abell 2256 ($z = 0.0594$) shown in X-rays in red and green image and radio (1.4 GHz) in blue and white contours. The X-ray emission shows two clear peaks, indicating a significant on-going merger, and the radio shows the presence of a Mpc scale central radio halo as well as Mpc radio relics. Figure is from Clarke and Ensslin [36].

diffusion time necessary to fill the volume these sources occupy. Therefore a form of in-situ particle (re)acceleration is required.

Giant radio halos are centrally located and are distributed co-spatially with the X-ray emitting intra-cluster medium (ICM). For radio halos there is a correlation between the X-ray luminosity $L_X$ (i.e., cluster mass) and radio power $P_{1.4\text{GHz}}$ (e.g. [77]; see Figure 4). The fraction of clusters hosting radio halos is still uncertain. Current statistical analyses suggest roughly 30–40% of the most X-ray luminous systems at low/intermediate redshifts ($z \lesssim 0.4$) host radio halos [57, 122, 124], while there is evidence that this fraction decreases at lower X-ray luminosity and mass [31, 34]. A complementary approach using massive, SZ-selected clusters from the Planck catalog indicates the fraction of SZ-selected clusters hosting radio halos is much higher (~80%) [112].

Radio halos have been explained by turbulence injected by recent merger events, which re-accelerates relativistic particles [25, 94]. In a competing model, the energetic electrons are secondary products of proton-proton collisions (e.g., [40]); however, important progress has been made that disfavors this second scenario. This includes (i) the discovery of ultra-steep spectrum radio halos that likely cannot be explained by secondary models [26], (ii) a clear relation of halo host clusters with merger signatures [23, 32], and (iii) the lack of $\gamma$-ray detection by Fermi [2, 27, 129]. This progress has been achieved by carrying out observations of representative cluster samples [68, 122, 124], as well as by targeted deep observations [e.g., 20, 48, 79].

Unlike halos, relics (again, see Figure 3) are mostly found in the outskirts of clusters and show a high degree of polarization. Like halos, the fraction of clusters with radio relics has been found to increase with $L_X$, to about 30% for the most massive clusters [90, 119]. Particularly interesting are the class of double relics, with the two relics located symmetrically on opposite sides of the cluster center tracing the two outgoing merger shocks (e.g., [6, 13, 16, 67, 117, 118, 120]). These relics often show spectral index gradients (rather than being described by a single or broken power law), as expected if they trace merger shocks traveling outwards. Long ($\gtrsim 500$ kpc) relics have been explained by particles directly (re)accelerated at shocks by the diffusive shock acceleration mechanism (DSA) in a first order Fermi process. How-

FIG. 4: Radio halo power and VLASS sensitivity to giant halos as a function of cluster mass and X-ray luminosity, using the approach in [22, 33] and the information in Table III. [34] estimated the sensitivity of surveys to giant halos by taking into account the brightness distributions of radio halos. The yellow region marks the sensitivity of VLASS in the redshift range $z = 0.2–0.3$, equivalent to the redshift range of the GMRT halos (for details see [34]). Based on these calculations, a survey in L or S Band would not differ significantly in its ability to detect new halos. Consequently, we report the case of L Band in C Config with RMS $= 1.5 \times$ the confusion (Table III). The dashed line is the sensitivity at $z = 0.5$. 
ever, cluster merger shocks typically have low Mach numbers ($M \sim 1-3$, e.g., [51 69 71 82]) and the efficiency with which such shocks can accelerate particles is unknown. Therefore, re-acceleration of pre-accelerated electrons in the ICM might be required to explain the observed brightness of relics, since re-acceleration is a more efficient mechanism for weak shocks (e.g., [51 69 71 82]). Such preexisting relativistic electrons could be fossil radio plasma deposited in the ICM by active radio galaxies. The shock re-acceleration model also explains why in some cases clear shocks are observed in the X-rays while no radio relics are present [105].

The properties of radio halos and relics provide direct proof of the presence of relativistic electrons and magnetic fields within the cluster volume. Hence, studies of these features provide a unique opportunity to probe the strength and structure of the magnetic field on Mpc scales [e.g. 116]. Of equal importance, the location and properties of these diffuse non-thermal sources can be related to cluster characteristics derived from optical and X-ray observations, and are tightly connected to the cluster’s evolutionary history. In particular radio halos and relics are always located in clusters showing merging processes even if not all merging clusters show the presence of a diffuse radio emission. The VLASS survey could address the remaining gaps in the particle acceleration mechanisms through deep observations of a few of these complex merging environments as well as through statistics from a large survey providing information on the relativistic particle and magnetic field content across a range of cluster environments.

In Figure 4 we show predictions for radio halo detection in an L or S Band survey that approaches 1.5x the confusion limit, corresponding to a sensitivity of 16 $\mu$Jy/bm for L Band in C Config or 21 $\mu$Jy/bm for S Band in D Config (see Table III). At these sensitivities, VLASS would be complete to $M_{500} \sim 3 \times 10^{14} M_\odot$ at $z \sim 0.3$, a factor of 2 lower than current surveys with the GMRT, which are only complete at the ~ 50% level percent for $M_{500} > 6 \times 10^{14} M_\odot$. A deep VLASS would therefore chart unexplored territory in radio halo statistics.

