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Thérèse Cantwell

Low Frequency Radio Observations of Galaxy Clusters and Groups

Doctoral Thesis accepted by
the University of Manchester, Manchester, UK

Springer

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It was of course an impossible task. But he was used to them. Dragging a rat all the way from the wood to the hole had been an impossible task. But it wasn't impossible to drag it a little way, so you did that, and then you had a rest, and then you dragged it a little way again… The way to deal with an impossible task was to chop it down into a number of merely very difficult tasks, and break each one of them *into a group of horrible hard tasks, and each one of* them *into tricky jobs, and each one of them…*

—Terry Pratchett, *The Bromeliad*

For my sister. I love you.

Supervisor's Foreword

Radio astronomy offers a unique perspective in astrophysics, revealing myriad phenomena across a vast range of scales and energies that are otherwise invisible to us. From the high-energy Universe, typified by spectacular active galactic nuclei, to the cold relic radiation of the Big Bang, the radio spectrum is full of information about how the Universe started and how it evolved and grew. Moreover, radio observations give us a window into a cosmic laboratory, where conditions exist that are simply impossible to replicate on Earth. These data augment our understanding of physics and allow us to progress scientifically beyond the constraints of terrestrial laboratories. Stretching over four decades in frequency, the radio spectrum encompasses a wide variety of astrophysical radiation processes. However, it is the low frequency (long wavelength) end of this spectrum that has historically been most difficult to explore. With radio wavelengths extending to tens of metres, this difficulty has been in part due to the structural problems in building receivers large enough to achieve resolutions anywhere near those needed for detailed astrophysical analysis; the corrupting behaviour of the ionosphere at low frequencies, coupled with the brightness of the Galactic background, and the crippling computing requirements to account for all of the other calibration and imaging effects make low frequency radio analysis one of the most demanding areas of astronomy research. As challenging as it may be, low frequency radio astronomy is also one of the most scientifically valuable probes of the Universe. As well as providing access to the redshifted neutral hydrogen line from the epoch of reionisation, it also probes a larger population of relativistic electrons that is accessible at higher radio frequencies. These synchrotron emitting electrons show us the true extent of galaxies, they reveal the large-scale structure of galaxy clusters and filaments, and they illuminate the structure of magnetic fields in the lowest density regions of the Universe. Magnetic fields are an ubiquitous ingredient of astrophysical structure, but the cosmic origin of these fields is still an open question. In this thesis, Dr. Cantwell uses low frequency radio measurements from the LOw Frequency ARray (LOFAR) and the Giant Metrewave Radio Telescope (GMRT) to examine magnetised plasmas in some of the largest astrophysical structures known: giant radio galaxies (GRGs) and radio haloes. Due to the observational limitations associated with capturing such huge astrophysical structures, giant radio galaxies are historically a poorly sampled population of objects; however, their preferential placement in the more rarified regions of the cosmic web makes them a uniquely important probe of large-scale structure. In particular, the polarisation of the radio emission from giant radio galaxies is one of the few tools available to us that can be used to measure magnetic fields in regions where the strength of those fields is a key differentiator for competing models of the origin of cosmic magnetism. This thesis presents new data on the giant radio galaxy NGC 6251. Polarisation analysis of these data reveals that the magnetic field strength in the locality of this giant radio galaxy is an order of magnitude lower than in other comparable systems. Such low frequency polarisation data are crucial for detailed analyses of magnetic structure, but they are also the most challenging observational data to work with. This thesis presents a beautifully coupled description of the technical and scientific analysis required to extract valuable information from such data, and as the new generation of low frequency radio telescopes reveals the larger population of giant radio galaxies, it will be a significant resource for future analyses.

Manchester, UK
July 2018

Prof. Anna Scaife

Preface

The detection of Mpc-scale emission, such as radio halos and radio relics, in galaxy clusters provides evidence that cosmic ray electrons, as well as cluster-scale magnetic fields are present in clusters. As such, radio observations of clusters provide a unique opportunity to study the non-thermal populations of the intra-cluster medium. The process responsible for this large-scale diffuse emission is still not fully understood. The current dominant model links the formation of radio halos with cluster mergers. However, research into the formation mechanism is limited by the relatively small number of known halos. Currently, there are of order 100 known halos compared with >100, 000 clusters. This thesis aims to increase the number of known halos by taking advantage of an optical parameter, the relaxation parameter, which links a cluster's optical properties with its dynamical state. If the production of a radio halo is linked to dynamical state, then the relaxation parameter could potentially be used to select clusters which host radio halos.

