# Untangling cosmic collisions: a study of particle acceleration and magnetic fields in merging galaxy clusters

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# ENGLISH SUMMARY

The Big Bang is the proposed beginning of the Universe, where the cosmos suddenly emerged in an explosion from a single point that contained all the energy that ever was and ever will be. As the Universe expanded and cooled, matter began to clump together under the influence of gravity. The first stars, galaxies, and groups of galaxies formed, and the Universe started shaping itself on the grandest scale as a cosmic spiderweb. Most galaxies reside in the filaments of this web, while outside the web's strands, there are vast empty spaces known as 'voids'. At the intersections of these filaments, the largest structures in the Universe, that are still held together by gravity, formed: clusters of galaxies (also called galaxy clusters).

## GALAXY CLUSTERS

Although the name suggests that they are simply large groups of hundreds of galaxies, galaxies are the least significant part of galaxy clusters. Clusters mainly consist of extremely hot and tenuous gas that is located in the space between the galaxies, in the so-called intra-cluster medium[4]. This gas is primarily composed of hydrogen and helium atoms, constituting more than 90% of the cluster's mass. The temperature of the gas is so high (10 million to 100 million degrees Celsius) that electrons are released from the atoms (ionisation). The gas is not visible in wavelengths that our eyes can see but emits X-ray radiation. Hence, clusters of galaxies are best understood as colossal clouds of gas (see Figure S.1, middle).

Figure S.1: The cluster of galaxies Abell 2256 at three different wavelengths. *Left*: Only the galaxies are visible in infrared light. *Middle*: In blue, the X-ray emission from the hot gas between galaxies is visible. *Right*: In red, radio emission is visible, originating from high-energy charged particles in the gas that bend around magnetic fields. Infrared: neoWISE (Meisner et al., 2017), X-ray: XMM-newton (Rajpurohit et al., 2023), radio: LOFAR (Osinga et al., 2023a), image overlay: Frits Sweijen

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[4] We are temporarily neglecting dark matter, which constitutes the majority of the mass but is not the focus of this dissertation. When accounting for dark matter, clusters have a total mass of hundreds to thousands of trillions of solar masses ($> 10^{14} M_{\odot}$).

Clusters are still in the process of forming and growing by attracting dust and gas from their surroundings, and colliding with other clusters. Collisions between two clusters are incredibly energetic, causing the gas to become shocked and mixed. The charged particles within the gas, such as protons and electrons (separated due to the high temperature), can be accelerated to speeds close to the speed of light by shockwaves and turbulence within the gas. In the presence of a magnetic field, electrons experience the strongest deflection and emit radio radiation. This radio radiation can be observed using telescopes like the *Low-Frequency Array* (LOFAR), whose core is located in Drenthe. LOFAR is particularly well-suited for these observations because the particles predominantly emit radio radiation at low frequencies, or long wavelengths (see Figure S.1, right).

In general, we observe three distinct classes of radio emissions from clusters. First, there are *radio halos*, large roundish radio structures in the central regions of clusters. The brightness of radio halos roughly follows the distribution of the hot gas, so they are brighter in the centre and fade towards the outer parts of the clusters. We believe that radio halos primarily reveal a particle acceleration process that arises due to turbulence within the gas. Second, there are *radio shocks*, which are named as such because they exhibit long and extended structures that often trace shockwaves within the gas. In these cases, electrons are accelerated by shockwaves resulting from massive cluster collisions. Lastly, there can be radio emission directly from the galaxies themselves. When a supermassive black hole, which resides in the centre of virtually all galaxies, has enough material around it, the galaxy is said to have an 'active galactic nucleus' (AGN). Part of the material surrounding such a black hole gets consumed, while some is expelled in the form of two enormous fountains, or radio jets. These jets are often much larger than the galaxy itself, reaching sizes of several million light-years[5]. As the galaxies producing these jets move through the hot gas of the cluster, the jets are often deflected, leading to a rich diversity of shapes. Radio jets are not exclusively found in clusters, as all galaxies can harbour an active black hole. However, it is thought that these radio jets can serve as a significant source of energetic electrons that gradually spread through the cluster and are re-accelerated when clusters collide.