C. Dynamically Relaxed Clusters and the Radio Minihalos in Their Cores

Some dynamically-relaxed clusters are known to host centrally-located, diffuse synchrotron radio emission in their cores, that typically fills the central cooling region ($r \sim 50 – 300$ kpc; see Figure 5). These extended radio sources – called minihalos – typically have low surface brightnesses ($> 2 \mu$Jy arcsec$^{-2}$) and steep radio spectra ($\alpha < -1$) [53]. Their emission encompasses the often-present central radio galaxy but extends to greater radii. An example is the minihalo in Perseus cluster, whose emission spans much larger radii than the inner $r \sim 30$ kpc region occupied by the prominent X-ray cavities and lobes of $3C$ 84. Only 15 clusters have confirmed minihalos, all of which are hot and massive systems with very X-ray luminous cool cores (Giacintucci et al. [53] and references therein).

The origin of these minihalos is still unclear. One attractive possibility is that the radio emission arises from pre-existing, aged relativistic electrons (for instance, from past activity of the central radio galaxy and/or hadronic collisions) that are being re-accelerated to ultra-relativistic energies by turbulence in the ICM [60]. Sloshing of dense gas in the cluster cores, revealed by arc-shaped cold fronts often observed in high-resolution X-ray images of cool-core clusters, can amplify the magnetic field in the core and generate turbulence that may be strong enough to re-accelerate low-$\gamma$ electrons to $\gamma \sim 10^5$. The combined effect is diffuse radio emission with morphology, radio power, and spectral index consistent with the observed minihalos [130]. A spatial connection of the minihalo radio emission and the X-ray sloshing cold fronts has indeed been observed [53 84 130], supporting the hypothesis that radio-emitting electrons are re-accelerated by sloshing. This opens an interesting possibility of studying low-level turbulence in the cores of relaxed clusters and – in conjunction with the forthcoming X-ray probes of ICM turbulence (Astro-H and possibly other future missions) – the efficiency of cosmic ray acceleration by MHD turbulence. Despite recent theoretical effort, the study of minihalos has been severely limited by their small number; only a fraction of cool-core clusters are known to host minihalos. A much larger sample is needed to determine their occurrence in clusters of various masses and cool-core types in order to investigate their origin and the relevant aspects of the ICM physics.

D. Whither the WHIM: Where is the Warm Hot Intergalactic Medium?

Approximately 50% of baryons in the Universe are currently unobserved, based on the estimates of $\Omega_b$ from nucleosynthesis and WMAP [13]. Simulations suggest that the collapsing diffuse intergalactic medium (IGM) was shock-heated and now resides in filaments as the warm-hot intergalactic medium (WHIM) with temperature $T \sim 10^5$–$10^7$ K (see Figure 6). Due its temperature, it is practically invisible at X-ray and optical wavelengths [35 39]. However, shocks and turbulence from infall into and along the filamentary structures between clusters are now widely expected to generate relativistic

FIG. 5: VLA 1.4 GHz observations (contours) of RX J1532.9+3021 ($z = 0.36$) overlaid on the Chandra X-ray image. The extended minihalo is denoted by white contours to separate it visually from the central AGN. Figure is from Giacintucci et al. [53].
plasmas which track the distribution of the WHIM (the “Synchrotron Cosmic-Web”, [4, 73, 96, 106, 110]). If such features are detected in the radio, they can be used to set limits on the (invisible) pressure of the thermal gas, delineate shock structures, and illuminate large scale magnetic fields.

However, observational confirmation of this paradigm remains to be seen. Obstacles include very low intrinsic surface brightness (< µJy arcmin−2 levels; [7, 95]), large spatial scales (> Mpc), and numerous sources of confusion (see [22] for a review). The most promising avenue for the VLASS to detect synchrotron emission associated with the WHIM is to detect shock structures in the filaments surrounding massive clusters of galaxies, including the powerful virial shocks. At frequencies greater than 1 GHz, radio observations suffer from lower intrinsic source surface brightness and insensitivity to large angular scales. However, polarization observations will provide the biggest gains when working above 1 GHz, especially when searching for these shock-structures. Structure formation shocks onto and along filaments are predicted to be narrow, flat spectrum ($\alpha > -1$), and highly polarized (e.g., [106, 111]). Therefore, both direct and statistical detection of these shocks can ideally be performed at $\nu > 1$ GHz (e.g. S Band). At the levels proposed by the VLASS survey in S-Band, only shocks with enhanced brightness due to, e.g., interaction with extended radio galaxies, would be detected directly. Stacking clusters with similar mass and distances, however, could reveal emission due to virial shocks if present [21].

E. Faraday Rotation Measure (FRM) Synthesis/Polarization

Magnetic fields can be found in almost every place in the Universe and most of the luminous matter we can observe is coupled to these fields. The onset of star formation, the density and distribution of the interstellar medium, the gaseous halos of radio galaxies and the evolution of galaxies themselves are all controlled in large by the action and presence of these magnetic fields. However, it is in clusters of galaxies where a knowledge of the importance of evolution of magnetic fields is crucial for our wider understanding of structure formation and cosmology. The existence of cluster-wide magnetic fields from diffuse synchrotron emission has been found in a number of clusters (see §III B), with the radio emission spanning several Mpc and in some cases following the filamentary networks of galaxies. The magnetic field strengths derived from such emission are intriguing as they suggest field strengths which are dynamically significant, but not dominant. As well as ordered fields in clusters, associated measurements using the Faraday rotation of background or embedded cluster radio sources have produced evidence for a tangled field, although current constraints on the slope of the power spectrum are poor. With improved observational constraints, clusters can provide an excellent experimental environment in which to test theories of MHD turbulence in large-scale structure and, with improved instrumental characteristics and data processing, even weaker fields will become observable, both within clusters of galaxies and in the wider web of large-scale structure.