Observations of Faraday rotation in sources embedded in cluster or group environments offer an alternative method for probing cluster and group magnetic fields. In particular, the variance in the Faraday depth of embedded sources has previously been used to determine the magnetic field in a number of clusters. Determining the magnetic field in galaxy groups using the same method is more difficult due to the lower density, and therefore smaller Faraday depths, present in these environments. The Faraday depths in galaxy groups are expected to be of order $1-10$ rad m^{-2}. The LOw Frequency ARray (LOFAR) has the highest precision available with a Faraday depth resolution of $\sim$1 rad m^{-2}. At LOFAR frequencies, most extra galactic sources are expected to be depolarised. The ideal targets for polarisation studies with LOFAR are nearby giant radio galaxies with high degrees of polarisation. These sources are often found in low-density group environments, the precise environments we would like to study, which minimises the effect of depolarisation. This thesis aims to test LOFAR's polarisation capabilities using observations of the giant radio galaxy NGC 6251 which is located in a poor group environment.

In Chap. 1 of this thesis, I review the current understanding of galaxy clusters, groups, and radio galaxies. I also describe some of the astrophysical processes important to this thesis.

In Chap. 2, I discuss the interferometry and the process of calibrating interferometric data. I also describe some of the techniques used later in the thesis such as QU-fitting and RM synthesis.

In Chap. 3, I present my observations of the massive merging galaxy cluster MACSJ2243.3-0935. I report the discovery of a radio halo in MACSJ2243.3-0935, as well as a new radio relic candidate, using the Giant Metrewave Radio Telescope and the KAT-7 telescope. The radio halo is coincident with the cluster X-ray emission and has a largest linear scale of approximately 0.9 Mpc. I measure a flux density of $10.0 \pm 2.0\,\mathrm{mJy}$ at 610 MHz for the radio halo. I discuss equipartition estimates of the cluster magnetic field and constrain the value to be of the order of 1 μG. The relic candidate is detected at the cluster virial radius where a filament meets the cluster. The relic candidate has a flux density of $5.2 \pm 0.8\,\mathrm{mJy}$ at 610 MHz. I discuss possible origins of the relic candidate emission and conclude that the candidate is consistent with an infall relic.

In Chap. 4, I present my GMRT observations at 610 MHz of three disturbed galaxy clusters, A07, A1235 and A2055. No diffuse emission was observed in any of the three clusters. In order to place upper limits on the radio halo power in these clusters, I have injected simulated halos at different radio powers into the UVdata. A07 has a radio halo upper limit of $P_{610\mathrm{MHz}} = 1.5 \times 10^{24}$ W Hz^{-1}. A2055 has a radio halo upper limit of $P_{610\mathrm{MHz}} = 1.8 \times 10^{24}$ W Hz^{-1}. A1235 has a radio halo upper limit of $P_{610\mathrm{MHz}} = 5.8 \times 10^{23}$ W Hz^{-1}. These limits are below the $P_{610} - L_{\mathrm{X}}$ relation and rule out bright radio halo in these clusters. I have identified these clusters as potential hosts for Ultra Steep Spectrum Radio Halo (USSRH). Observations with LOFAR should be capable of confirming whether or not these clusters host USSRH.

In Chap. 5, I present observations of the giant radio galaxy NGC 6251 with LOFAR HBA. NGC 6251 is a giant radio galaxy with a borderline FRI/FRII morphology located in a poor group. The images presented in this chapter are the highest sensitivity and resolution images of NGC 6251 at these frequencies to date. Analysis of the low frequencies spectral index did not reveal any change in the low frequency spectra when compared with the higher frequency spectral index. NGC 6251 is found to be either at equilibrium or slightly electron dominated, similar to FRII sources. I calculated the ages of the low-surface brightness extension of the northern lobe and the backflow of the southern lobe, which are only clearly visible at these low frequencies, to be 205 Myr $< t <$ 368 Myr and 209 Myr $< t <$307 Myr, respectively. This could indicate that these components are relics of an earlier epoch of activity.

I present the first detection of polarisation at 150 MHz in NGC 6251, including a weak detection of polarisation in the diffuse emission of the northern lobe. Taking advantage of the high Faraday resolution of LOFAR, I detect Faraday complexity in the knot of NGC 6251 and interpret the weaker component as emission from the lobe located behind the knot. I place an upper limit on the variance in the Faraday depth in the knot of NGC 6251 of $\sigma_{\mathrm{RM}}^2 < 5 \times 10^{-3}$ rad^2 m^{-4} and an upper limit on the magnetic field in the group of $B < 0.2$ μG.

Manchester, UK
September 2017

Dr. Thérèse Cantwell

Declaration

No portion of the work referred to in this has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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