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Introduction

1.1 Evolution and composition of the Universe

The 'Big Bang' theory proposes that the Universe started in a hot, dense state about 13.7 billion years ago (Planck Collaboration et al. 2015). Shortly after its birth (10^{-36} s), the Universe passed through 'inflation' (Guth 1981), a period of rapid expansion over a few orders of magnitude, when the Universe slowly cooled thus allowing the condensation of elementary particles, such as electrons, protons and neutrons. Between three and twenty minutes after the 'Big Bang', the temperature dropped to the point where hydrogen and helium nuclei could bind. Around $377,000$ years after the birth of the Universe, in the 'recombination' phase, the temperature dropped to the point where positively charged atoms were capable of capturing electrons to become neutral atoms and photons were now able to travel freely. We have observed the relic emission of the 'recombination' process as the Cosmic Microwave Background (CMB) radiation (Penzias & Wilson 1965).

In the currently adopted cosmological ΛCDM model, the Universe is a soup of different components. 'Normal' baryonic matter does not dominate, but currently only accounts for a little under 5 per cent of the content of the Universe (Planck Collaboration et al. 2015). Almost 27 per cent of the present Cosmos is dark matter, which does not emit any form of radiation. Dark matter was originally proposed by Zwicky (1933), who measured a velocity dispersion of the Coma cluster too large to be explained by the mass contained in the luminous matter. However, during the 'recombination' epoch, the Universe was dominated by dark matter, amounting to over 60 per cent.

The study of the CMB has revealed that the Universe on large scales is astonishingly uniform and isotropic. However, on smaller scales, inhomogeneities in the matter distribution left imprints in the CMB temperature (Mather et al. 1990; Smoot et al. 1992; Mather et al. 1994; Kovac et al. 2002). Under the influence of gravity, seed fluctuations in the the early Universe density field grew over the next 13 billion years to form structures hierarchically from small to large scales. In the gravitational potential wells created by the high densities of dark matter (White & Rees 1978), baryonic matter aggregates to form the first astronomical sources: Population III stars and quasars, followed by Population II and I stars which bound together to form galaxies. At the location of the highest primordial inhomogeneities, galaxies grouped together to form galaxy clusters and even larger superclusters connected in a cosmic web through low-density filaments. At the opposite pole, primordial negative peaks in the matter distribution resulted in the lowest density area which fill the space between galaxy clusters: voids (e.g. Peacock et al. 2001).

1.2 Galaxy clusters

Cluster of galaxies, located at the top of hierarchical structure formation, have masses of 10^{14-15} $M_\odot$ and contain hundreds of galaxies within a few Mpc^3 volume (Sarazin 1986, 2002).

Most of the mass in galaxy clusters is distributed in between the galaxies, in the form of dark matter and hot (10^{7-8} K), X-ray emitting plasma. The dense intra-cluster medium has a profound impact on the evolution of the cluster galaxies. Field star-forming spiral galaxies suffer a morphological transformation as they fall into a cluster environment, as the fraction of star-forming galaxies drops from void-like environments towards cluster cores (e.g. Dressler 1980; Goto et al. 2003). Ram pressure strips the gas fuelling star formation away from the host galaxy (Gunn & Gott 1972), while tidal forces truncate the halo and disk of infalling spiral galaxies or channel gas out of the host galaxy (Moore et al. 1996; Larson et al. 1980).

Clusters evolve through mergers, in the most energetic events after the 'Big Bang', releasing 10^{64} erg (40 orders of magnitude higher than an atomic bomb) on time scales of $1-2$ billion years (Hoeft et al. 2004). After two clusters pass through each other, dark matter and galaxies become separated from the cluster gas (e.g. Clowe et al. 2006; Dawson et al. 2012). This offers unique opportunities to study cosmological structure formation and the nature of dark matter. Part of the merger energy is dissipated through the intra-cluster medium (ICM) via turbulence and shocks. In this sense, cluster shocks are the largest particle accelerators in the Universe, 19 orders of magnitude larger than the Large Hadron Collider.

