Radio emission from merging galaxy clusters : characterizing shocks, magnetic fields and particle acceleration

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CHAPTER 1

Introduction

1.1 Cosmology & large-scale structure formation

Observations reveal that the Universe has an age of 13.75 ± 0.11 billion years (Komatsu et al. 2011). The current standard model of cosmology is the ΛCDM model which consists of dark energy, cold dark matter and baryonic matter. These contribute about 73%, 22%, and 5%, to the energy density, respectively. This model has successfully explained some of the key properties of our Universe. These include the large-scale distribution of galaxies (e.g., Abazajian et al. 2009), the primordial abundances of the elements hydrogen, helium and lithium, the existence and properties of the Cosmic Microwave Background (CMB) radiation (e.g., Mather et al. 1990; Smoot et al. 1992; Mather et al. 1994; Kovac et al. 2002), and the observed large-scale flat geometry and isotropy. In addition, the ΛCDM model also includes the observed accelerated expansion of the Universe (Riess et al. 1998).

A key ingredient of the ΛCDM model is cosmic inflation, where just after the Big Bang the Universe underwent a short period of rapid exponential expansion. Quantum physics implies that temperature fluctuations should have existed immediately after the Big Bang, while the temperature of the CMB has precisely the same value all over the sky (within one part to 10^{-5} – 10^{-6}). Inflation has been invoked to smooth out the quantum fluctuations which also results in a flat space geometry. This assures isotropy and homogeneity on the largest scales. Furthermore, it explains why different regions of the Universe, that are not casually connected because of the large distances between them, have the same physical properties, the so-called horizon problem. This could also explain the lack of observed magnetic-monopoles, which should have otherwise been produced just after the Big Bang.

Observations of the CMB reveal the matter distribution in the Universe to be extremely homogenous 3.8×10^5 yrs after the Big Bang, but in 1992 tiny variations variations in the CMB temperature were discovered (Smoot et al. 1992). These temperature anisotropies correspond to small-scale density variations. In the ΛCDM model, these tiny fluctuations grow hierarchically under the influence of gravity. These form halos of cold dark matter that merge and subsequently acquire more mass (e.g., Springel et al. 2006). The baryonic matters follows the dark matter halos, but its physics is much more complicated as other interactions besides gravity have to be taken into account. These include gas heating, cooling, ionization and recombination. Dark matter only interacts with baryonic matter through gravity. The nature of this dark matter remains one of the biggest mysteries in astronomy. Eventually the baryonic matter cools and collapses, forming stars, galaxies, and clusters of galaxies. On the largest scales the distribution of baryonic matter forms sheets and filaments of galaxies. At nodes, where filaments meet, galaxy clusters are located. Clusters and filaments are surrounded by voids, large empty regions devoid of visible matter (e.g., Peacock et al. 2001).

1.2 Galaxy clusters

Galaxy clusters play a very special role, as they are the largest gravitationally bound structures that formed out of the CMB fluctuations. They also formed relatively late in the process, at a time when the Universe had roughly half of its present age. As of today galaxy cluster are still acquiring more mass and new clusters are being formed. Galaxy clusters consist of dark matter ($\sim$ 75% in total by mass), hot ionized gas (20% by mass) that emits at X-ray wavelengths (Byram et al. 1966; Gursky et al. 1971), called the intracluster medium (ICM), and stars, cold gas, and dust, which are mostly found in galaxies (5% by mass). The ICM has temperatures in the range of about 0.1 keV to $\sim$ 40 keV. The global X-ray luminosity and temperature of clusters scale with the cluster mass, but significant spatial temperature variations within clusters exist (e.g., Markevitch et al. 2002; Fabian et al. 2006; Ma et al. 2009). Typical masses for galaxy clusters are in the range of 10^{14} –10^{15} $M_{\odot}$, and clusters span about 5 Mpc in the present day Universe.

