Fossil Galaxy Groups – Ideal Laboratories for Studying the Effects of AGN Heating.

Nazirah N. Jetha*, Habib Khosroshahi†, Somak Raychaudhury**, Chandreyee Sengupta‡ and Martin Hardcastle§

*Department of Physics, University of Alabama, Huntsville, AL, 35899
†School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P. O. Box 19395-5531 Tehran, Iran
**School of Physics and Astronomy, University of Birmingham, UK
‡NCRA-TIFR, Pune, India
§University of Hertfordshire, UK

Abstract. We present the first of a sample of fossil galaxy groups with pre-existing Chandra and/or XMM-Newton X-ray observations and new or forthcoming low frequency GMRT data – RXJ1416.4+2315 (z=0.137). Fossil galaxy groups are ideal laboratories for studying feedback mechanisms and how energy injection affects the IGM, since due to the lack of recent merging activity, we expect the IGM to be relatively pristine and affected only by any AGN activity that has occurred in the group. Our Chandra X-ray observations reveal features resembling AGN-inflated bubbles, whilst our GMRT radio data show evidence of extended emission from the central AGN that may be filling the bubble. This has enabled us to estimate the work done by the central AGN, place limits on the rates of energy injection and discuss the nature of the plasma filling the bubble.

Keywords: Galaxy groups, radio galaxies, X-ray, radio
PACS: 98.65.Bv 98.54.Gr 95.85.Nv 95.85.Bh

INTRODUCTION

Outbursts from active galactic nuclei (AGN) are the most likely method of energy injection into galaxy groups and clusters to prevent catastrophic cooling of the intergalactic medium (IGM) ([1], [2], [3] for simulations; [4], [5] for observations). Their cyclic nature allows them to be triggered when the IGM is cooler, and for the outflow to terminate when the gas has been sufficiently heated (e.g. [6], [7], [8], [9]). There is evidence to suggest that the AGN and IGM interact in a complex feedback loop [e.g. 6], whereby whether the AGN is active or not is controlled by the thermal state of the IGM, and the energy output is regulated by the amount of cool gas that accretes onto the AGN.

In many cases, the AGN inflates bubbles into the IGM, seen as depressions in the X-ray surface brightness. The thermal properties of gas in and surrounding these bubbles allow us to estimate to within an order of magnitude, just how much work the AGN does on its surroundings (see [10], [4] and [11] amongst others). However, in most groups and clusters on-going galaxy-galaxy mergers may also trigger AGN. For this reason, it is not clear that every instance of relic AGN activity in a group/cluster is feedback triggered, making it difficult to accurately investigate how the environment triggers, and is affected by the AGN.

Fortunately, fossil galaxy groups provide an ideal laboratory in which to study the
effects of AGN heating. These groups are dominated by a single luminous elliptical galaxy at the center of an extended X-ray halo similar to those seen in bright X-ray groups. The X-ray emission in fossils is regular and symmetric, indicating the absence of recent galaxy merging. Observationally a galaxy group is classified as a fossil if it has an X-ray luminosity of \( L_{\text{X, bol}} \geq 10^{42} h_{50}^{-2} \) erg s\(^{-1}\) that is spatially extended to \( \sim 100s \) of kiloparsecs, and the dominant galaxy is at least 2 R-band magnitudes brighter than the second ranked galaxy within half the projected virial radius of the group [12]. The dominant galaxy tends to be a giant elliptical galaxy with an optical luminosity similar to BCGs. The observed properties of fossils suggest that an overwhelming majority of these must be early-formed systems, and have a higher dark matter concentration compared to non-fossil groups and clusters of comparable mass [13][14][15].

The early formation epoch implies sufficient time for a cool core to have developed, and provides an ideal environment to study how feedback mechanisms work, since the lack of recent merger activity implies that any visible AGN activity, even if relic activity, should be purely feedback-driven. This makes fossil groups ideal laboratories to study galaxy evolution and IGM heating in the absence of recent mergers. Here, we present the results of a preliminary multi-wavelength study utilizing Giant Metrewave Radio Telescope (GMRT), *Chandra* and *XMM-Newton* observations, of the fossil galaxy group RX J1416.4+2315, which is at \( z = 0.137 \) (kpc/arcsec = 2.4). We discuss the implications for the nature of the radio plasma, and the energetics required for the heating model.

