AGN feedback in galaxy groups: a joint GMRT/X-ray study

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Abstract. We present an ongoing study of 18 nearby galaxy groups, chosen for the availability of Chandra and/or XMM-Newton data and evidence for AGN/hot intragroup gas interaction. We have obtained 235 and 610 MHz observations at the GMRT for all the groups, and 327 and 150 MHz for a few. We discuss two interesting cases - NGC 5044 and AWM 4 - which exhibit different kinds of AGN/hot gas interaction. With the help of these examples we show how joining low-frequency radio data (to track the history of AGN outbursts through emission from aged electron populations) with X-ray data (to determine the state of hot gas, its disturbances, heating and cooling) can provide a unique insight into the nature of the feedback mechanism in galaxy groups.

Keywords: Galaxy groups, Radio galaxies, X-ray observations

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INTRODUCTION

Several feedback mechanisms have been invoked to balance the cooling process in the hot X-ray emitting gas halo of clusters and groups of galaxies. These include gravitational heating, supernovae, subcluster mergers, thermal conduction, and AGN-driven outbursts. In rich clusters, the radio outbursts from the AGN harboured in the central galaxy appear to be the dominant source of heating. However most of the galaxies and baryonic matter in the Universe reside in less massive units, such as poor clusters and groups of galaxies. Thus the study of feedback in these environments is fundamental to understand the mechanism by which feedback operates and how it has influenced the formation and thermal history of most of the baryons in the Universe.

OUR ONGOING GMRT/X-RAY STUDY OF GALAXY GROUPS

To investigate the impact of AGN feedback in galaxy groups, we are carrying out an in-depth study of a representative collection of 18 galaxy groups (listed in Tab. 1), using low (and multi) frequency radio observations, obtained at the Giant Metrewave Radio Telescope (GMRT), and deep archival Chandra and XMM-Newton X-ray data. The groups were chosen on the basis of structures, either in the X-ray surface brightness and temperature maps or radio morphology, which strongly indicate interaction between
TABLE 1. List of galaxy groups and status of the GMRT observations.

| Group name | 235 MHz | 610 MHz | Group name | 235 MHz | 610 MHz |
|------------|---------|---------|------------|---------|---------|
| UGC 408*   | Aug 2007| Aug 2008| NGC 3411   | Aug 2006| Feb 2008|
| NGC 315    | Feb 2008| Aug 2008| NGC 4636   | Aug 2006| Feb 2008|
| NGC 383    | Feb 2008| Aug 2008| HCG 62     | Feb 2008| Feb 2008|
| NGC 507    | July 2006| Aug 2008| NGC 5044† | Feb 2008| Feb 2008|
| NGC 741    | Aug 2006| Aug 2007| NGC 5813*  | —       | Aug 2008|
| HCG 15     | Aug 2006| Aug 2008| NGC 5846   | Aug 2006| —       |
| NGC 1407   | July 2006| Aug 2008| AWM 4**    | Aug 2006| Jul 2006|
| NGC 1587   | Aug 2006| Aug 2008| NGC 6269   | Feb 2008| Feb 2008|
| MKW 02‡    | Aug 2003| July 2005| NGC 7626*  | Aug 2007| Aug 2008|

* observed at 150 MHz in Cycle 16 (summer 2009)
† observations presented in David et al. (2009); also observed at 327 MHz;
** observations presented in Giacintucci et al. (2008); also observed at 327 MHz;
‡ observations from Giacintucci et al. (2007).

the radio source and the intragroup medium. All groups, except two, were observed with the GMRT both at 610 MHz and 235 MHz during Cycle 12, 14 and 15. The observing period for each frequency is given in Tab. 1. GMRT observations at 327 MHz and 150 MHz were also obtained for few targets (see notes to Tab. 1) as part of the follow-up ongoing at these frequencies. The data from all observations in Tab. 1 have been completely reduced. The sensitivity achieved in the final images is in the range 35-100 µJy at 610 MHz and 0.2-1 mJy at 235 MHz for a typical observing time of ∼2-3 hours on source. The ongoing analysis shows that the sources are diverse, covering a range of spatial scales and total powers, from classic double FR-I to core-halo radio sources (Giacintucci et al. in preparation).

