# Intergalactic Magnetic Fields

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**Abstract**

The objective of this research project is to understand intergalactic magnetic fields. This topic is pertinent is relevant in the understanding of intergalactic particle interaction. This paper focuses on cosmic rays, radio halos, radio relics, and how the intergalactic medium came to be magnetised. Radio halos prove the existence of intergalactic magnetic fields. Radio relics are suitable environment for the creation of high-energy cosmic rays, which can be observed from Earth to give us information on how intergalactic magnetic fields affect the intergalactic medium. The methodology used is the reading of various textbooks, research papers, review papers, and articles on the topic of intergalactic magnetic fields, as well as using illustrations to show intergalactic objects. This paper contains explanations on the above-mentioned aspects related to intergalactic magnetic fields, and details on a case study on the A 2256 cluster to show how intergalactic magnetisation occurred. Overall, this paper yields an introduction to intergalactic magnetic fields.

**Abstract – French Translation**

L'objectif de ce projet de recherche est d’acquérir une meilleure compréhension des champs magnétiques intergalactiques. Ce sujet est pertinent en vue des interactions particulaires intergalactiques. Ce document se concentre sur les rayons cosmiques, les halos radio, les reliques radio et la façon dont le milieu intergalactique a été magnétisé. Les halos radio prouvent l'existence de champs magnétiques intergalactiques. Les reliques radio constituent un environnement propice à la création de rayons cosmiques de haute énergie qui peuvent être observés depuis la Terre pour nous donner de l’information sur la façon dont les champs magnétiques affectent le milieu intergalactique. La méthodologie employée est la lecture de divers manuels, documents de recherche, rapports de synthèse et articles sur les champs magnétiques intergalactiques, ainsi que l'utilisation d'illustrations montrant des objets intergalactiques. Cet article contient des explications sur les aspects susmentionnés liés aux champs magnétiques intergalactiques et des détails sur une étude de cas sur l'amas de galaxies A 2256 pour montrer comment la magnétisation intergalactique s'est produite. Dans l'ensemble, cet article constitue une introduction aux champs magnétiques intergalactiques.

## Introduction

Although invisible to the naked eye, the effects of magnetic fields can be observed in daily life in a straightforward manner through simple magnets with opposing poles, often labeled “N” for North and “S” for South. Magnetic fields are generated by the motion of electric currents. The direction of magnetic field lines is always from the north magnetic pole to the south magnetic pole. Opposing poles attract and like poles repel one another (Openstax, 2016). The Earth has been observed to have a magnetic field that is generated by the movement of its very hot core (Openstax, 2016). That being said, the Earth is not the only stellar object to possess a magnetic field. Galaxies, which contain an enormous number of stars and other stellar objects, also have their own magnetic field generated by what can be considered similar to the motion within the Earth itself, but this time, the motion within the galaxy. Furthermore, each galaxy’s magnetic field interacts with other galaxies’ magnetic fields, namely, our Milky Way galaxy and the neighbouring Andromeda galaxy. In this paper, we will discuss the effects of the intergalactic magnetic fields between neighbouring galaxies, like Andromeda and the Milky Way.

## Cosmic Rays

The expression “cosmic ray” is misleading because these interstellar objects are not actually rays, they are particles that behave like light particles by travelling at a speed very close to the speed of light ($c$). Let us draw a parallel to further explain this misnomer. Light exhibits particle-wave duality in its behaviour, and particles of light are called photons. When light is emitted by a lightbulb, human eyes cannot distinguish the individual photons and see the light coming out of the bulb simply as a continuous ray. That is because particles of light move at the cosmic speed limit ($3 * 10^8 \frac{m}{s}$) and according to the most up-to-date knowledge, there are no objects in the universe that can move faster than this speed. Light particles travel so fast and so many of them are emitted every second that it becomes impossible to tell them apart like individual grains of sand on a beach. Thus, this misnomer rises from the fact that most cosmic rays move at $v \cong 0.9c$, so they move at around 90% of the speed of light.

Cosmic rays are composed of atomic nuclei and electrons. The majority of cosmic rays, roughly 99% of them, are positively charged, with only within 1% of them carrying a negative charge. Among those with a positive charge, there are two main categories of elemental composition with 90% of all cosmic rays being hydrogen protons (because they have no electrons and therefore, are atoms with a positive charge), and with 9% of all cosmic rays being helium nuclei (and any other heavier element) that also lack electrons. The remaining 1% of all cosmic rays have the same mass as an electron. Among those, an average of 15% of them are particles that are positively charged but have the same mass as an electron. That is unusual because typically, protons (and neutrons, by definition) are much more massive than electrons, and yet these specific particles have the mass of an electron but carry a positive charge. These particles are called positrons (Openstax, 2016, p. 712).