**THE X-RAY AND RADIO DATA**

**X-Ray Data**

An X-ray analysis of the group was performed and reported in [13]; it was observed both by the *Chandra* and *XMM-Newton* X-ray telescopes, for 15 and 9 ks respectively, and has an X-ray luminosity within the cooling radius of \( L_{\text{X}} = 2 \times 10^{42} \) erg s\(^{-1}\). We used the *XMM-Newton* data to obtain density, temperature and pressure profiles for the group out to large radii (as shown in [14]), and use these profiles to estimate the work done by the AGN on the IGM.

**Radio Data**

The group was also observed with the GMRT at 610 and 1420 MHz, and the data reduced as described in Khosroshahi *et al.* (in prep.). At 1420 MHz we detect a central point source with no extended emission, whilst at 610 MHz we detect the central point source together with an extension to the SE that corresponds to a depression in the X-ray surface brightness (see Fig. 1). Given the feature’s extended nature, spatial coincidence with the surface brightness feature, and steep spectral index, we assume this to be a relic bubble feature that is created and possibly filled by the SE radio jet.
ENERGETICS OF THE SOURCE

Assuming that the bubble was inflated in situ, at a sub-sonic rate, we calculate that the bubble must be approximately $7 \times 10^7$ years old. Then, if the bubble has done $PdV$ work against the IGM, we calculate, using the pressure profile calculated in [14], that the radio source has done $8.8 \times 10^{50}$ erg of work over the lifetime of the source, corresponding to an average energy injection rate of $\sim 4 \times 10^{43}$ erg s$^{-1}$. This is comparable to, but an order of magnitude higher than the X-ray luminosity of the source within the radius affected by the bubble, $2 \times 10^{42}$ erg s$^{-1}$, and suggests an inefficient coupling of energy. Further, using the central density of the X-ray emitting medium, we calculate that if the AGN was powered by Bondi accretion, then the Bondi power, $P_{\text{BONDI}} \sim 8 \times 10^{42}$ erg s$^{-1}$, suggesting that a feedback-driven accretion mechanism is indeed plausible [see also 6].

PHYSICAL NATURE OF THE PLASMA

If the bubble is indeed the result of a fairly young AGN outflow, as suggested by the dynamical age, then there are two possible explanations for the physical conditions in the plasma filling the bubble, and for the steep-spectrum nature of the source. Either, the bubble plasma is partially composed of very hot gas, which may leave a signature in the X-ray, or the plasma is non-thermal in origin and simply deviates strongly from equipartition. To test the first case, we follow the method described in [16], and find that the X-ray spectrum of the bubble requires no extra thermal component above the ambient IGM unless $k_B T_{\text{plasma}} \gg k k_B T_{\text{IGM}}$, suggesting this scenario is unlikely.

In the second case, either that the magnetic field is significantly different from the equipartition field, or the plasma is dominated by non-radiating particles. Using inverse Compton limits from the X-ray spectrum, together with the radio measurements presented here, we find that either the plasma must be magnetically dominant with the magnetic field being two orders of magnitude greater than the equipartition field; or the plasma dominated by non-radiating particles, with the ratio of radiating to non-radiating particles, $k \geq 100$, [see also 11].

CONCLUSIONS

We have presented an X-ray and radio study of the fossil galaxy group RXJ 1416.4+2315, and have shown the potential of using a sample of fossil galaxy groups to investigate feedback-driven AGN activity. For the case of RXJ 1416.4+2315, simple Bondi accretion, suggesting a feedback-driven scenario, can account for the current outburst and the work done on the IGM. Using limits from the X-ray and radio data we have shown that the plasma is likely dominated by non-radiating particles, indicating that it is likely that the jets in these sources are hadronic in nature (see also [17]). Further work will concentrate on using new deep GMRT observations, combined with the existing X-ray data, to further investigate heating and the nature of the plasma in a larger sample of fossil groups.
FIGURE 1. *XMM-Newton* false colour image overlaid with 610 MHz GMRT contours. The radio extension to the SE co-incides with a depression in the X-ray surface brightness, which we assume is induced by the AGN outflow.

ACKNOWLEDGMENTS

NNJ would like to thank NCRA-TIFR for their hospitality during her visit there, and Massimiliano Bonamente and Marshall Joy for useful discussions regarding this work.

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