## MAGNETIC FIELDS

The fact that we see radio emission coming from clusters means that there must be magnetic fields in the gas. This is because the radio emission exhibits characteristics of synchrotron radiation, emitted by charged particles moving within a magnetic field. However, it remains a significant mystery how these magnetic fields originated and evolved within the space between the galaxies. The prevailing theory suggests that magnetic fields in clusters gradually grew during the formation of clusters from an initially weak magnetic field that was already present during cluster formation. However, the origin of this initial magnetic field remains uncertain. Two main hypotheses exist regarding the origin of these magnetic fields. They could be a fundamental component of the Universe, generated shortly after the Big Bang or during the formation of the first structures in the cosmos (*primordial origin*), or they might have been injected into space later by supernova explosions and active

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[5] To give some context to this incomprehensible scale, the distance from Earth to the Sun is about 8 light minutes, and the distance from Earth to the centre of the Milky Way is about 26,000 light years.

galaxies (*astrophysical origin*). Regardless of their origin, magnetic fields play a crucial role in energy transport through the hot gas and in particle acceleration during cluster collisions. However, little is known about the characteristics of current magnetic fields within clusters.

The most effective way to determine the properties of magnetic fields in clusters is through the Faraday effect (see Figure S.2). As light is an electromagnetic wave with both electric and magnetic field waves perpendicular to the direction of motion (and to each other), there are many possible orientations for the electric field wave. When it has only one specific orientation, we call the light (linearly) polarised. The polarization angle is rotated when light travels through a magnetic gas, such as that found in clusters. The degree of rotation depends on the strength of the magnetic field, the density of free electrons in the gas, and the wavelength of the light. By observing multiple wavelengths simultaneously with a radio telescope and using an X-ray telescope to determine the density of free electrons, the properties of the magnetic field can be inferred. However, a challenge with Faraday effect studies is that polarised radio sources are relatively rare, requiring deep observations of nearby clusters to locate enough polarised radio sources. Alternatively, observations from different clusters can be stacked on top of each other. With the (presumably strong) assumption that all clusters are approximately the same, the average properties of the magnetic field in clusters can be determined statistically.

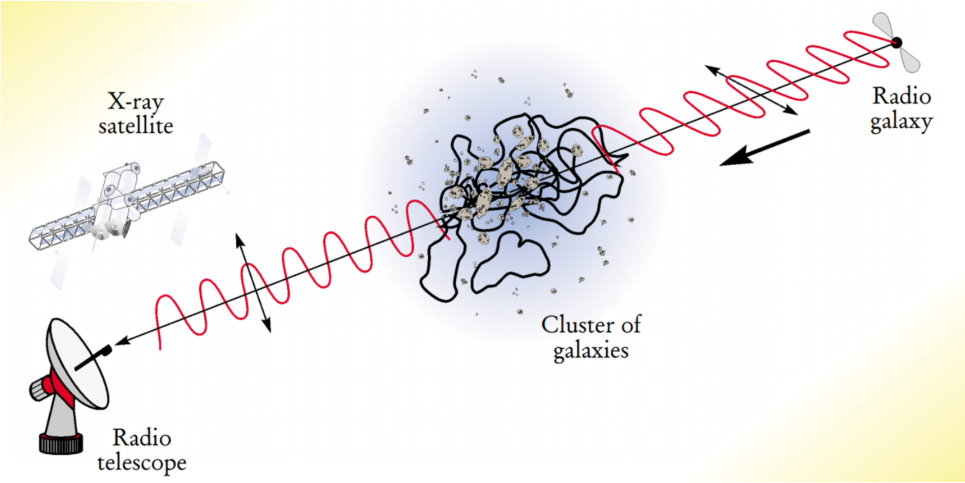

Figure S.2: An illustration of the Faraday effect. A distant active galactic nucleus emits polarised radio emission with an electric field wave at a specific angle. As the wave reaches the magnetic gas within the cluster, the angle is rotated, depending on the light's wavelength and the properties of the gas. This rotation can be observed using a radio telescope that observes at different wavelengths. Image: Philipp P. Kronberg, Physics Today, December 2002.

## THIS DISSERTATION

This dissertation explores the particle acceleration process and magnetic fields that contribute to radio emission within galaxy clusters. By gaining a better understanding of these topics, we can learn more about the formation process of clusters, as cluster collisions are closely linked to both subjects. On the one hand, the particle acceleration process is best studied at low frequencies (~ 100 MHz), for which LOFAR is particularly suitable. On the other hand, magnetic fields are best investigated at higher frequencies (~ 1000 MHz), as the Faraday effect becomes too strong at lower frequencies, leading to a loss of polarization (depolarisation). Therefore, this dissertation utilises The Karl G. Jansky Very Large Array (VLA), a telescope in New Mexico, to gain a better understanding of magnetic fields within clusters.