Numerous studies have been conducted in the search of the origin of cosmic rays. It is difficult to tell exactly where cosmic rays come from. That is due to their movement patterns in the interstellar medium. Due to the charged nature of cosmic rays, their motion is influenced by magnetic fields, be it galactic or intergalactic. The path that a charged particle travels along becomes much less straight once it encounters a magnetic field; its path curves, and the charged particle might change directions multiple times before entering the Earth's atmosphere where we can detect it. As a result, the cosmic rays that breach earthen atmosphere, especially the ones who carry lower energy, are very likely to have revolved around the Earth numerous times before finally entering a detectable zone. Some of the cosmic rays that modern tools have detected carry relatively extremely high levels of energy. These particles are less affected by magnetic fields and therefore, two conclusions can be derived. First, the cosmic rays that exist in the Milky Way can avoid influence from its galactic magnetic field and hence, escape the Galaxy. Second, cosmic rays in other galaxies must be able to escape their respective galaxy, as well. All of this implies that some of the highest-level cosmic rays detected from Earth possibly come from extragalactic locations. Despite that, most cosmic rays do not have high enough energy levels to be able to exit the Milky Way Galaxy. Therefore, most of these particles originate from within the Milky Way (Openstax, 2016).

In terms of figuring out how cosmic rays were born inside of the Milky Way Galaxy itself; the most credible theory suggests that the particles were formed out of ejected residue from the supernova explosions. Supernovas are explosions of stars that occur when a star nears the end of its life because it is running out of nuclear fuel. This happens either when a binary star (two-star system with common orbital focus point) nearing the end of its life due to an exhaustion of its nuclear fuel (called a white dwarf) has tried to accumulate so much matter from its neighbouring star that it cannot carry its own mass, or when a very heavy star collapses on its own weight due to inward gravitational forces (Bernoskie, Deiss, & Miller, 2013). A supernova explosion emits immense shock waves due to matter being suddenly expelled outwards. Among those particles of matter, some are charged and get trapped in shock waves, more specifically, they get trapped in their self-generated magnetic fields, a phenomenon that occurs when electrically-charged particles are in motion. As a result of being pushed back and forth in the oscillations of these very strong waves, the charged particles are accelerated to nearly the speed of light which allows them to exit the waves. From then on, those particles are called cosmic rays (Openstax, 2016).

*Figure 1 - 'Before' and 'After' Supernova Explosion (NASA, 2011).*

## Radio Haloes

Galaxy clusters have masses of $10^{14}$ to $10^{15}$ times the mass of the Sun located at the center of our Solar System. Besides containing hundreds of galaxies, much of the matter that makes up their volume is in the form of very hot plasma (Boxelaar, van Weeren, & Botteon, 2021). Plasma is a state of matter in which gas is at such a high temperature that all the atoms are ionized and therefore, electrically charged (Openstax, 2016, p. 531). This plasma takes on the name of intracluster medium (ICM) and is a good conductor for electromagnetic fields. Cluster radio halos, or in other words, radio halos of galaxy clusters, are considered to be a form of diffuse non-thermal radio emissions and indicate the presence of cosmic rays and magnetic fields spread over the entire ICM (Boxelaar, van Weeren, & Botteon, 2021). Diffuse non-thermal emission implies that it spreads widely rather than it being compacted at a specific location. It can be compared to how dust is spread out in the universe. The intensity ($I$) of radio halos, when measured at a frequency of 1.4 GHz is approximately $10^{-6}\,\frac{Jy}{beam}$ (Klein & Fletcher, 2014). In the field of radioactivity, intensity is measured in jansky (Jy) per unit of beam, where $1\ Jy = 10^{-26}\,\frac{W}{m^2\ Hz}$. The term "beam" is an arbitrary nominal area of brightness (Van Moorsel & Ott, 2018). Radio halos have a spectral index ($\alpha$) greater or equal to one, which follows the accepted theory that non-thermal sources of radiation tend to have a spectral index greater or equal to zero (Sasao & Fletcher, 2006, p. 4). A spectral index is defined by the following relationship of direct proportionality:

$$S_{(f)} \propto f^{\alpha}$$

where $f$ is the frequency and $S$ is the flux density in $\frac{W}{m^2}$ as a function of the frequency (Burke & Graham-Smith, 2009). The flux density is a measurement of how strong radiation is per unit of area. Radio halos are also unpolarised based on present-day detection levels of radio electromagnetic wave synchrotron radiation emission, which means that there is no detected uneven distribution of charges within them over the ICM (Klein & Fletcher, 2014). Synchrotron radiation is a type of energy emission that is different from the more general thermal radiation. For example, the energy that goes from the Sun to the Earth travels through thermal radiation. Typically, the energy of a photon, measured in joules (J) is inversely proportional to its wavelength, such that $E = \frac{hc}{\lambda}$ where $h$ is Planck's constant. Intensity, on the other hand, is a measurement of power ($P$) per unit of area, such that $I = \frac{P}{A}$, where power is measured in joules per second. Through an indirect relationship between energy and power, since intensity is directly proportional to power and by definition, to energy, then by proxy, intensity must be inversely proportional to wavelength. Therefore, in typical electromagnetic radiation, higher intensity is obtained at shorter wavelengths. However, in the case of synchrotron radiation, it is emitted by negatively charged particles that have been accelerated by strong magnetic fields and reaches higher intensity levels at longer wavelengths (Openstax, 2016, p. 392).

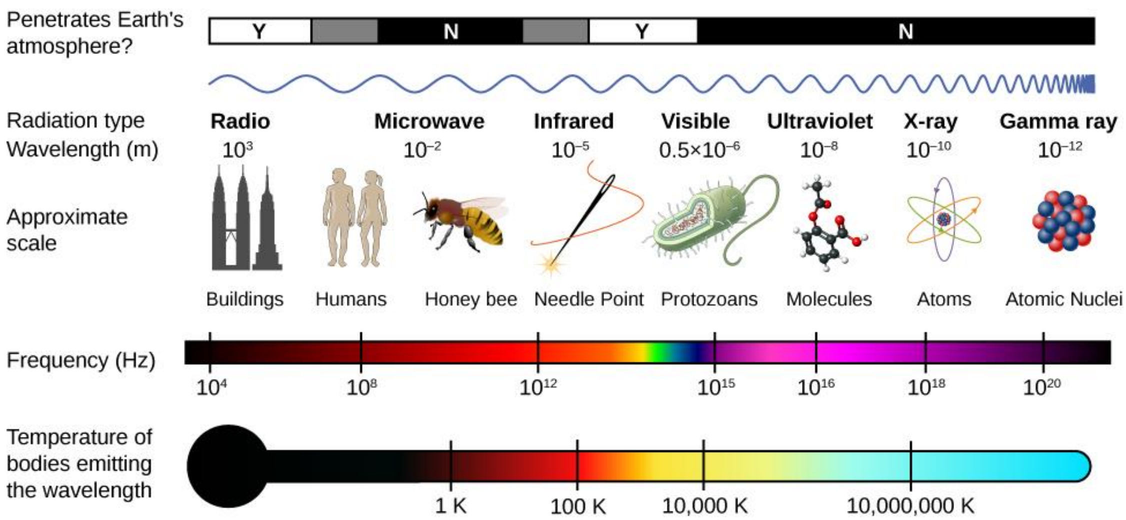


*Figure 2 - Electromagnetic Spectrum (Openstax, 2016).*

As shown in Figure 2, on the typical electromagnetic spectrum, radio waves tend to have a longer wavelength ($10^3$) and a lower frequency ($10^4\ Hz = 10^{-5} GHz$). And yet, the cut-off frequency of radio halos is measured to be greater than 1 GHz (Klein & Fletcher, 2014). This unusually high frequency at a long wavelength is an indication of synchrotron radiation which proves the existence of magnetic fields within the ICM, that is, intergalactic magnetic fields.

Originally, radio halos were discovered in the Coma Cluster. The following equation gives the exact equipartition strength of the magnetic field of a radio halo:

$$B = 0.57\ (1 + \beta)^{0.26}$$

where $\beta$ is a value of the ratio of energy of the protons to that of the electrons ($\frac{E_p}{E_{e^-}}$). Equipartition strength is an assumption that energy is divided equally throughout the entirety of the radio halo. Their total magnetic field was measured to be on average, around 0.6 μG (Klein & Fletcher, 2014, p. 211).