As predicted by the hierarchical model of structure formation galaxy cluster grow by mergers with other clusters and galaxy groups, as well as through the continuous accretion of gas from the intergalactic medium (IGM, or the warm-hot intergalactic medium, WHIM). In fact, about 50% of the total baryon mass is thought to reside in the IGM (Cen & Ostriker 1999). Both galaxy cluster mergers and the accretion of gas create shocks in and around galaxy clusters, heating the ICM. Cluster merger events are the most energetic events in the present day Universe, releasing energies of 10^{63} – 10^{64} erg. They therefore play an important role in the energy budget of the ICM and dynamical state of clusters.

Magnetic fields are another important component of galaxy clusters. Magnetic fields reveal themselves by the synchrotron radiation (e.g., Willson 1970; Jaffe et al. 1976) from charged relativistic particles (also called cosmic rays, CR) spiraling around the field lines. In addition, magnetic fields can be studied through Inverse Compton (IC) X-ray emission (e.g., Finoguenov et al. 2010) and polarized radio emission, e.g., by Faraday rotation of polarized radio sources located behind or within the ICM (e.g., Clarke et al. 2001; de Bruyn & Brentjens 2005).

1.3 Radio emission from galaxy clusters

Radio observations show that some clusters host diffuse radio sources that are not associated with any of the individual galaxies in clusters. This emission generally has a low surface brightness, $\sim 1\mu$Jy arcsec^{-2} at 1.4 GHz, and relatively steep radio spectrum with $\alpha < -0.5$[1], but more typically $\alpha \lesssim -1$. With the improved capabilities of radio interferometers the number of these diffuse sources known has increased considerably over the past 15 years. Currently, more than 50 of these diffuse sources are known. The classification of these sources has been driven by the observed properties of the radio sources, these include the location with respect to the ICM, morphology, polarization properties, size, and radio spectrum.

Three main classes of diffuse sources in clusters have been identified. These are radio halos, mini-halos, and relics. In addition, claims have been made of radio emission originating from the space between galaxy clusters (e.g., Bagchi et al. 2002; Kronberg et al. 2007), these sources have been called *radio filaments*. Radio mini-halos are found in relaxed cool-cores clusters (e.g., Fabian et al. 1991; Peterson & Fabian 2006). They surround the central radio-loud active galactic nuclei (AGN) and have sizes of $\lesssim$ 500 kpc. We focus here on the halos and relics that are found in merging galaxy clusters.

1.3.1 Radio halos

Radio halos are large ($\sim$ 1 Mpc) diffuse sources that have a steep radio spectrum ($\alpha \leq -1$). Halos are centrally located and have a regular smooth morphology. They are all found in clusters with a disturbed dynamical state (e.g., Cassano et al. 2010b). For a number of halos a point-to-point spatial correlation is observed between the radio and X-ray brightness, indicating an interaction between non-thermal and thermal components (e.g., Govoni et al. 2004). A spatial correlation between the radio spectral index and X-ray temperature of the gas is also observed, in the sense that regions/clusters with a higher temperature tend to have flatter radio spectra (Feretti et al. 2004; Orrú et al. 2007; Giovannini et al. 2009). Usually no polarized emission is detected from radio halos.

Unlike the thermal X-ray emission from clusters, radio halos are not a common phenomena. From a complete X-ray sample ($0.2 < z \leq 0.4$, $L_{\mathrm{X},0.1-2.4\ \mathrm{keV}} > 5 \times 10^{44}$ erg s^{-1}) Venturi et al. (2008, 2007) found the fraction of clusters hosting radio halos to be 0.29 ± 0.09. This fraction seems to increase for the more luminous/massive clusters. For cluster with $L_{\mathrm{X},0.1-2.4\ \mathrm{keV}} > 8 \times 10^{44}$ erg s^{-1} the fraction is 0.38 ± 0.13.