Observations of such fields are important not only for cluster physics, but also for constraining the origin of cosmic magnetism more generally: early type seed fields may be truly primordial, with a seed field formed prior to recombination; alternatively fields can be produced by the Weibel instability - small scale plasma instabilities at structure formation shocks; late type fields can be injected into the WHIM via super-massive blackholes and other outflows. Within evolved clusters, highly efficient amplification is expected to occur; however, in spite of this, a clear distinction between the evolution of the magnetic field strength with redshift is expected in the case of early and late type fields.

In order to extract the maximal information contained in the polarization components of both background and embedded cluster radio sources it is necessary to use the technique of RM Synthesis [19], whereby the depolarization caused by Faraday rotation in wide bandwidth data when averaging for optimal sensitivity is avoided. This technique uses the pseudo-Fourier relation between wavelength squared and Faraday depth to construct the Faraday depth spectrum along the line of sight.
for each direction, isolating features of particular Faraday depth and preserving the information content of the full bandwidth. The further analysis of such Faraday spectra is a field still in its infancy, although rapid progress is now being made, as these spectra provide a uniquely powerful tool for probing a wide range of different astrophysical environments.

Faraday rotation itself is caused when polarized emission passes through a magnetized ionized medium, such as the ICM. The degree of rotation which affects that emission is a linear function of both the electron density and the parallel component of the magnetic field strength along the line of sight. Unlike other methods commonly used to probe the magnetic content of clusters it does not necessarily rely on model dependent parameters, the presence of a non-thermal particle population or assumptions of equipartition and provides independent complementary information to field strength measurements derived from such methods. The linear dependencies of rotation also make it ideal for examining regions where both electron density and magnetic field strength are expected to be low, such as the outskirts of clusters and potentially the inter-cluster medium and wider cosmic web of large-scale structure.

Resolution in Faraday depth space is determined by \( \Delta \lambda^2 \), the width of the \( \lambda^2 \) coverage of the observation. A large \( \Delta \lambda^2 \) improves the resolution and also removes \( nt \) ambiguities. RM synthesis with the VLA provides \( \Delta \phi_s \approx 200 \, \text{rad} \, \text{m}^{-2} \) (in S Band) or \( \Delta \phi_L \approx 50 \, \text{rad} \, \text{m}^{-2} \) (in L Band) resolution in Faraday depth – note this is the FWHM of the rotation measure transfer function (RMTF), not the accuracy with which an RM can be recovered, which is a function of signal-to-noise. The maximum observable Faraday depth before bandwidth depolarization within a single channel becomes important is \( \gtrsim 5000 \, \text{rad} \, \text{m}^{-2} \) at both L- and S-band, far higher than is expected for cluster RMs. The maximum observable Faraday width of a feature which is extended in Faraday depth space (i.e. mixed rotation and emission) before strong depolarization occurs is \( \Delta \phi_{\text{max},L} \approx 35 \, \text{rad} \, \text{m}^{-2} \); \( \Delta \phi_{\text{max},S} \approx 140 \, \text{rad} \, \text{m}^{-2} \).

Detailed studies of Faraday depth can give information on the magnetic field distribution at different locations in galaxy clusters [e.g. 14, 17], in clusters in a different physical state [e.g. 15] and in clusters at different cosmological distance.

Recently Govoni et al. [63] demonstrated that simulated radio halos are intrinsically polarized at full-resolution. The fractional polarization at the cluster center is \( \sim 15-35 \% \) with values varying from cluster to cluster and increasing with the distance from the cluster center. However, the polarized signal is undetectable if observed with the comparatively shallow sensitivity and low resolution of current radio interferometers. However Govoni et al. [63] found that surveys planned with the SKA precursors will be in principle be able to detect the polarized emission in the most luminous halos known, while the halos of intermediate and faint luminosity will still be hardly detectable. In particular they showed that the VLA already has the potential to detect polarized emission from strong radio halos.

**F. Multi-wavelength Complementarity**

A number of ongoing and completed cluster surveys provide useful catalogs for studying the non-thermal emission from the ICM, directly and through stacked statistical results that will probe how the radio properties scale with cluster mass and thermal properties. VLASS will be the top level radio survey to study non-thermal properties in the Universe.

The primary energy band used in comparisons that constrain non-thermal astrophysics of diffuse sources in galaxy clusters is the X-ray, which probes the dynamical and thermal properties of the ICM. Statistically, a large improvement in the number of known cluster diffuse radio sources was obtained in a cross comparison by Giovannini et al. [50] of the NVSS radio survey with the the sample of X-ray-brightest Abell-type clusters (XBACs) [42]. The XBAC sample comprises 283 clusters/subclusters from the catalogue of Abell et al. [11] (ACO) detected in the ROSAT All Sky Survey (RASS). Indeed, most radio statistical analyses are derived from X-ray data [29, 32, 109] and properties of radio emission are characterized in general using X-ray temperature and luminosity [see e.g. 54 and references therein]. Predictions based on turbulent re-acceleration models agree well with the radio observations of halos [30]. In this sense, strong spatial correlations between X-ray and radio brightness and between SZ-signal and radio brightness are also found in a number of cases (e.g. [61, 89, 112]).