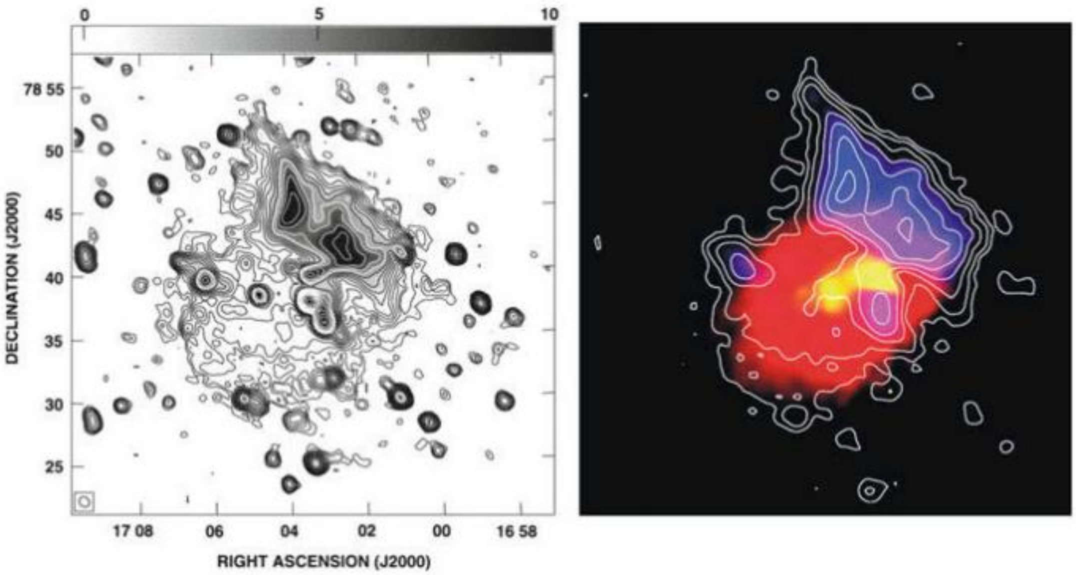


*Figure 3 – Radio halos of the A 2256 cluster (Klein & Fletcher, 2014, p. 214).*

## Radio Relics

Radio relics are fairly similar to radio halos, being that they are another form of diffuse non-thermal radio emission. However, while radio halos are located at the center of galaxy clusters, radio relics are situated towards the periphery of the clusters. While radio halos are circular, radio relics tend to adopt irregular shapes and stretch out lengthwise to take on more oval outlines. Furthermore, radio relics are very polarized, meaning that they do not exhibit an even distribution of charges. Radio relics are also found very frequently during the merging of galaxy clusters which causes huge shock waves (Klein & Fletcher, 2014, p. 217-218). Due to their highly polarized nature, these sources become great environments for particle acceleration which can create cosmic-ray particles, more specifically, the previously mentioned highest-level energy cosmic rays that can be formed outside of the Milky Way Galaxy in the ICM. There also exists mini radio halos, however, they will not be discussed in this paper because they cannot contribute to intergalactic magnetic fields due their pressure confinement to the center of clusters (Klein & Papaderos, 2011).