The 1.4 GHz radio power of halos ($P_{1.4\mathrm{GHz}}$) correlates with the X-ray luminosity. This L_{X}–$P_{1.4\mathrm{GHz}}$ correlation for giant radio halos (e.g., Liang et al. 2000; Cassano et al. 2006) could reflect a dependence of the radio halo power on the cluster mass. Observations from Venturi et al. (2008, 2007) separate the radio halo clusters from clusters without radio halos, showing a bimodal distribution of clusters in the $P_{1.4\ \mathrm{GHz}}-L_X$ diagram, i.e., a fraction of clusters hosts giant radio halos, while the majority of clusters does not show evidence of diffuse cluster-scale radio emission (Brunetti et al. 2007, 2009). The upper limits on the radio power of clusters without radio halos lie about one order of magnitude below the L_{X}–$P_{1.4\mathrm{GHz}}$ correlation. Therefore, the bimodal distribution does not arise from observational biases.

1.3.1.1 Origin of radio halos

The radiative lifetime of the synchrotron emitting electrons is about 10^8 yr at $\sim$ 1 GHz. Within this time the CR electrons can only diffuse over about 1–10 kpc (in the Bohm approximation, e.g., Drury 1983). However, radio halos have Mpc sizes. This implies that the electrons must

[1] $F_\nu \propto \nu^\alpha$, where α is the spectral index

be accelerated in-situ (Jaffe 1977). The clear connection with cluster mergers strongly suggests that some fraction of the gravitational energy released during merger events is channelled into the production of the non-thermal particles in ICM.

Two main classes of models have been proposed for the origin of radio halos:

- Primary models: primary CR electrons are re-accelerated by the turbulence generated during cluster merger events (Brunetti et al. 2001; Petrosian 2001). These primary electrons are injected into the ICM by for example radio galaxies, supernovae, or galactic winds.

- Secondary models: electrons are secondary products which originate from hadronic collisions between long-lived relativistic protons and thermal ions in the ICM (Dennison 1980; Blasi & Colafrancesco 1999). Since the energy losses for protons are very small this allows them to diffuse over the large distances required to from Mpc-size radio halos. The relativistic protons accumulate over the entire formation history of a cluster and could for example originate from accretion shocks or radio galaxies. A consequence of the secondary models is that gamma ray emission is expected, through the decay of neutral pions generated by the hadronic collisions.

Observations mostly support the primary re-acceleration models. These observations include (i) the connection with cluster mergers (e.g., Cassano et al. 2010b), (ii) the existence of the radio halo bi-modality (Venturi et al. 2007) which suggests that the radio emission is suppressed and amplified on a time-scale significantly shorter than 1 Gyr. This is difficult to reconcile with the hypothesis that the radio emission is suppressed due to dissipation of magnetic fields in galaxy clusters, as is required for the secondary models (Brunetti et al. 2009). (iii) The lack of Gamma rays from the ICM (e.g., Jeltema & Profumo 2011), (iv) the radial radio brightness profiles (e.g., Donnert et al. 2010a; Brown & Rudnick 2011), i.e., the brightness profiles of the synchrotron emission from secondary models are much steeper than what is seen in observations, (v) the existence of radio halos with $\alpha < -1.5$ (Brunetti et al. 2008) which in the case of secondary models requires an unrealistic amount of energy in the relativistic protons, and (vi) the similar magnetic field properties between clusters with and without halos (Bonafede et al. 2011). This poses problems for the secondary models since they require a difference in the magnetic field strength between clusters with and without radio halos (e.g., Dolag & Enßlin 2000; Pfrommer & Enßlin 2004). Although, it should be noted that all these results are still actively being debated (e.g., Enßlin et al. 2011).

1.3.2 Radio relics

Radio relics are elongated, filamentary, sometimes arc-like sources unrelated to individual galaxies. Their sizes range from 50 kpc to 2 Mpc. They can be highly polarized with fractional polarization levels of 20 – 40% (e.g., Andernach et al. 1984; Clarke & Ensslin 2006). Their integrated radio spectra range from $\alpha \approx -1$ for large relics to $\alpha < -2$ for smaller relics. Relics have been divided into three groups (Kempner et al. 2004).

