Summary and future perspectives

7.1 Summary

The work carried out in this thesis was aimed at studying the physical properties of the halos and the relics in two low-redshift galaxy clusters: A2255 and Coma. They are well known clusters hosting important examples of diffuse extended radio sources showing interesting properties. The most important results and conclusions from this thesis can be summarized as follows:

- X-ray studies of A2255 and Coma revealed that they are in a perturbed dynamical state (Feretti et al. 1997a; Sakelliou & Ponman 2006; Briel et al. 1992; White et al. 1993). This conclusion is supported by our radio maps, where both clusters show many relic-like structures at large projected distance from the cluster center (Figs. 2.1 and 6.3). Their morphological and spectral properties and their location within the cluster (environment) suggest an association with LSS-shocks (Chapter 2, pg. 46, and Chapter 6, pg. 192);

- the picture of galaxy clusters in the radio domain is much more complex than what was previously known. The multi-frequency observations of A2255 and Coma showed that they both host very steep-spectrum features around the central radio halo (Chapter 3, pg. 69, and Chapter 6, pg. 189). Their nature is puzzling. It is still not clear whether they should be considered halo-related structures or examples of a new class of very steep-spectrum objects detectable in clusters at very low frequencies only (Mpc-size diffuse structures, MDS);

- the morphology of halos, relics, and radio galaxies becomes progressively more complex at low frequencies (Chapter 3, Figs. 3.3-3.5, and Chapter 6, Fig. 6.3). Multi-frequency observations carried out with good resolution are crucial for a better comprehension of their origin and evolution and their interaction with the ICM;

- several studies of cluster radio sources in the literature have pointed out an apparent pressure imbalance between internal minimum pressure and that of the ambient medium (Morganti et al. 1988; Feretti et al. 1990; Dunn & Fabian 2004; Dunn et al. 2005; Bürzan et al. 2008). The extended cluster radio sources of A2255 and Coma show the same property (Chapter 3, pg. 88, and Chapter 6, pg. 197). The discrepancy between internal and external pressure could be
partly due to projection effects, which affect the value of the external pressure at the real location of the sources. Also the uncertainty associated with the equipartition parameters could be an important factor. High values for the ratio of protons and electrons \((k \sim 10^3 - 10^4)\) in galaxy clusters are suggested to account for the discrepancy (Dunn & Fabian 2004; Dunn et al. 2005; Birzan et al. 2008). They would imply the presence of a large amount of relativistic protons in the ICM, favouring secondary models rather than primary models for the origin of the electrons in radio halos;

- the radio halo of A2255 shows three bright and highly polarized filaments at the borders. This apparently represented the first detection of a polarized halo in the literature (Govoni et al. 2005). Through a rotation measure tomography of the cluster, we proved that the filaments, in fact, lie at large distance from the cluster center. Their morphological and polarimetric properties suggest that they could be relics in the foreground of the cluster rather than part of the radio halo (Chapter 4, pg. 137). This result proves that projection effects play an important role in the study of the physical properties of galaxy clusters;

- in the presence of polarized cluster radio sources, RM-synthesis is the key technique to unveil the 3-D structure of galaxy clusters (Chapter 4);

- low-frequency studies in total intensity and polarization are challenging. The stability of the ionosphere, as well as the incidence of RFI, influences the quality of the final results. These can be improved by means of available techniques, such as peeling, correction for the ionospheric Faraday rotation, flagging, etc... These processes are very computer and time intensive (Chapter 3, pg. 53 and Chapter 4, pg. 105);

- at frequencies of \(\sim 350\) MHz our Galaxy dominates the polarized emission detected in cluster fields at intermediate Galactic latitudes (\(\sim +35^\circ\)). This allows us to investigate in detail the physical properties of Galactic foregrounds at these frequencies (Chapter 5), but makes the study of the polarization of cluster sources more difficult (Chapter 4, pg. 118).