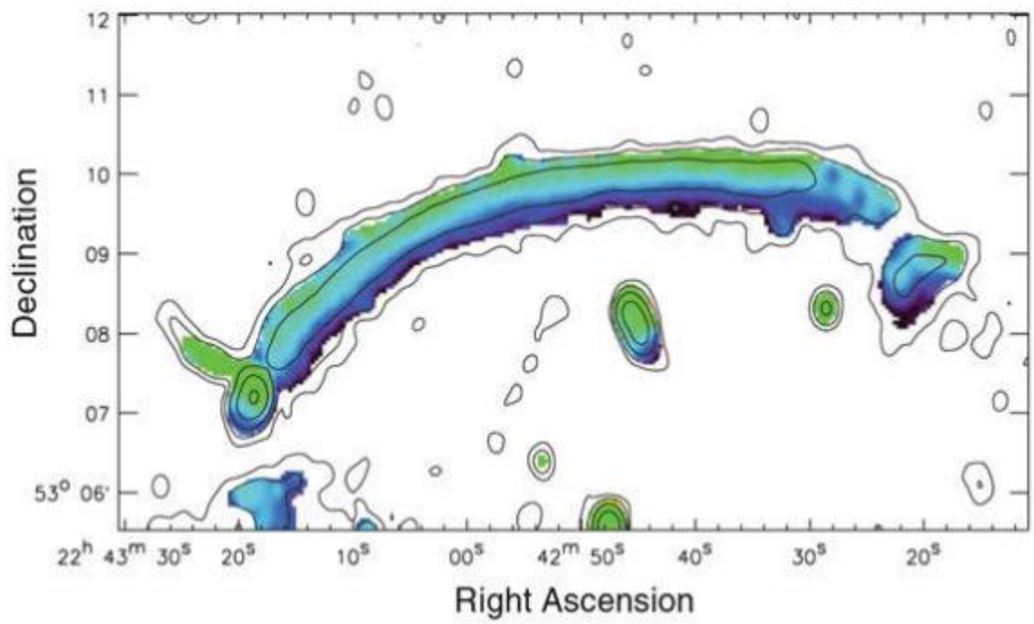


*Figure 4 – Radio relic observed on the edge of the elongated galaxy cluster CIZA J2242.8C+5301 (Klein & Fletcher, 2014, p. 218).*

**Magnetisation of the Intergalactic Medium**

According to a paper written in 2011, dwarf galaxies are important to understand how the ICM (which can also be called the IGM) came to be magnetised. Among various scenarios in galaxy formation theory, one specific scenario is called the 'bottom-up', in which the very first galaxies expelled their residues from star formation into the ICM in large volumes. This concept can be applied to dwarf galaxies expelling their plasma into the ICM. This process can be achieved because the number of existing dwarf galaxies is high, meaning they can pollute the ICM with large amounts in total, and because due to their lower masses, their escape velocity is lower. As seen in the following equation, the escape velocity is directly proportional to the square root of the mass ($M$) of the object in question.

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Since the escape velocity is lower compared to other galaxies, gas particles can exit the orbit of a dwarf galaxy a lot more easily. These escaping gas particles create galactic winds.

A study case on the dwarf galaxy NGC 1569 showed that the galactic winds had a velocity greater than the galaxy's escape speed and the gas particles were able to achieve temperatures higher than that of stable particle-interaction. Therefore, these particles enter the plasma state of matter. There is a radio halo in NGC 1569. As shown in Figure 5, its radial magnetic field points outwards from the center of the source and because the energy density of the wind is much, much greater than the energy density of the magnetic field, the magnetic field is forced to follow along the galactic winds, leading it right into the ICM. When applied to the numerous dwarf galaxies that exist inside of a galaxy cluster, this process ends up magnetising the ICM and creates intergalactic magnetic fields (Klein & Papaderos, 2011).

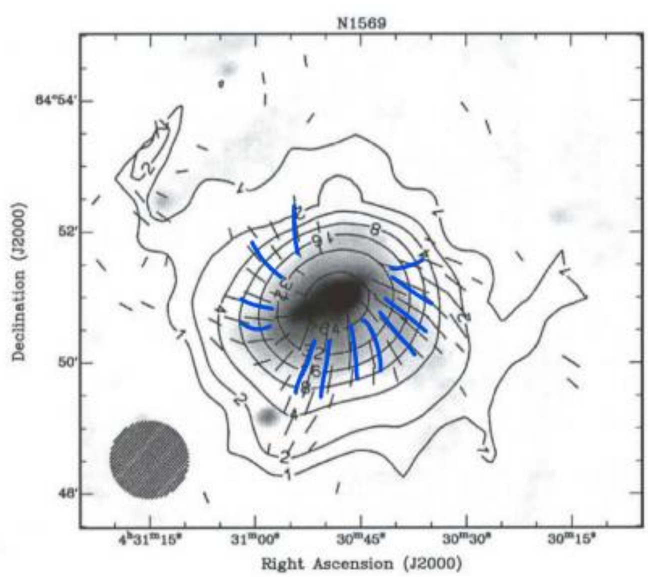


*Figure 5 - NGC 1569, magnetic field lines emphasized in blue (Klein & Papaderos, 2011).*

## Conclusion

All in all, there exist numerous intergalactic objects that are affected by magnetic fields in the IGM. Among those, we focused on cosmic rays, which are great sources of information on locations for particle-acceleration processes, such as radio relics. Furthermore, radio halos prove the presence of intergalactic magnetic fields, for which the initial formation can be observed from intergalactic winds generated by dwarf galaxies. This paper allows for a better understanding of the existence of intergalactic magnetic fields and how they affect cosmic rays. Due to limitations on the length of this paper, we could not discuss ways of measuring the strength of such magnetic fields using inverse-Compton X-ray emission and detail on the Biermann battery effect. This paper could be further improved by adding explanations on those concepts because they are pertinent to the topic and would deepen our understanding of intergalactic magnetic fields.

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