In **Chapter 2**, the orientation of radio jets from active galaxies is investigated. Previous studies have found that the orientation of radio jets is not random across large portions of the sky, with jets of galaxies that appear closer to each other often pointing in the same direction. This could have significant implications for the formation of the Universe's structure. However, small systematic measurement errors can lead to biased results. It is therefore important to consider the distance of the radio jets to Earth (via the redshift of the host galaxy) and measure whether jets that are physically close to each other (in 3D) actually point in the same direction or merely appear to do so on the sky (in 2D). By analyzing a sample of 7,555 distinct radio jets from the *LOFAR Two Meter Sky Survey* (LoTSS), the null hypothesis that radio jets have no preferred direction in both 3D and 2D is tested. Evidence is found that the null hypothesis can be rejected in 2D, confirming that radio jets from galaxies that appear close to each other in the sky indeed have a preferred direction. However, no evidence is found to reject the null hypothesis in 3D, indicating that there are probably unknown systematic measurement errors in the data, and that the orientation of jets in the Universe is random at large distances.

In **Chapter 3**, we investigate whether smaller galaxy clusters with lower mass and thus less energetic collisions compared to those previously studied, can still exhibit radio emission in the form of radio halos. The deepest radio maps ever created at a frequency of 150 MHz, as part of the *LOFAR Two Metre Sky Survey Deep Fields*, were analyzed. The observations revealed that a cluster with relatively low mass (only 300 trillion solar masses), even at a relatively high redshift (z=0.77), exhibited a radio halo. A possible detection was also made in another cluster with a slightly lower mass. Combined with upper limits set on clusters from which no radio emissions were detected, the results were consistent with the known relationship between cluster mass and radio halo luminosity, although the sample size was small.

In **Chapter 4**, LOFAR is pushed to its limits with observations of the nearby galaxy cluster Abell 2256 down to the extremely low frequency of 16 MHz. This is difficult because the upper layer of the atmosphere, the ionosphere, strongly deflects and changes the direction of radio waves at low frequencies. Still, we present good quality LOFAR images of Abell 2256 between 16 and 168 MHz where we detect and resolve the radio shock, radio halo and various other radio sources. By comparing with literature data at higher frequencies, we measure the integrated spectrum of the radio halo between 24 and 1500 MHz and the radio shock between 24 and 3000 MHz. Both exhibit simple power laws, where the radio emission $S$ becomes brighter at lower frequency $\nu$ as $S \propto \nu^{\alpha}$, with $\alpha = -1.56 \pm 0.02$

for the radio halo and $\alpha = -1.00 \pm 0.02$ for the radio shock. Additionally, a new source of aged radio plasma is detected with an extremely steep spectrum ($\alpha = -1.90 \pm 0.1$) that was missed at higher frequencies. Finally, a model for generating the radio halo is tested using a combination of radio and gamma-ray observations.

In **Chapters 5 and 6**, observations of 124 clusters with the VLA radio telescope are presented. The goal of these observations is to statistically infer the properties of the magnetic field in clusters by stacking them together. A total of 819 polarised radio sources were found, of which the magnitude of the Faraday effect has been measured. **Chapter 5** presents the analysis of the depolarization of the radio emission. For the first time, a clear trend is observed in which polarised sources behind clusters (as shown in Figure S.2) increasingly depolarise as their projected distance to the centre of the cluster decreases. Using X-ray data from the *Chandra* telescope, theoretical models are compared with the data to determine the properties of the magnetic fields. **Chapter 6** improves this analysis by incorporating information from the Faraday rotation of the polarization angle. A clear increase in the variance of rotation measures towards the centre of clusters is observed, consistent with an average magnetic field strength of about $3\,\mu$G. By combining depolarization and rotation measures and comparing them with a model, the best agreement is found for a magnetic field with a central strength of $B = 5\,\mu$G that decreases with the density $n$ of the hot gas as $B \propto n^{0.5}$. In the best-fitting model, the magnetic field fluctuates on scales exceeding a million light years, indicating turbulence injected on large scales, for example by cluster mergers.