The upcoming eROSITA X-ray satellite [131] [100] will soon launch, and will perform the first all-sky X-ray survey in over the two and half decades since the ROSAT All-Sky Survey (RASS). Just as NVSS and RASS were complementary in many respects, VLASS and eROSITA All-Sky Survey (EASS) are well timed to complement each other. EASS is expected to find \( \sim 9 \times 10^4 \) clusters above a mass of \( 0.7 \times 10^{14} \, M_\odot \) [97]. Using the radio halo power – X-ray luminosity scaling relations of [54], all clusters with an \( L_X > 10^{45} \, \text{erg} \, \text{s}^{-1} \) at \( z < 0.6 \) will be detectable at \( > 5 \sigma \) for an L or S Band survey reaching 100 \( \mu \text{Jy} \). For a standard ACDM cosmology and a typical “on” fraction of 30\%, this is roughly 80 clusters in a wide-area (30,000 deg\(^2\)) survey with VLASS, using the predicted cluster counts in [86]. While uch lower radio powers will be accessible at lower redshifts (\( z \leq 0.2 \), see Figure [3]), this argues that a deep survey or targeted follow-up of EASS-discovered clusters will be necessary to probe to lower radio powers (and \( L_X \)) at high-\( z \).

Optical information, such as that provided by the Sloan Digital Sky Survey (SDSS) [132], Dark Energy Survey (DES) [133], or the Large Synoptic Survey Telescope (LSST) [134], is another important way to investigate the dynamics of cluster mergers [59]. The spatial distribution and kinematics of galaxy members allow us to detect substructures and to analyse possible pre- and post-merging groups, and to distinguish between evolving mergers and remnants. Moreover, optical data are complementary to X-ray information because the ICM and galaxies react on different timescales during a collision Roetgter et al. [103]. The importance of combining X-ray and optical data to study merger scenarios has been clearly shown by, for example, the simulations of the Multi-wavelength Sample of Interacting Clusters (MUSIC) project [89].

Increasingly, microwave observations of the galaxy clusters are being used to probe galaxy cluster astrophysics as well. The Planck satellite recently completed the first all-sky survey to exploit the inverse Compton scattering of photons from the cosmic microwave background (CMB) – known as the Sunyaev-Zel’dovich (SZ) effect – to locate previously unknown galaxy clusters. Analysis of the first 15.5 months of
Planck data has produced a catalog of 1,227 clusters [69]. A large fraction of these clusters are massive, disturbed systems which have extended diffuse radio emission in the form of halos and/or relics. ACTPol [89], the polarization and detector upgrade to the Atacama Cosmology Telescope, is now performing a deep, arcminute-resolution SZ survey of roughly 4,000 square degrees of the southern sky at $\delta \geq -40^\circ$, accessible in a wide VLA survey of the sky. Projections for ACTPol indicate it will locate >1,000 clusters with a higher median redshift than those in the Planck catalog.

G. Concurrent and Upcoming Radio Surveys

A number of completed, ongoing, and planned radio surveys – such as NVSS, FIRST, WENSS, WISH, VLSSr, POSSUM, WODAN, SUMSS, TGSS, EMU, MIGHTEE, and LOFAR-MSS to name a few – also will complement VLASS. These surveys will be summarized in a concurrent white paper by the VLASS Science Organizing Committee (Myers et al. 2014, in prep.). We include here a figure from Jarvis et al. 2014 [66] summarizing these surveys’ sensitivities and areal coverage (see Figure 5), noting the sensitivities listed are largely valid for unresolved, compact (point) sources, and do not address the sensitivities required for diffuse extended emission.

After the discovery of the Coma radio halo at 408 MHz with the 250-ft radio telescope at Jodrell Bank [76], confirmed from interferometric Cambridge One-Mile telescope radio data [126], observations carried out mostly with single dish radio telescopes, and the WSRT found about 10 other clusters with a diffuse halo-type radio emission [see 64].

A significant breakthrough in the study of radio halos and other diffuse cluster radio sources was obtained thanks to the NRAO VLA Sky Survey (NVSS). Giovannini et al. [56], combining radio data from the NVSS and X-ray catalogues, detected 18 new halo and relic candidates, in addition to the 11 already known, owing to the good surface brightness sensitivity of the VLA D configuration used for NVSS. All new candidates were confirmed by more sensitive targeted follow-up observations, mostly performed with the VLA. Kempner and Sarazin [72] presented seven new candidates from a search in the Westerbork Northern Sky Survey [WENSS] at 327 MHz. Recently, other extensive radio observations have been published, such as the recent Giant Metrewave Radio Telescope (GMRT) survey of massive galaxy clusters at $z = 0.2$–0.4 [121] [123].

The NVSS is even now still a great resource for finding diffuse cluster radio sources. Most of the halo and relic sources studied in detail with deep multi-frequency observations started with a preliminary identification within the NVSS. In the latest cluster diffuse emission review [49] identified the current sample of 42 radio halos, 39 relics (including double relics), and 11 minihalos. This number is increasing however as new more sensitive observations are made.

In spite of the many encouraging results obtained, we do not know yet a few important points for a deeper knowledge of the non-thermal emission in clusters of galaxies. Key is the occurrence and the luminosity function of diffuse radio sources. The correspondence between cluster mergers and the presence of a diffuse radio emission is well established, and this dichotomy is supported by many observational and theoretical papers. Luminous relaxed X-ray clusters are not expected to show a radio halo or relic. What is uncertain still is if all bright X-ray clusters in a strong merger phase have diffuse non-thermal emission. The crucial question remains, namely how the collision of massive clusters gives rise to the wide range of observed non-thermal properties which run the gamut from radio quiet to the presence of a radio halo and/or one or more radio relics. Since mergers with similar global properties (e.g., mass, X-ray luminosity, radio-galaxy luminosity function) often exhibit very different non-thermal properties, the key to understanding the origin of the diffuse radio emission is likely to lie in the details of the complex interactions of the cluster constituents (dark matter, intra-cluster gas, galaxies) during a merger event, and how they relate to and affect the non-thermal components, i.e., relativistic particles and magnetic fields embedded in the ICM. In order to shed light on this point a survey with a better sensitivity with respect to the NVSS will be necessary.