(1) *Radio gischt* are large elongated, often Mpc-sized, radio sources located at the periphery of merging clusters. Among these are rare *double-relics*. In this case two relics are located on opposite sides of the cluster center (e.g., Bonafede et al. 2009b; van Weeren et al. 2009b; Venturi et al. 2007; Bagchi et al. 2006; Röttgering et al. 1997; van Weeren et al. 2010; Brown et al. 2011; Bagchi et al. 2011). It has been proposed (Ensslin et al. 1998; Miniati et al. 2000)

that gischt relics trace shock fronts in which particles are accelerated via the diffusive shock acceleration mechanism (DSA; Krymskii 1977; Axford et al. 1977; Bell 1978a,b; Blandford & Ostriker 1978; Drury 1983; Blandford & Eichler 1987; Jones & Ellison 1991; Malkov & O'C Drury 2001). According to DSA theory, the injection radio spectral index is related to the Mach number of the shock. However, the efficiency with which collisionless shocks can accelerate particles is unknown and may not be enough to produce the observed radio brightness of relics. A closely linked scenario is that of shock re-acceleration of pre-accelerated electrons in the ICM, which is a more efficient mechanism for weak shocks (e.g., Markevitch et al. 2005; Giacintucci et al. 2008; Kang & Ryu 2011).

An alternative scenario for gischt has been proposed by Keshet (2010). This model is based on a secondary cosmic ray electron model, where the amplification and time evolution of magnetic fields and the cosmic ray distribution are taken into account to explain both halos and giant relics.

Very recently, X-ray brightness discontinuities have been found at the location of a few relics, most likely these discontinuities are shocks with Mach numbers of ~ 2 (Finoguenov et al. 2010; Macario et al. 2011). By comparing the limit on the IC X-ray emission with the measured radio flux, a lower limit of 3 μG on the magnetic field strength has been obtained for the bright relic in the cluster Abell 3667 by Finoguenov et al. (2010).

The class of double radio relics is particular interesting as, based on current models of electron acceleration for this class of radio sources, it enables us to explore the connection between clusters mergers and shock waves (e.g., Roettiger et al. 1999a). These relics are thought to trace diametrically outward traveling shocks emanating from the cluster center, and created during a binary cluster merger event. In this case, steepening of the spectral index in the direction towards the cluster is expected due to the radiation losses of the electrons in the shock downstream region.

An alternative shockwave-inducing mechanism is that of external "accretion" shocks, where filaments of galaxies from the cosmic web funnel into the clusters (Miniati et al. 2000; Miniati 2003; Keshet et al. 2003). Merger shocks are weaker than the external accretion shocks, as the gas has already been heated by these external shocks. The external accretion shocks occur farther out than the merger shocks, up to a few times the virial radius of the cluster. The gas density is very low at these distances from the cluster center and so are the energy densities in the CR electrons and magnetic fields. Therefore, the radio emission from external accretion shocks is likely too faint to be detected with the current radio telescopes (e.g., Hoeft et al. 2008).

Besides the above discussed radio gischt there are (2) *AGN relics* and (3) *Radio phoenices*. AGN relics are associated with extinct or dying radio galaxies. The radio plasma has a steep curved spectrum due to synchrotron and IC losses. AGN relics can be compressed adiabatically by merger shock waves producing so-called radio phoenices (Enßlin & Gopal-Krishna 2001; Enßlin & Brüggen 2002). Phoenices again have steep and curved radio spectra due to radiation losses. Proposed examples of phoenices are the relics found by Slee et al. (2001).