### 7.2 A2255 and Coma: open questions and future investigations

In the thesis we have often pointed out the importance of further low-frequency observations with good resolution and sensitivity to better understand the properties of A2255 and Coma. LOFAR (the LOw Frequency Array) will play a major role in such investigations. Its unprecedented sensitivity and resolution in the frequency range 30-240 MHz will allow us to:

- understand the origin of the relativistic particles in radio halos. In the case of A2255, for example, it is suggested that the radio galaxies could provide the radio halo with the relativistic particles for its own emission (Feretti et al. 1997a). This is also indicated by our low-resolution observations at 85 cm and
at 2 m, where the Beaver radio galaxy shows spectral index values at the end of the tail similar to those of the southern regions of the halo (Fig. 3.17). A similar situation has been found by Giovannini et al. (1993) for the Coma radio halo and the radio galaxy NGC 4869. Better resolution and sensitivity are needed to confirm this result;

- clarify whether the origin of the radio halo of A2255 is compatible with primary or secondary models. Our observations at 25, 85, and 200 cm show that there is a clear flattening of the spectrum of the halo towards its periphery, due to the presence of the filaments at this location. Our polarimetric results, however, proved that these structures are not physically related to the radio halo, but that their location at the cluster center is due to projection effects. Removing the contribution of both the filaments and the radio galaxies embedded in the halo is crucial to determine the spatial distribution of the spectral index. This is an important parameter in the investigation of the origin of halo radio sources. High resolution data are essential for this purpose;

- determine the range of physical distances from the cluster center at which the filaments of A2255 could be located. This could help to clarify whether they should be considered features related to merger or LSS shocks. To do this, we need to know the detailed spatial variance in RM of these structures, as well as their fractional polarization at low frequencies;

- reveal the origin of the observed depolarization of the cluster sources towards low frequencies. By reducing, or even eliminating, the importance of beam depolarization, high resolution low-frequency observations could test whether the depolarization is occurring internally to the sources or in a foreground screen;

- detect and study the relic-like features imaged at large projected distance from the centers of A2255 and Coma. By confirming a link of these structures with LSS-shocks, this result will imply that the new generation of low-frequency arrays will be able to reveal the cosmic web at radio wavelengths.

Together with deeper and higher resolution observations, simulations of the polarized Galactic foreground emission in cluster fields will be essential. They will allow low-frequency studies of cluster radio sources also at intermediate and low Galactic latitudes, where the emission of our Galaxy dominates (Chapter 5).

7.3 The future of low-frequency observations of galaxy clusters

The knowledge of the physics of the non-thermal components of galaxy clusters has significantly increased during the past few years, thanks to the improved capabilities of the available instruments. Detailed spectral index maps of a few radio halos and relics, as well as deep X-ray observations of galaxy clusters, helped to investigate the connection between the non-thermal phenomena of the ICM and shock
waves and turbulence in cluster environments. Important open questions are still under debate. The theories on the origin of halos and relics need to be tested further, since they fail in explaining many aspects of the observations. Although current observational results favour primary models as the mechanism at the origin of the particle acceleration in clusters, secondary models cannot be ruled out (see Sect. 7.1). To reach a definitive conclusion, it is important to establish how common the non-thermal phenomena of the ICM are in clusters. Do they occur in merging systems only? In this case, why do not all the known merging clusters show the presence of halos and relics? Are other physical effects playing a role in their formation, or do we just need a higher sensitivity to detect them?