Another crucial point is the redshift distribution of radio halos and relics. This is an important component missing in studies of the evolution of magnetic fields properties in clusters. Most of the clusters studied up to now are at $z < 0.3$. Only 9 radio halos, 5 relics and 1 minihalo are known at $z > 0.3$. However the recent detection of the radio relics and halo in the El Gordo massive cluster at $z = 0.87$ [78], suggests that a possible population of diffuse sources in high redshift clusters could be present, but we need a deeper and higher angular resolution survey with respect to NVSS.

A third point is the study of structure beyond galaxy clusters. Cosmological theories and simulations predict that galaxy clusters are connected by intergalactic filaments along which they accrete mass. Shocks from infall into and along the filaments are expected to accelerate particles. These accelerated particles can emit synchrotron radiation if cosmic magnetic fields are present. Attempts to detect diffuse radio emission beyond clusters, i.e. in very rarefied regions of the intergalactic space, have shown recent promise in imaging diffuse synchrotron radiation of very low level.

Some examples of this emission are the filament surrounding the cluster ZwCl2341.1+0000 [55], the bridge connecting A399 and A401 [69], the X-ray filament between A222 and A223 [125], the structure in A3444 [57], and the diffuse radio bridges connecting the halo to the relic observed in Coma [20] [55] [74] and A2255 [62] [98].

All these data support the existence of an intergalactic magnetic field more widespread and somewhat lower than that in the intra-cluster medium within clusters. This field may represent the seed field for galaxies and clusters, and may play an important role in the formation of large-scale structure.

IV. OBSERVATIONAL REQUIREMENTS TO ADDRESS FOREFRONT GALAXY CLUSTER SCIENCE

In this section we consider the fact that the VLASS will be designed to accommodate a wide range of scientific goals and thus currently the frequency (or frequencies) as well as configuration(s) of the survey are uncertain. We therefore consider combinations of frequencies and VLA configurations and highlight the implications for extended cluster emission studies.

In Table 4 we summarize common cluster radio features and their physical and angular scales for a few redshifts of interest.
TABLE I: Characteristic physical and angular scales of extended radio emission features in clusters at $z = 0.1–0.5$

| Feature         | Scale (kpc) | $\theta(z = 0.1)$ (°) | $\theta(z = 0.2)$ (°) | $\theta(z = 0.3)$ (°) | $\theta(z = 0.5)$ (°) |
|-----------------|-------------|------------------------|------------------------|------------------------|------------------------|
| AGN Jets        | 10–100      | 5.4–54                 | 3.0–30                 | 2.2–22                 | 1.6–16                 |
| WATs/NATs       | 10–100      | 5.4–54                 | 3.0–30                 | 2.2–22                 | 1.6–16                 |
| Relics          | 10–1000     | 5.4–540                | 3.0–300                | 2.2–220                | 1.6–160                |
| Minihalos       | 50–300      | 27–162                 | 15–90                  | 11–66                  | 8.2–49                 |
| Halos           | 1000–1500   | 540–810                | 300–450                | 220–340                | 160–250                |
| Bridges/Filament| >1500       | >810                   | >450                   | >340                   | >250                   |

Note that because of effects of the volume of the observable Universe, merger rate, the higher efficiency of cooling by inverse Compton scattering of CMB photons at high redshifts, the cluster halo numbers are expected to peak in the redshift range $z = 0.2–0.5$ [30]. However the recent detection of 2 radio relics and a halo in the high-$z$ ($z = 0.87$) SZ-selected massive cluster “El Gordo” suggests that an exciting population of diffuse sources in high redshift clusters could exist [78].

A. Angular and linear scales

From the science drivers described above for this white paper, it is clear that the VLASS must be able to probe scales from tens of kpc to $\gg 1$ Mpc over a wide range in redshifts. In particular:

- Mpc scale halos and (potentially) large scale filamentary structure are the principle drivers for the largest angular scale (LAS) requirements. For instance, a radio halo of 1 Mpc (typical value for this class of sources), has an angular extent of $\sim 9'$ at $z = 0.1$, $\sim 3'$ at $z = 0.4$, and $\sim 2'$ at $z = 0.8$.

- Minihalos are generally $\sim 100–300$ kpc in scale, so are a less severe of a constraint except for the most nearby systems. For instance, a 300 kpc minihalo would have a LAS $\sim 6.5'$ at $z = 0.04$.

- Radio relics can be more than one Mpc long in one direction but are compact and filamentary in the direction perpendicular to the shock that generates them. In a sky survey this is not an issue in terms of LAS since the areal coverage includes the entire relic and the narrow axis should be much less stringent of a constraint than halos or minihalos.

- The radio emission from individual galaxies does not pose severe constraints on the largest angular scales, exception made for possible Mpc–size nearby extended radio galaxies. On the other hand, angular resolutions of the order of few arcseconds, i.e. in the range 3''–20'' would be necessary to cover both the nuclear activity and to study the emission along the jets and lobes over a wide range of redshifts.

- In terms of angular resolution, a range between 10'' – 20'' would be wide enough to accommodate observa-
tions of minihalos, giant radio halos, and radio relics over a wide range of redshifts and intrinsic linear scales.

- For the detection of diffuse radio sources, the sensitivity to low surface brightness emission is the critical parameter. The surface brightness of cluster diffuse sources can be as low as \(1 - 0.2 \mu Jy \text{arcsec}^{-2}\). Assuming a survey depth of 100 \(\mu Jy\) RMS (see Sect. 4.4), we will need a relatively large beam to image these low brightness sources (S-Band, D array will produce images with a brightness sensitivity of 0.2 \(\mu Jy \text{arcsec}^{-2}\) or even better; C array images in the S Band will have only a sensitivity of 2 \(\mu Jy \text{arcsec}^{-2}\)).