Enormous Mpc-wide, diffuse radio sources associated with the intra-cluster medium (ICM) are often found in merging galaxy clusters (e.g. reviews by Feretti et al. 2012; Brunetti & Jones 2014). Their spectral and polarisation properties indicate that they are synchrotron emission caused by relativistic electrons (cosmic rays) gyrating in a weak magnetic field ($1-10\ \mu$G).

Radio **relics** are arc-like patches of emission located at the periphery of clusters and are believed to be formed when relativistic particles are accelerated by low Mach number ($M = 1-5$) shocks produced at the merger of two massive clusters (Ensslin et al. 1998). Markevitch et al. (2005) propose the seed electrons are pre-accelerated, for example through past radio galaxy activity. The electrons, no matter if they are thermal or relativistic, are accelerated to a power-law energy distribution spectrum and emit over a broad radio range. Observations and simulations indicate that the shock also compresses and aligns the magnetic fields with the shock surface (e.g., Bonafede et al. 2009; Finoguenov et al. 2010; van Weeren et al. 2011a; Iapichino & Brüggen 2012). In terms of the cosmic evolution of radio relics, models predict for example that increasing merger rates at high redshift cause the fraction of clusters hosting relics to rise as well and that relics are hosted by the most massive clusters (Nuza et al. 2012).

Radio **halos** are diffuse emission that follows the X-ray ICM distribution, believed to form when particles are re-accelerated by turbulence injected by the cluster merger (Brunetti et al. 2001). Blasi & Colafrancesco (1999) propose that the emission comes from secondary electrons injected by proton-proton collisions (hadronic model).

Shocks and turbulence drive the evolution of clusters in the context of structure formation (Brunetti & Jones 2014). The study of clusters with diffuse radio emission can unveil particle acceleration in conditions which cannot be found in other astronomical contexts and cannot be reproduced on Earth (large scales, weak shocks, weak magnetic fields and low density). While the past decade has seen significant progress in our understanding of merging clusters, due to the lack of suitable instruments to detect relics and haloes, most research still relies on a few individual, low-redshift sources observed in one or two radio frequency bands. With a mainly radio and X-ray focused view of merging clusters, the nature and evolution of the cluster star-forming and AGN galaxies remains unexplored. Unanswered questions in the field include:

Cosmic evolution of diffuse cluster emission: Are there massive, merging clusters hosting diffuse radio emission at high-redshift? What is their dynamical history? What is the cosmic evolution of diffuse sources?

Nature and physics of diffuse cluster radio emission: How are cosmic rays injected and accelerated to form relics and halos? How do Mach numbers and speeds of radio shocks relate to cluster mass, temperature, redshift? What is the magnetic field topology at cluster outskirts? How do electrons interact with the magnetic field such that they lose their energy?

Galaxy evolution in merging clusters with shocks: Do the merger, the shocks and the turbulence drive the evolution of cluster galaxies?

1.3 This thesis

This PhD thesis combines complementary broad-band radio data, optical imaging, spectroscopy and spectral modelling, to study merging clusters hosting radio relics. The thesis focuses on two massive merging clusters, nicknamed the 'Sausage' (van Weeren et al. 2010) and 'Toothbrush' (van Weeren et al. 2012b), which host Mpc-wide double-relics, with spectacular, regular morphologies. The clusters appear to have relatively simple merger histories, resulting from binary mergers of two equal mass systems in the plane of the sky. This thesis aims to obtain a complete picture of these two clusters focusing on the way shocks interact with electrons and magnetic fields to produce diffuse emission and on the the way the merger of massive systems affects star formation in cluster galaxies.