1.4 This thesis

Because radio halos and relics are diffuse, have low luminosities and steep radio spectra, they are difficult to observe with radio telescopes that mostly operate above 1 GHz. Therefore studies of non-thermal processes in the ICM, as traced by the diffuse radio sources, are mainly limited to the brightest and most nearby clusters. It is expected though that there are still a significant number of radio halos and relics to be found in the NVSS (Condon et al. 1998), WENSS (Rengelink et al. 1997) and VLSS (Cohen et al. 2007) surveys, but a problem is how to recognize these sources in the survey data. As a result there are only a few dozen radio halos and relics known. The origin of the radiating electrons is currently still being debated, and for many radio halos and relics spectral and polarization studies are missing which could distinguish between the different acceleration models. Some of the main questions that need to be answered are:

- How are the particles accelerated that form the radio halos and relics?
- How common are diffuse cluster radio sources? What is the occurrence of these sources as function of cluster properties, such as mass, temperature and substructure.
- What are the properties of merging clusters (mass ratios, impact parameters) and how do these properties evolve over cosmic time?
- What is the contribution of cosmic rays and magnetic fields to the energy budget of the ICM?
- What are the properties of the magnetic fields (topology and strength) in the ICM? How do they relate to models for the origin of these fields in clusters?

To start answering these questions (i) larger samples of diffuse cluster radio sources have to be compiled, (ii) multi-frequency and polarization observations are needed, (iii) halos and relics should be observed at very low frequencies, and (iv) radio observations of merging clusters need to be compared with simulations and observations at other wavelengths.

In this thesis an interferometric study of diffuse radio sources in and around galaxy clusters is performed to address some of the above mentioned points. Multi-frequency observations from the Giant Metrewave Radio Telescope (GMRT), Westerbork Synthesis Radio Telescope (WSRT), and Very Large Array (VLA) radio telescopes are analyzed to measure the spectral and polarimetric properties of diffuse cluster sources. A search for new relics and halos is carried out based on existing radio surveys. As a theoretical part of this thesis numerical simulations of cluster mergers, with the aim of constraining the cluster mergers parameters from observations of double radio relics, are carried out. In addition, one of the first LOFAR observations of cluster-scale diffuse radio emission is presented. LOFAR is a new pan-European radio telescope that operates at the lowest radio frequencies accessible from the surface of the Earth. These observations are very challenging due the large fields of view, radio frequency interference (RFI), ionospheric phase distortions, differential Faraday rotation, spatially and time varying stations beams, direction dependent calibration, and enormous data-rates. In spite of these challenges, the LOFAR images are the deepest ever obtained at frequencies below 100 MHz.

In **Chapters 2** and **3** GMRT, VLA, and WSRT observations of a sample of 26 diffuse (angular size $\gtrsim 15''$) ultra-steep spectrum radio sources selected from the 74 MHz VLSS survey are presented. Most of these sources have a spectral index of $\alpha \leq -1.35$, between 74 and 1400 MHz. The aim of these observations was to search for steep-spectrum radio halos and relics, either associated with clusters or the cosmic web. It turns out that the majority of the sources in the sample are associated with galaxies in clusters or groups. Most likely these sources trace old (possibly compressed) radio plasma from AGN activity. One large radio halo and relic in a distant massive galaxy cluster is found (see also **Chapter 5**). By complementing the observations with measurements from the literature, correlations between the physical size and spectral index of relics are found, in the sense that smaller relics have steeper spectra. Furthermore, larger relics are mostly located in the outskirts of clusters while smaller relics are located closer to the cluster center.

In **Chapter 4** a search for radio halos and relics in the NVSS and WENSS surveys is described. Candidate halos and relics were followed up with GMRT, WSRT, and VLA observations. These observations revealed 6 new radio relics and 2 radio halos. In addition, the presence of diffuse radio emission in four galaxy clusters is confirmed. With a sample of 35 radio relics, it is found that relics are mostly located along the major axis of the X-ray emission from the ICM, while their orientation is perpendicular to this axis. The location and orientation of radio relics with respect to the ICM elongation is consistent with the scenario that relics trace merger shock waves. The X-ray luminosity and redshift distributions of clusters with relics are compared to an X-ray selected cluster sample from the NORAS and REFLEX surveys. There is evidence for an increase in the relic fraction with X-ray luminosity and redshift.