B. Observing frequencies and polarization studies

Two important considerations regard the spectral and polarization studies of the emission. Both are critical to understanding the underlying astrophysics of these sources.

Mpc-scale cluster radio sources, i.e. both classical GHz radio halos and relics, have a spectral index of roughly \(\alpha \sim -1.3\). While relics can be studied at up to 5 GHz with sufficient sensitivity to smooth large scale emission (e.g. [51]), only the Bullet Cluster ([77]) and the Coma cluster have been imaged above 1.4 GHz. Radio minihalos have similar spectral indices and current studies of minihalo systems show that they can be studied at up to, and possibly above, 5 GHz ([53]).

For a few cases, the spectra of radio halos and relics are not well described by powerlaws, and a steepening at higher frequencies is observed. A clear example is the prototype radio halos in the Coma cluster [28,115]. The location of the break is closely related to the (re)acceleration processes at play, and is thus important to constrain.

The 2–4 GHz frequency range (S Band) is best suited to detect the spectral break in nearby relics and minihalos; S Band observations in D array be a critical configuration in which to obtain data. On the other hand, the steeper spectrum halos driven by smaller-mass mergers and those relics due to adiabatic compression of fossil radio plasma will however be below detection limits at frequencies above 400 MHz. For these sources, observations with the VLAs new P Band will be necessary. See the VLASS white paper on VLITE by Clarke et al. as a possible small effort addition to obtain 10 antenna narrow-band P Band data simultaneously with VLASS.

Polarization studies at low frequencies suffer significantly from depolarization as well as large Faraday rotations (see Mao et al. 2013 VLASS white paper) whereas the highest frequencies are only sensitive to very high RMS through the densest media. Studies in the 2–4 GHz regime are well-suited to RM synthesis studies of the ICM, where RMS can range from ~10–1000 rad/m\(^2\) (see [III]). We recommend that any survey taken in the cm range be done with full polarization capabilities in mind.

C. Considerations on the frequency selection

Following on the legacy of NVSS and FIRST [3], it is tempting to consider L Band, especially considering that L Band is now 1 GHz wide, thus covering a frequency range which is particularly interesting for galaxy cluster science. However, the fractional contamination of L Band is large, leaving typically 60% unflagged bandwidth, and a wide L Band VLASS may offer only an incremental improvement over FIRST and NVSS. With the upcoming EMU [135], POSSUM [136], and MEERKAT [137] surveys of the sky observable with the Australian and South African SKA Pathfinders, it becomes increasing difficult to justify L Band except to provide a Northern complement that extends their coverage to the entire sky.

| Band | Freq (GHz) | Bandwidth (GHz) | \(t_{\text{int}}\) (s) | \(\theta_{\text{mb}}\) (") | \(\theta_{\text{res}}\) (") | Mapping Speed | Scan Rate (deg/hr) | Scan Rate (deg/m) |
|------|------------|-----------------|----------------|----------------|----------------|--------------|------------------|------------------|
| P    | 0.23–0.47  | 0.20            | 8553           | 122 24.0      | 0.98           | 0.01         |                  |                  |
| L    | 1–2        | 0.60            | 37             | 30 5.6        | 13.90          | 0.65         |                  |                  |
| S    | 2–4        | 1.50            | 7.7            | 15 2.7        | 16.53          | 1.56         |                  |                  |
| C    | 4–8        | 3.03            | 4.4            | 7.5 1.3       | 7.21           | 1.36         |                  |                  |
| X    | 8–12       | 3.50            | 3.9            | 4.5 0.78      | 2.96           | 0.93         |                  |                  |

It is natural then to consider an adjacent frequency band to complement the above surveys. Using the survey speeds reported in Capabilities of the Jansky VLA for Sky Surveys [138], which we reproduce in Table II, S Band stands as the fastest band for reaching a survey depth of 100 \(\mu Jy\) RMS. Furthermore, due to its large bandwidth, spectral index and clean rotation measures of the ICM can be performed directly using S Band, while its data would leverage spectral indices jointly using L Band from complementary surveys.

The uniform target sensitivity of 100 \(\mu Jy\) RMS in Table II could be misleading, considering that nearly all diffuse emission is brighter at lower frequencies with a spectral index steeper than \(\alpha < -1\). A survey utilizing P Band would provide valuable spectral leverage on known radio source and would not have to reach the same sensitivity level as an S or L Band survey to detect the same diffuse features. A P Band flux limit of ~ 850 (400) \(\mu Jy\) RMS is conservatively equivalent to an S (L) Band limit of 100 \(\mu Jy\) RMS, (assuming \(\alpha = -1\)). With this relaxed sensitivity requirement, a P Band survey can also be performed more quickly. It would take roughly 1225 hours to reach a level of 500 \(\mu Jy\) RMS in a wide survey of 30,000 deg\(^2\), compared to the 1815 hours for S Band to reach 100 \(\mu Jy\) RMS. The situation for P Band only improves when considering most spectra are steeper than \(\alpha = -1\), and many more sources with lower mass and hence radio power would be detectable in P Band. While excellent for steep spectrum sources, P Band and lower frequencies do have a drawback in that they suffer from rapid depolarization.

We note that the availability of a survey at the S and P Band will largely increase scientific possibilities also in different research fields, and the potential for new discovery is likely greater than it is for L Band.

Based on our considerations in the earlier sections, frequen-
cies above 4 GHz (C Band and higher) are not suited for cluster diffuse emission science. While a good probe for polarization and total intensity measurements of small scale features like AGN cores and jets in the inner regions of clusters, its smaller field of view (and hence limited LAS) and slower survey speed means many steep spectrum sources would be missed by C Band in any configuration.