Chapter 2 deals with the influence of the cluster merger history on the radio galaxies and on particle acceleration in the context of diffuse radio emission. The analysis is based on the very wide range radio data of the 'Sausage' cluster from the Giant Metrewave Radio Telescope and the Westerbork Synthesis Radio Telescope (150 – 2300 MHz. Through spectral index, spectral curvature and radio color-color techniques, we show that the twin radio relics in the 'Sausage' cluster have most likely been accelerated by symmetrical merger shocks produced at the core-passage of two sub-clusters that are traced by tailed radio galaxies. The analysis indicates that the electrons are accelerated by the shock front, while their pitch angle to the magnetic field is continuously isotropised.

Chapter 3 tackles the issue of mismatching radio and X-ray measurements of the shock Mach number in radio relics. We perform the first spatially-resolved spectral modelling of a radio relic and alleviated the resolution effects which previously affected the radio measurement of the Mach number in the 'Sausage' relic and brought it in agreement with the X-ray. We find a systematic increase in spectral age from the northern side of the 'Sausage' relic into the downstream area. This indicates that the shock is moving northwards at about 2500 km $s^{-1}$and represents the first direct test that the steepening of the radio spectrum is a consequence of electrons losing energy through synchrotron emission and inverse Compton interactions. We show that there are other important effects (re-acceleration by turbulence and line-of-sight mixing) which have not been previously considered in the formation mechanism of relics.

Chapter 4 presents the highest radio frequency measurement of diffuse emission to date, at 16 GHz, made possible with the Arcminute Microkelvin Imager. Such measurements are crucial for quantifying the interaction of the electrons with the magnetic field and distinguishing between various models for the origin of the synchrotron emitting electrons. The high-frequency data indicates a trend of steepening in the integrated radio spectrum of the 'Sausage' relic, challenging the currently-accepted view of radio relic formation.

Chapters 5 and 6 present the Hα mapping of the 'Sausage' and 'Toothbrush' clusters, which serve as the first direct proof that the shock affects star formation in cluster galaxies. We find numerous Hα emitting galaxies in close proximity to the radio relics in the 'Sausage' cluster, which are extremely massive, metal-rich and star-forming. There are no such examples in the 'Toothbrush' cluster. We interpreted these results in the context of the different timescales of the clusters, taking into account simulations which indicate that the 'Toothbrush' cluster is $\sim$ 1 Gyr older than the 'Sausage'. We propose that the passing of the shock momentarily excites star-formation, accelerating the transformation of gas-rich spirals into ellipticals.

In **Chapter 7**, we use Westerbork Synthesis Radio Telescope HI observations of the 'Sausage' cluster to investigate the effect of the merger and the shocks on the gas reservoirs fuelling star formation in cluster galaxies. Contrary to previous research which finds that galaxies become increasingly HI deficient towards cluster cores, we find that the star-forming galaxies in the 'Sausage' cluster have as much HI as their field counterparts. We find evidence of vigorous supernova remnant emission in cluster galaxies, which indicates they have been forming stars for at least 100 Myr.

1.4 Future prospects

Detailed studies of individual sources can provide crucial insight into the physics of particles and galaxies in clusters at particular phases in their evolution. However, in order to trace the evolution of shocks and cosmic ray particles up to the epoch when the first massive clusters formed, we require a sample of clusters hosting radio relics and halos, with a wide spread in mass and redshift. Excellent multi-wavelength data will enable us to discover the required sources and study their properties in detail. With the recent availability of the first high-z massive cluster samples (e.g. Planck Collaboration et al. 2014) it has become clear that this next important step can now be taken.

Targeted observations of clusters recently discovered by the Planck mission with telescopes of unprecedented sensitivity over the entire radio spectrum (30 MHz −16 GHz, Low Frequency Array, Very Large Array, Giant Metrewave Radio Telescope, Arcminute Microkelvin Imager) will enable the detection of diffuse radio emission at the highest redshifts. With samples of clusters up to $z \sim 1$, evolution models of diffuse emission populations can be constrained.