In **Chapter 5** the diffuse radio emission in the cluster MACS J0717.5+3745 ($z = 0.5548$) is discussed. This cluster hosts the most luminous and distant radio halo. MACS J0717.5+3745 is also one of the hottest (~ 11.6 keV) and most X-ray luminous clusters known and display signs of undergoing a triple merger event. Furthermore, the cluster hosts a giant relic, which location roughly coincides with regions of the ICM that have a significant enhancement in temperature as shown by Chandra. This could mean that the relic traces a merger-related shock wave, where particles are accelerated via the diffusive shock acceleration mechanism. Alternatively, the relic traces an accretion shock of a large-scale galaxy filament extending to the southeast.

Chapters 6 and **7** deal with the discovery of double radio relics in the galaxy clusters ZwCl 2341.1+0000 and ZwCl 0008.8+5215. Both clusters show an elongated ICM and the galaxy distributions are also either elongated or bimodal. The relics are located on opposite sides of the cluster center, along the major axis of the X-ray emission, at the location where outwards traveling merger shock waves are expected. For ZwCl 0008.8+5215 there is steepening of the spectral index across the relics in the direction towards the cluster center. It is concluded that the double relics in ZwCl 2341.1+0000 and ZwCl 0008.8+5215 are best explained by two outward moving shock waves in which particles are (re)accelerated through the diffusive shock acceleration mechanism.

In **Chapter 8** GMRT, WSRT and VLA observations of a new radio relic in the cluster CIZA J2242.8+5301 are presented. This relic has a large ~ 2 Mpc extent, but its width measures only 55 kpc. For the relic, highly aligned magnetic fields and a strong spectral index gradient, in the direction towards the cluster center, are observed. The power-law integrated spectral index, clear spectral index gradient and aligned magnetic fields are evidence for particle acceleration in an outward moving shock wave. The very small width of the relic makes it possible to derive the magnetic field strength at the location of the relic, without resorting to equipartition arguments. A magnetic field strength of 5–7 μG is found.

In **Chapter 9** multi-frequency and polarization observations of a new massive galaxy cluster ($z = 0.225$) are analyzed. The cluster hosts a large bright 1.9 Mpc radio relic, an elongated ~ 2 Mpc radio halo, and two fainter relics. Part of the bright radio relic has a very peculiar linear morphology. For the bright relic, a clear spectral index gradient is observed, with spectral steepening in the direction towards the cluster center. The results from Rotation Measure (RM) Synthesis suggest that some of the observed Faraday rotation is caused by the ICM and is not due to galactic foregrounds. Color-color radio diagrams for the bright relic are constructed, which allow for a detailed spectral analysis. This points towards (i) an injection spectral index of −0.6 to −0.7, (ii) increasing spectral index and curvature in the post-shock region, and (iii) an overall power-law spectrum between 74 MHz and 4.9 GHz with $\alpha = -1.10 \pm 0.02$. From the analysis, it is found that mixing of emission in the beam and spectral ageing are probably the dominant factors that determine the shape of the radio spectra. Changes in the magnetic field, total electron content, or adiabatic gains/losses do not seem to play a major role.

In **Chapter 10** simulations of binary cluster merger events are carried out. A method is developed to use these simulations in combination with the observations to derive cluster merger parameters. This method is applied to the double radio relics in the cluster CIZA J2242.8+5301 (see also **Chapter 8**). It is found that CIZA J2242.8+5301 is undergoing a merger in the plane of the sky (less then 10° from edge-on) with a mass ratio of about 2 : 1, and an impact parameter $\lesssim 400$ kpc. The core passage of the clusters happened about 1 Gyr ago. From these simulations it is also concluded that the morphology of radio relics constrains the degree of clumping in the outskirts of the ICM. Determining the ICM clumping is important to properly measure the baryon fraction, density and entropy profiles, around the virial radius and beyond.