Our recommendations for probing the large scale diffuse cluster emission are highlighted in bold. Configurations and bands that lead to insufficient resolution or severely limited largest angular scales (LAS) recovered are denoted in red. The confusion limit is provided by the VLA Exposure Calculator, currently available at https://obs.vla.nrao.edu/expCalc14A/evlaExpoCalc.jnlp We find that the confusion level that could be reached will be negligible for all but the deepest surveys (which are specifically designed to approach the confusion limit). We also note that complementary higher resolution information (e.g. S Band observations in B Configuration) are necessary for ICM weather (Section III A 2), AGN feedback (Section III A), and for constraining the flux contributions from compact sources when observing the large scale diffuse emission. We indicate this higher resolution requirement in italics in the table.

### TABLE III: Scales recovered in various survey configurations, using the information provided by

https://science.nrao.edu/facilities/vla/docs/manuals/oss2014a/performance/resolution. Our recommendations for probing the large scale diffuse cluster emission are highlighted in bold. Configurations and bands that lead to insufficient resolution or severely limited largest angular scales (LAS) recovered are denoted in red. The confusion limit is provided by the VLA Exposure Calculator, currently available at https://obs.vla.nrao.edu/expCalc14A/evlaExpoCalc.jnlp We find that the confusion level that could be reached will be negligible for all but the deepest surveys (which are specifically designed to approach the confusion limit). We also note that complementary higher resolution information (e.g. S Band observations in B Configuration) are necessary for ICM weather (Section III A 2), AGN feedback (Section III A), and for constraining the flux contributions from compact sources when observing the large scale diffuse emission. We indicate this higher resolution requirement in italics in the table.

| Band (Freq.) | Config. | LAS | Resolution | Confusion |
|-------------|---------|-----|------------|-----------|
| P (230–470 MHz) A | 155 | 5.6 | – |
| P (230–470 MHz) B | 515 | 18.5 | 39 |
| P (230–470 MHz) C | 4150 | 60 | 390 |
| L (1–2 GHz) B | 120 | 4.3 | – |
| L (1–2 GHz) C | 970 | 14 | 10.72 |
| L (1–2 GHz) D | 970 | 46 | 107.2 |
| S (2–4 GHz) B | 58 | 2.1 | – |
| S (2–4 GHz) C | 490 | 7.0 | 1.37 |
| S (2–4 GHz) D | 490 | 23 | 13.7 |
| C (4–8 GHz) B | 29 | 1.0 | – |
| C (4–8 GHz) C | 240 | 3.5 | 0.21 |
| C (4–8 GHz) D | 240 | 12 | 2.11 |

### D. Configurations

We briefly summarize the merits of different configurations below and in Table III.

L Band, D Config: res = 46″, LAS = 970″, confusion=110 μJy/bm: on the positive side it is sensitive to the largest halos and good for steeper spectrum sources. However, the insufficient resolution to separate radio galaxies from halos and relics at higher redshift is a major issue for this choice of frequency and array. Moreover, it is difficult to motivate from a uniqueness perspective, as NVSS covered L Band in D configuration.

S Band, D Config: res = 23″, LAS = 490″, confusion=13.7 μJy/bm: confusion is not significant, this frequency will be sensitive to Mpc halos above z > 0.1, the resolution is marginally low but close to sufficient to separate radio galaxies from halos and relics. Sources with the steepest spectra, as well as lower mass and less powerful sources, will be missed by a survey at these frequencies. However, it will probe the critical break frequency region for many relics and the Faraday studies are of interest for background AGN probes as well as relics.

C Band, D Config: res = 12″, LAS = 240″, confusion not an issue. On the positive side the resolution is sufficient for separation of radio galaxies from halos and relics. A major negative is that the VLASS will lose sensitivity to Mpc scale halos at z ≤ 0.3. Also this high frequency will miss steep spectrum sources, weaker relics that have a significant break around 2-4 GHz, and even miss details of nearby large relics.

P Band, D Config: This should generally be avoided, since such combination of frequency and array is seriously contaminated by RFI and quickly confusion limited.

L Band, C Config: res = 14″, LAS = 970″, confusion=11 μJy/bm. Still, sensitivities as above to the largest relics and also the steeper sources but now there is sufficient resolution as well to separate the radio galaxies from the halos and relics. This configuration would probe a new regime between the NVSS and FIRST for 21 cm studies, and is good for polarization and RM studies. And since the vast majority of results for cluster sources have relied on NVSS and FIRST, a new survey here would allow for direct comparison with previous results.

S Band, C Config: res=7″, LAS=490″, confusion not a problem. As above, very good for a large variety of reason for the science case. WAT/NAT studies would benefit greatly from this band, as it provides both spectral leverage and better resolution for high-z sources. The main drawback is that, because of the high angular resolution, the surface brightness sensitivity to diffuse cluster sources and extended radio galaxies will be low. It is necessary to properly map extended low brightness regions to study physical properties of clusters on large scales (e.g. magnetic fields).

C Band, C Config: res=3.5″, LAS=240″, confusion not an issue. However the resolution is too high and the available LAS unsuitable for the regions of interest. The band is not appropriate for halos and relics. Only a small part of the galaxy cluster science could be addressed by this and higher frequencies.