By applying spectral modelling techniques to a sample of diffuse radio sources using wideband radio data, we can obtain a consistent set of shock parameters (Mach number M, shock speed) and test whether the spatial distribution of shock strengths is consistent with hydrodynamical simulations. Simulations predict that strong shocks ($M > 3$) in clusters are rare, but low-Mach number shocks are ubiquitous (e,g, Pfrommer et al. 2006). Particle acceleration at high Mach number shocks ($M > 100$) is well understood from studies of supernova remnants. Theory predicts that low-Mach number shocks ($M < 5$), such as those in clusters are extremely inefficient at accelerating particles from the thermal pool and cannot account for the observed relic emission (see review by Brunetti & Jones 2014). From the spectrum and morphology of the relics we will be able to pinpoint the nature of the ICM electrons: pre-accelerated, rather than thermal, electrons originating from radio jets would alleviate the injection efficiency problem. Turbulent re-acceleration in the downstream area of the shock could also explain the observed emission. The re-acceleration model predicts ultra steep spectrum halos, which have yet to be detected because they are very faint in the typical frequency ranges explored. If this model is correct, deep, low-frequency data will enable the discovery of halos with steep spectra. The combination of radio and X-ray data breaks degeneracies due to magnetic field changes and adiabatic gains/losses to clearly measure the intrinsic spectral shape of the diffuse emission and help discriminate between formation models of relics and halos. By studying the filamentary morphology and radio polarization properties of the diffuse emission, we can test whether the magnetic field is constant, aligned, turbulent or intermittent. Future telescopes such as Astro-H will provide the first high-resolution X-ray spectral mapping of clusters, directly measuring bulk and turbulent motions in the ICM, which in comparison with radio data will provide key insights on the acceleration processes in radio halos.

By using the emission lines as a well-calibrated, sensitive indicator of recent star formation, we will unveil for the first time the role of the merger, turbulence and shocks in suppressing or enhancing star formation in cluster galaxies. With a proper sample of radio relic and halo clusters, we will be able to test whether the evolutionary path of star-forming galaxies is a function of host cluster mass, age, merger state and dynamical history. By following up the samples of star-forming galaxies with spectroscopy (e.g. optical and near-infrared multi-object spectroscopy), we will be able to determine the power source of the emission. From the metallicity of the HII regions, we can determine whether the line emission is coming from accretion of matter onto the super-massive black holes at galaxy nuclei or it is purely generated by star-formation. Integral field unit data will reveal any preferential alignment in the 3D distribution of gas. Could the gas be stripped or compressed at all scales, as expected from shock fronts, or does that only occur at the outer regions of the galaxy, indicative of small-scale motions induced by intra-cluster medium turbulence? High resolution Hubble and in the future James Webb Space Telescope imaging will clearly indicate the presence of star-forming tails, knots and filaments in the galaxies infalling into the cluster and in those that recently interacted with the shock front. By comparing these observations with simulations which predict that after a shock passes through a gas-rich galaxy, significant star formation occurs in the galactic disk only at radii where the gas will be stripped in due course and in knots throughout stripped tails (Roediger et al. 2014).

By comparing Hα measurements to Atacama Large Millimeter/sub-millimeter Array and Herschel data which trace dust-obscured SF over longer timescales (100 Myr), we can test whether the number of dusty star-forming galaxies increases from low to high densities and from relaxed to merging clusters or the AGN activity and/or quenching rate is higher in denser, more disturbed regions. With new-generation sub-mm/mm facilities such as ALMA, we will be able to perform in-depth studies of the fuelling source for future SF and AGN episodes. CO rotational transitions are for example sensitive to dense and thermally excited gas in the central starburst/AGN regions, as well as the overall low-density sub-thermally excited molecular gas distribution. The radio jets coming from the galaxy nucleus can expel large amounts of cold gas, which is the raw ingredient for future formation of stars, but could also increase turbulence and lead to instabilities which induce SF. Does the merger shock induce outflows that will eventually lead to a shut-down of SF in a few hundred million years? Ultimately, we will be able to test the prediction that cluster shocks and turbulence compress the gas within galaxies, which then collapses and cools to form stars, dramatically changing the fates of galaxies within clusters.

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