GMRT 325 MHz and WSRT 115–165 MHz radio continuum observations of Abell 2256 are presented in **Chapter 11**. Three new steep-spectrum ($\alpha \lesssim -1.5$) sources are revealed in the cluster, located about 1 Mpc from the cluster center. Two are located to the west of the cluster center, and one to the southeast. The extremely steep spectral index suggests these sources are most likely the result of adiabatic compression of fossil radio plasma due to merger shocks. We did not find any optical counterparts to the radio sources in the WHT images. The discovery of the steep spectrum sources implies the existence of a population of faint diffuse radio sources in (merging) clusters with such steep spectra that they have gone unnoticed in higher frequency ($\gtrsim 1$ GHz) observations. Considering the timescales related to AGN activity, synchrotron losses, and the presence of shocks, we find that most massive clusters should possess similar sources.

LOFAR observations of Abell 2256 are discussed in **Chapter 12**. The observations were taken at 18 to 67 MHz with 25 stations. The longest baseline for these observations was about 80 km. The 63 MHz image clearly reveals the radio halo and relic. In addition, the presence of an ultra-steep spectrum source, earlier reported in deep GMRT and WSRT observations, is confirmed (see **Chapter 11**). Images made around 20 and 30 MHz also reveal the diffuse cluster emission, but they are affected by direction dependent ionospheric phase distortions. Removing these effects will be crucial to fully exploit the high-spatial resolution LOFAR offers at low frequencies.

1.5 Future prospects

During the last decade considerable progress has been made in our understanding of diffuse radio emission in galaxy clusters. In addition, new radio telescope are becoming operative (e.g., LOFAR, ASKAP, MWA) and older telescopes are being upgraded (VLA, WSRT, GMRT).

These new and upgraded facilities will greatly improve our knowledge about the non-thermal component in clusters. Extending the wavelength coverage towards much lower frequencies is a crucial aspect. In particular, the turbulent re-acceleration model predicts the existence of large population of ultra-steep spectrum radio halos that can only be uncovered through sensitive low-frequency observations (e.g., Cassano et al. 2010a). Also, it is expected that there should be many fossil radio sources, dying radio galaxies or AGN relics, that have such steep radio spectra that they are missed by current higher frequency ($\gtrsim$ 100 MHz) observations.

Extending the wavelength coverage to frequencies $\gtrsim$ 5 GHz is also important. The high-frequency spectral shapes can be used to distinguish between various models for the origin of the synchrotron emitting electrons. Polarization measurements are another area where progress can be made. This will allow to study the magnetic field strength and topology in more detail (e.g., Govoni et al. 2006; Vacca et al. 2010; Pizzo et al. 2011; Bonafede et al. 2011).

Models for the formation of relics and halos can be tested through statistical studies of correlations between the non-thermal and thermal components of the ICM (Liang et al. 2000; Feretti et al. 2006; Cassano et al. 2006, 2007, 2008, 2010a). With large unbiased samples it is possible to study the redshift evolution of halos and relics. LOFAR will play a crucial role here because of its (i) good sensitivity, (ii) large field of view, and (iii) multi-beaming capability. At higher frequencies, the ASKAP and upgraded WSRT will complement the LOFAR surveys. Extremely deep observations of selected clusters, with LOFAR and the extended VLA, might also reveal new and unexpected phenomena.

Finally, combining the radio data with observations at other wavelengths is important, in particular with sensitive X-ray, gamma ray, and Sunyaev-Zel'dovich effect (Zeldovich & Sunyaev 1969) measurements. This will allow a much better understanding of shocks, particle acceleration mechanisms, magnetic fields, and the interplay between the non-thermal and thermal components of the ICM.