The occurrence of halos and relics in merging clusters is currently difficult to establish, given the observational limitations of the available radio telescopes. Feretti & Giovannini (2008) derived that, if present, Mpc-size halos in intermediate/low-luminosity X-ray clusters \( \left( L_{\text{X}}^{[0.1-2.4\text{kev}]} \leq 5 \times 10^{44} h_{70}^{-2} \text{ erg s}^{-1} \right) \) would have a surface brightness lower than the current limits obtained in the literature and in the NVSS. At higher X-ray luminosities, more constraints on halo statistics have been obtained by Brunetti et al. (2007) and Venturi et al. (2007) with 610 MHz GMRT observations of 34 luminous \( \left( L_{\text{X}}^{[0.1-2.4\text{kev}]} \geq 5 \times 10^{44} h_{70}^{-2} \text{ erg s}^{-1} \right) \) clusters within redshifts \( 0 < z < 0.4 \). The bulk of galaxy clusters does not show any diffuse radio halo emission, with upper limits to the radio luminosity that are well below the \( P_{1.4\text{GHz}} - L_{\text{X},\text{bol}} \) relation derived from the previously known radio halos (see top panel of Fig. 1.3). This bimodality of cluster distribution in the \( P_{1.4\text{GHz}} - L_{\text{X},\text{bol}} \) plane supports primary models. They predict a relatively fast (\( \sim 10^8 \) yr) transition of clusters from a radio quiet state to the active phase, where they remain for \( \leq 1 \) Gyr. A wider scatter in the correlation is instead predicted in the case of secondary models, which, to be reconciled with the observations, would require a significant dissipation of magnetic fields in clusters (Brunetti et al. 2007).

Observations of halos and relics offer a unique opportunity to study large-scale and inter-cluster magnetic fields. From detailed polarization information on the ICM non-thermal components, Murgia et al. (2004) and Govoni et al. (2006) have been able to estimate the strength and topology of cluster magnetic fields. The discrepant results obtained by applying different methods suggest, however, that further investigations are needed in order to clarify what is the origin and evolution of cluster magnetic fields.

On a general point of view, the improved knowledge on the non-thermal phenomena of the ICM will have an impact on cosmology. If halos and relics are related to cluster mergers, the study of the statistical properties of these sources will allow us to test the current cluster formation scenario, giving hints on detailed (astro)physics of large-scale structure formation (e.g. Evrard & Gioia 2002).

Complementary cosmological studies, as the EoR (epoch of re-ionization), will benefit of these investigations. To detect the EoR signal one must remove the contributions of halos and relics, which are the strongest diffuse extragalactic foreground sources. This requires better modeling of the diffuse radio emission in clusters (Jelić et al. 2008).

To solve the problems reported above, an increased statistics and knowledge of the physics of halos and relics is required. High resolution and high sensitivity ob-
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Figure 7.1: The spectrum of Coma C with superimposed the frequency range domain of LOFAR (low band: 30–80 MHz, high band: 110–240 MHz).

Observations are needed to achieve these goals. Given the steep spectra of halos and relics, low-frequency radio observations with a good sensitivity are the key for their detection. This is shown in Fig. 7.1, where the frequency coverage of LOFAR is superimposed on the spectrum of Coma C (Chapter 6). Currently, instruments like the VLA, the WSRT, and the GMRT are still playing an important role in such investigations, thanks to their improved capabilities towards low frequencies. However, a proper comparison between theoretical models and observations requires multi-wavelength investigations of large statistical samples of diffuse radio sources. Current telescopes require too long exposure-time per cluster (≥ 1 – 2 hours) to reach the sensitivity needed for the detection of halos and relics. This makes statistical analyses of diffuse radio emission in clusters extremely time-demanding.

The LOFAR array will enormously increase the detection rate of halos and relics. It will cover the optimal wavelength domain for detecting these sources and will achieve much higher sensitivities and resolutions than the current instruments at such low frequencies. A LOFAR survey at 120 MHz (rms 0.1 mJy), covering half of the sky is expected to detect ~ 500 halos/relics up to z=1 (Röttgering 2003).
The LOFAR cluster Surveys KSP

The science that can be conducted with LOFAR is very broad. A few key science projects (KSP) have been designed. Among them, the Surveys KSP (SKSP) will observe large fractions of the sky with wide frequency coverage (Röttgering et al. 2006). This project is therefore playing an important role in designing the first LOFAR observations. Different sub-projects, with different scientific goals, are part of the SKSP. Cluster science is one of the main tasks and its observational and scientific goals are:

- **survey of diffuse radio emission**: the LOFAR surveys are expected to detect about 350 giant steep-spectrum ($\alpha \lesssim -1.5$) radio halos at redshifts $z \lesssim 0.6 - 0.7$ (Cassano et al. 2009). This will allow an improvement in our understanding of the statistical properties of giant radio halos and of their origin and evolution with cosmic time;

- **studying the merger-radio halo connection**: X-ray cluster catalogs in the northern hemisphere, such as NORAS and REXCESS (Bohringer et al. 2000) contain more than 600 galaxy clusters in the redshift range $z = 0 - 0.6$ with X-ray and optical information. Observing the brightest clusters of this sample with the excellent sensitivity and the adequate spatial resolution offered by LOFAR will allow us to address the connection between the formation of radio halos and cluster mergers with unprecedented statistics;

- **spectrum of radio halos**: The shape of the spectrum of radio halos is an important tool to understand the mechanisms responsible for particle acceleration in the ICM (Brunetti 2003; Petrosian & Bykov 2008). Present observations fail in providing solid constraints due to the small frequency range available. LOFAR can easily detect the known radio halos and allow an accurate determination of their flux density and spectra, with much better angular resolution than the current facilities;

- **spectral and polarization studies of radio relics**: although a connection between shocks and relics is now well accepted, it is not yet clear whether the origin of relics is due to shock acceleration of thermal particles (Enßlin et al. 1998; Roettiger et al. 1999) or to re-energization of “ghost” relativistic plasma released by AGN in clusters through the shock passage (Enßlin & Gopal-Krishna 2001). Since these models have different expectations on the polarization and synchrotron spectrum, low-frequency observations are the key to test them. The very steep-spectrum emission left behind the shock passage will also be imaged at low frequencies. This will allow the study of both the dynamics of the shock and the amplification of the magnetic fields (Roettiger et al. 1999; Clarke & Enßlin 2006; Markevitch et al. 2005; Giacintucci et al. 2006).

To achieve the aforementioned goals, two sets of observations should be performed:

- nearby clusters at 30, 60, 120, and 200 MHz. These observations are crucial to test the available pipelines for the data reduction and to improve them in order to image the diffuse extended cluster emission;
• survey of the northern hemisphere at 15, 30, 60, 120, 200 MHz. This survey should unveil the diffuse synchrotron emission in galaxy clusters from both halos and relics, up to a redshift $z \sim 1$. Spectral index information on the detected emission will be obtained, providing constraints on the origin and evolution of radio halos.

7.5 Technical issues

To achieve the scientific goals that drive the cluster SKSP, it is crucial to test the capabilities of the available software developed for the LOFAR data reduction. The technical issues related to the imaging of extended cluster radio emission can be summarized as follows:

• **RFI mitigation**: to have high-fidelity images for large angular size structures, it is important to recover all the possible information from short baselines in the presence of severe RFI. New pipelines for automatic data flagging have been recently developed and need to be tested (Offringa et al. 2009);

• **ionospheric calibration**: the ionospheric conditions below 70 MHz are poor and not well constrained. It is important to test them in order to improve the available calibration schemes (such as SPAM, Intema et al. 2009). LOFAR observations will require better ionospheric TEC (total electronic content) models, that are essential for ionospheric refraction and Faraday rotation predictions.

• **polarization calibration**: full polarization calibration across the primary beam is needed in order to perform RM-synthesis on large-scale diffuse emission;

• **dynamic range and confusion limit**: dynamic range and confusion limit issues need to be addressed by combining multi-frequency LOFAR observations of clusters containing both bright and diffuse radio sources.

• **wide field imaging, peeling, etc.**: the LOFAR surveys will face issues related to the imaging of wide fields of view, which are heavily affected by off-axis errors. Peeling and ionospheric modeling are new approaches that will be needed to achieve good scientific results.

The properties shown by A2255 and Coma in polarization and total intensity make them excellent targets for pioneering LOFAR observations.
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