P Band, B Config: The only major consideration for B configuration for this white paper would be the new P band. This is well suited to having a large FoV, sensitivity to steep spectrum emission, angular resolution of 18.5″ (well suited to separate radio galaxies from halos and relics), LAS=515″ so Mpc scale features above redshift of z > 0.1 are detectable. The survey speed for steep spectrum (α = -1.3) sources is much faster than any of the other frequencies and this frequency would provide spectral information in an interesting regime. Polarization studies are not ideal at this frequency, although it is possible that for the lower rotation measures of the WHIM it would be critical. The resolution matches that of TGSS, which provides interesting complementary information, despite the different sensitivities.

**Final comment:** The C and D configurations nominally have similar sensitivities to LAS for full synthesis (see Table III), and have roughly comparable survey speeds. Ostensibly then C configuration for S or L band, and B configuration for P
band, could probe sufficiently large scales for halos and LSS, while still resolving features that are 10's of kpc in scale. However, C configuration is limited in the number of baselines it provides that actually probe extended emission, and an S band survey in C config would suffer severe limitations in its ability to recover large scale structure (as discussed in §IV A). Observations in B configuration in S or L band would resolve smaller \( \lesssim 10 \) kpc scales, but would perform even worse for LSS, failing to distinguish radio halos from minihalos. The high-resolution A configuration runs the risk of not even being able to constrain features such as jets, NATs, WATs, and head-tail galaxies, which can span a few to a tens of arcseconds; in addition to missing important science on galaxies and feedback in cluster environments, these features must be removed in order to accurately recover the large scale, diffuse halo and minihalo emission.

However, as discussed before, the sensitivity to low surface brightness emission is the most critical parameter in the study of diffuse cluster sources. Observations in S Band will require the VLA D configuration to obtain images of sources with a surface brightness \( \lesssim 0.2 \mu Jy \text{ arcsec}^{-2} \); C configuration S Band observations with an RMS of 100 \( \mu Jy \) will only have a surface brightness level \( \sim 2 \mu Jy \text{ arcsec}^{-2} \).

E. Sky Coverage

Wide and Shallow: While the obvious choice to provide a legacy archive comparable to, but deeper than, FIRST and NVSS (which are still being mined for new science), it is not necessarily the best choice for detailed studies of cluster astrophysics. Despite this, the sensitivity limits considered for VLASS will have a significant impact on the study of non-thermal emission from galaxy clusters. If, however, VLASS covers two different bandwidths (specifically, S and P Bands), the resulting archive will have a scientific value never obtained in previous surveys. Another strategy would be to complement upcoming southern radio surveys in L band (see §III G), using the VLA to cover the \( 1/3 \) of the sky inaccessible from South Africa and Australia.

Narrow and Deep: Many of the arguments above are applicable here, except the deep drilling fields would be ideal places to use the power of frequency coverage provided by the VLA to significantly enhance the science. For example, S band D + L band C + P band B would be a powerful combination to go deep on supercluster fields, where one could easily probe much of the cluster extended emission over a very interesting environment. The addition of higher frequencies to such deep fields would provide the resolution for deep studies of star formation, AGN activity, and lensed background sources behind the cluster potentials.

Targeted Sample: Targeted follow-up of well-defined samples from e.g. eROSITA, Planck, and/or ACTPol would also enable much of the science discussed above. However, eROSITA's sample will not be available by the start of VLASS, and a targeted survey in general would not provide the kind of legacy archive comparable to FIRST and NVSS.

Hybrid Survey: Wide and Shallow + Narrow and Deep: Another possibility to maximize the return of a new survey on galaxy cluster science would be the combination of a wide field survey, combined with a deep survey over a smaller portion of the sky. This deep survey could be performed at a different frequencies and in different configuration. One possible combination could be L band with C array for the wide and shallow survey, and S band and C array for the deep survey. As an example, the deep field could be the North Galactic Cap, where SDSS ancillary data are available and eROSITA coverage will be deeper.

Multi-frequency + Multi-Configuration Survey: A final possibility would be a wide survey covering \( \sim 10,000 \text{ deg}^2 \) in L, S, and C bands in B, C, and D arrays respectively. This would reduce the demand from VLASS for one particular configuration, and thus impact concurrent science with the VLA less. Nearly continuous spectral coverage from 1–8 GHz would powerfully leverage spectra – mainly of compact structures such as AGN due to the limited LASs of L Band + B Array and C Band + D Array. It would also leverage rotation measures of magnetic fields.

V. CONCLUSIONS

For cluster-scale diffuse emission, the choices of S Band + D Configuration, L Band + C Configuration, and P Band + B Configuration offer sufficient resolutions for constraining galactic interactions and feedback in cluster environments, while still probing large scale structure and the bulk cluster environment itself. A VLA survey using L Band + C Configuration would complement and build upon the results of both NVSS and FIRST, while also probing larger scales than upcoming southern radio surveys. However, from a uniqueness perspective, VLASS will likely have more impact on cluster astrophysics if it were to target P and/or S Band (in B and D Config, respectively), both of which provide larger fractional bandwidths than L Band. The advantage of P Band is that less sensitivity would be required to probe fainter cluster sources, while S Band is better suited for Faraday rotation measure studies and the detection of not very steep spectrum sources (e.g. \( \alpha \approx -0.7 \) radioagelaxies and radio loud AGNs). Finally, we note that complementary observations at higher resolutions (e.g. the \( \sim 1 \) arcsecond resolution from S Band in B Configuration) are indispensable for the study of AGN and ICM weather in cluster environments, and aid in constraining the flux contributions from compact sources that contaminate measurements of the diffuse emission.

While the push to probe higher redshifts and lower mass limits strongly favors a narrow and deep (or even targeted) survey strategy, we note that a wide survey covering roughly 1/4–2/3 of the sky will have significant scientific return, discovery potential, and archival value.

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