A CLOSER VIEW OF TWO REMARKABLE GALAXY GROUPS

We have selected two systems from the above sample - NGC 5044 and AWM 4 - which exhibit different kinds of AGN/hot gas interaction, to show how the combination of deep X-ray data and high-sensitivity low frequency radio observations can provide a unique insight into the nature of the feedback mechanism in galaxy groups.

NGC 5044. The new Chandra observation reveals that the group hosts many small radio quiet cavities, filaments, and a semi-circular cold front (Fig. 1; David et al. 2009). The GMRT 610 MHz image (right) shows the radio core and a lobe which extends along a filament of cold gas. The 235 MHz emission (left) is much more extended, with little overlap with the 610 MHz image. The emission fills the S cavity, curves toward the W just behind the cold front, and then sharply bends by ∼90°. A second component, a detached radio lobe, is visible toward the S-E, and its western edge is coincident with the cold front, suggesting that the relativistic material in this structure might have been produced by an earlier outburst and that it is currently compressed by the motion of NGC 5044 toward the S-E. The lack of any detected emission at 610 MHz in the same
FIGURE 1. NGC 5044: GMRT 235 MHz (left) and 610 MHz contours (right) on the Chandra unsharp masked image in the 0.3-2.0 keV band (David et al. 2009). The radio beam is $22'' \times 16''$ and $18'' \times 16''$, respectively. The lowest contour is shown at $3\sigma=0.75 \text{ mJy b}^{-1}$ and $0.075 \text{ mJy b}^{-1}$, respectively.

FIGURE 2. AWM 4. Left: Chandra radial profiles of deprojected temperature and abundance. Crosses and diamonds refer to fits carried out in the 0.7-7.0 keV band with 8000 net counts/spectrum (370 cts for the central bin) and 12000 net counts/spectrum, respectively. Right: GMRT 610 MHz contours (beam $5'' \times 4''$; lowest contour at $3\sigma=0.15 \text{ mJy b}^{-1}$), superposed on the Chandra residual image, after subtraction of the best-fitting surface brightness model.

region as the 235 MHz emission indicates that the radio spectrum must be very steep. The GMRT data thus appear to reveal 2 (or possibly 3) separate outbursts. The youngest outburst can be identified with the 610 MHz emission, and the oldest burst with the detached radio lobe.

AWM 4. Previous XMM-Newton observations showed AWM 4 to be isothermal at \sim 2.5 keV out to at least 160 kpc from the centre, even though the cooling time in
the middle is \( \sim 2 \) Gyr (O’Sullivan et al. 2005). Its powerful central radio galaxy was proposed as the most likely source of heating. Our deep GMRT observations at 235, 327 and 610 MHz, presented in Giacintucci et al. (2008), revealed the full extent of the radio source and allowed us to determine its age, orientation, energy and physical parameters. However, with no indications of X-ray cavities associated with the radio source, the question of the coupling between jets and intra-group gas remained unresolved (see also Gastaldello et al. 2008). Our new 80 ksec \textit{Chandra} image reveals the small-scale galactic corona surrounding the AGN; the radial temperature and abundance profiles show a clear decrease in the central \( \sim 2 \) kpc-radius region (Fig. 2; left), corresponding to the corona. The existence of this corona might explain the long timescale of the outburst, as it fuels the AGN but is largely unaffected by the radio jets. We do not detect clear cavities in the \textit{Chandra} image associated with the radio lobes. Some weak X-ray features are visible in the residual image obtained after subtraction of the best-fitting surface brightness model, shown in Fig. 2 (right) with overlaid the GMRT 610 MHz contours. A faint depression is visible in the region of the eastern lobe, and two channel–like structures appear to be associated with the inner jets. No cavity is detected in the western lobe. The detailed analysis of these features and their implications is ongoing (O’Sullivan et al. in prep.).

**SUMMARY**

Our ongoing X-ray/GMRT study of the AGN feedback in galaxy groups shows that low frequency observations play a crucial role in the estimate of the total radio energy input from the central AGN and are important in the study of the history of the energy injection and transfer, since they can reveal old, steep-spectrum radio emission and structures related to previous AGN outbursts (e.g., NGC 5044). As shown by our analysis of AWM 4, the combination of the low frequency information with deep and high resolution X-ray data offers a unique tool to investigate the AGN/hot gas interaction (see also Gitti et al., these proceedings). This is of fundamental importance to determine the thermal history of the intragroup and intracluster medium and shed light on the role of the AGN feedback on the formation and evolution of galaxies in these environments.

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