Merging galaxy clusters: probing magnetism and particle acceleration over cosmic time

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SUMMARY

Galaxy clusters are the largest objects in the Universe held together by gravity. They can reach a size of a few millions of light years ($\gtrsim$ 1 Megaparsec) and masses of hundreds of trillion times the mass of the Sun ($\gtrsim 10^{14}$ $M_\odot$). Galaxy clusters consist of thousands of galaxies, which only represent a small percentage of the total mass of these objects. The largest fraction of the visible light is emitted by particles (electrons and protons) filling the space in-between galaxies, the so-called the *intracluster medium* (ICM). The ICM is visible at X-ray wavelengths (Fig. 6.14). According to the current models, galaxy clusters grow via collisions with other clusters or galaxy groups. Galaxy clusters in the phase of collision are called *merging clusters*. Multi-wavelength studies have set an approximate time for the formation of these large structures when the Universe was only 3–4 billion years old.

Cluster mergers are the most energetic events since the Big Bang. During these events, part of the energy is released in turbulence and shock waves. These affect the ICM, which is therefore observed to have a disturbed morphology. Moreover, cluster mergers are able to accelerate the electrons roaming between galaxies to velocities close to the speed of light, and to amplify cluster magnetic fields. The interaction of accelerated particles with cluster-scale magnetic fields produces large-scale diffuse radio emission, which is not associated with the emission from black holes at the centre of galaxies (i.e. radio galaxies). These diffuse radio sources are called *radio halos* or *radio relics* (Fig. 6.14).

- Radio halos are roundish, roughly smooth sources located in the cluster centre. They generally follow the morphology of the intra-

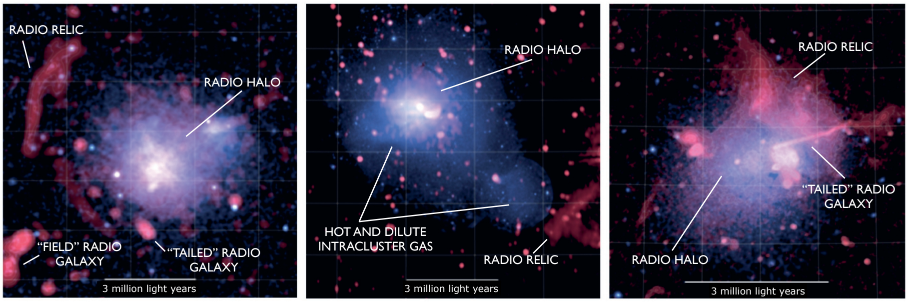

Figure 6.14: Three examples of local clusters of galaxies observed at radio (red) and X-ray (blue) wavelengths. From left to right: Abell 2744, Coma and Abell 2256. The radio emission traces accelerated particles and magnetic fields, while the X-ray emission traces the hot and dilute intracluster gas. Images taken and adapted from van Weeren et al. (2019).

cluster medium from the X-rays.

- Radio relics are elongated structures located in the cluster outskirts. Recent observations have found that they are located at the position of X-ray shocks. Radio observations at high resolutions have revealed that relics have a filamentary structure.

Despite the progress in our understanding during the last decades, it is still unclear what the origin of the diffuse radio emission in clusters is. Radio relics are thought to be produced as a consequence of the shock propagation towards the cluster outskirts. The basic idea is that the shock wave aligns and amplifies magnetic fields, while particles become ultra-relativistic by scattering back and forth across the shock. The detailed physical understanding of the acceleration mechanisms is unclear. One of the challenges is that cluster shocks have mild strengths ($\mathcal{M} \lesssim 3$), and hence should not be able to efficiently accelerate the particles associated with the ICM. Therefore, the presence of pre-existing relativistic plasma, like that in the lobes of radio galaxies, is required. In some clusters, a clear morphological link between radio galaxies and radio relics has been found, supporting the latter scenario. Finally, as a consequence of the magnetic field alignment and compression, radio relics are also polarised structures. Radio halos are thought to be produced as a consequence of the turbulence generated by the cluster mergers. Recent studies have found a clear relation between the cluster dynamical state and the characteristics of radio halos. In particular, the most massive (and therefore energetic) systems have been found to host the most luminous radio halos.

Diffuse radio emission in the cluster volume is compelling evidence of the presence of μGauss-level magnetic fields. This value is obtained in nearby objects, analysing the change of the polarised emission from background sources (i.e. Faraday Rotation Measurements). It is still an open question where the magnetic fields come from. Two main scenarios have been identified: one assumes that magnetic fields are generated during the first phases of the Universe's history, before the formation of the first stars and galaxies (i.e. *primordial origin*); the other one assumes that magnetic fields are ejected from galaxies, winds and/or jets (i.e. *astrophysical origin*). For both scenarios, the initial magnetic fields need to be amplified over cosmic time to reach the levels we measure in the present-day Universe. It is widely believed that turbulence due to cluster mergers plays a major role, although the exact amplification process is still not well understood.

This Thesis aims to investigate the acceleration mechanisms driven by merger-induced shock waves and turbulence, and the evolution of the diffuse radio emission (and therefore cluster magnetic fields) over cosmic time. This was possible thanks to high-sensitivity and high-resolution radio and X-ray observations. Particularly, throughout this Thesis, radio observations with the Karl-Jansky VLA, LOFAR and upgraded GMRT have been combined with X-ray Chandra, XMM-Newton and Suzaku observations. In **Chapter 2** and **Chapter 5** the spectral and polarisation properties of the radio relic in CIZA J2242.8+5301 have been studied. Thanks to deep high-resolution VLA observations, it was discovered that the source consists of several filaments. It remains unclear whether this is due to the complex shape of the shock surface and/or magnetic field inhomogeneities. The properties of the shock in ZwCl 0008.8+5215 have been presented in **Chapter 3**. Using deep Chandra and Suzaku observations, variations in the shock strength along the length of the shock were investigated to explain the morphological properties of the diffuse radio emission. The evolution of the cluster-scale magnetic fields is presented in **Chapter 4**, studying a sample of distant ($z \geq 0.6$) galaxy clusters observed with LOFAR. The similar radio luminosity to that measured in nearby systems, in the same cluster mass range, results in surprisingly high magnetic fields ($\sim$ few μGauss). The spectral properties of these distant radio halos are investigated in **Chapter 6**, using new uGMRT observations. This information is crucial to test the current model for formation of the diffuse radio emission.