AGN Feedback in Galaxy Groups: the two interesting cases of AWM 4 and NGC 5044

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Abstract. We present AGN feedback in the interesting cases of two groups: AWM 4 and NGC 5044. AWM 4 is characterized by a combination of properties which seems to defy the paradigm for AGN heating in cluster cores: a flat inner temperature profile indicative of a past, major heating episode which completely erased the cool core, as testified by the high central cooling time (> 3 Gyrs) and by the high central entropy level (∼50 keV cm²), and yet an active central radio galaxy with extended radio lobes out to 100 kpc, revealing recent feeding of the central massive black hole. A recent Chandra observation has revealed the presence of a compact cool corona associated with the BCG, solving the puzzle of the apparent lack of low entropy gas surrounding a bright radio source, but opening the question of its origin. NGC 5044 shows in the inner 10 kpc a pair of cavities together with a set of bright filaments. The cavities are consistent with a recent AGN outburst as also indicated by the extent of dust and Hα emission even though the absence of extended 1.4 GHz emission remains to be explained. The soft X-ray filaments coincident with Hα and dust emission are cooler than those which do not correlate with optical and infrared emission, suggesting that dust-aided cooling can contribute to the overall cooling. For the first time sloshing cold fronts at the scale of a galaxy group have been observed in this object.

Keywords: cooling flows — galaxies: clusters: general — galaxies: clusters: individual (AWM 4, NGC 5044) — X-rays: galaxies: clusters

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AGN FEEDBACK IN GALAXY GROUPS

A growing number of clusters and elliptical galaxies have deep multi-wavelength data (X-rays, radio and optical) to study the rich phenomenology of cool cores and AGN feedback in a detailed spatially resolved fashion, whereas only an handful of groups with such coverage exists and therefore, “unfortunately, AGN heating is not as well studied in groups as in clusters” [1]. Examination of AGN feedback at the mass scale of groups is valuable because, although the scale of outbursts in groups is less energetic and often on a smaller spatial scale than in clusters, the impact can be even more dramatic than in rich clusters due to the shallower group potential. Here we present the cases of the rich phenomenology of the cores of two brigh galaxy groups, AWM 4 and NGC 5044.
THE PUZZLE OF THE CORE OF AWM 4

AWM 4 is a poor cluster whose X-ray emission is extended and regular and the peak of the X-ray emission is coincident with the brightest central galaxy (BCG) NGC 6051. It has a bolometric luminosity of $3.93 \pm 0.06 \times 10^{43}$ erg s$^{-1}$ and a mass weighted temperature of $2.48 \pm 0.06$ keV within 455 kpc, and a mass of $1.04 \pm 0.10 \times 10^{14} M_\odot$ within $r_{500} = 708 \pm 23$ kpc. It therefore lies at the low end of the mass and temperature range defining clusters of galaxies. 28 galaxy members have been identified, most are absorption line systems with a strong concentration of early-type galaxies in the center and with a smooth gaussian velocity distribution centered at the velocity of NGC 6051; the velocity dispersion of the system is $439^{+93}_{-58}$ km s$^{-1}$ [2]. NGC 6051 is considerably brighter than the galaxies around it and recent deep R-band imaging [3] has established the fossil nature of this system. NGC 6051 harbors a powerful radio source with 1.4 GHz flux of $607 \pm 22$ mJy [from the NVSS catalog.4].

The XMM observation [see the analysis reported in 5] revealed a unique temperature profile for a relaxed object, with an isothermal core out to 200 kpc [as found also in 6] and then a decline at large radii. They also show a clear abundance gradient, from $\sim 0.2 Z_\odot$ at 400 kpc to $1.2 \pm 0.1$ in the inner 20 kpc, another indication of a fairly relaxed system [e.g., 7]. To characterize the entropy profile, determined by computing the adiabatic constant $K = kTn_e^{-2/3}$ we fitted a power law plus a central constant $K = K_0 + K_{100}(r/100\text{kpc})^\alpha$, finding $K_0 = 52 \pm 6$ keV cm$^2$, $K_{100} = 122 \pm 51$ keV cm$^2$ and $\alpha = 1.14 \pm 0.08$ with $\chi^2$/dof = 7/6. The elevated central entropy of AWM 4 is reflected in the long central cooling time, $3.0 \pm 0.2$ Gyr in the inner bin. In this regard AWM 4 seems to share the same characteristics of the two radio-quiet clusters, A 1650 and A 2244, described in Donahue et al. [8] and would be consistent with the hypothesis that a major past AGN outburst has completely erased the cool core. But the current 1.4 GHz radio activity implies a recent (not much more than $\sim 10^8$ yr ago) feeding of the central black hole, which is unlikely to come from the ambient hot gas which has an order of magnitude longer cooling time. AWM 4 shows a surprising lack of low entropy gas surrounding an active and bright radio source at 1.4 GHz: its anomalous nature stands out clearly in a plot of radio power versus central entropy $K_0$, as in the plot of the BCGS of the Chandra sample of Cavagnolo et al. [9]: there are very few outliers showing radio emission above a threshold of 30 keV cm$^2$. These objects may be special cases of BCGs with embedded coronae, very compact "mini-cooling cores" ($\lesssim 5$ kpc) with low temperatures and high densities; coronae are a low entropy environment and may provide the thr conditions necessary for gas cooling to proceed [10]. The XMM data could not rule out the presence of low-entropy gas at scales smaller than the inner 20 kpc and indeed a recent Chandra observation has revealed the presence of a cool ($\sim 1$ keV) compact and extended corona associated with the BCG NGC 6051. If this discovery solves the mystery of the apparent lack of low entropy gas surrounding a bright radio galaxy and makes AWM 4 consistent with the idea that "every BCG with a strong radio AGN has an X-ray cool core", being the cool core a large scale bonafide cool core or a small corona [11], it also opens the question of the origin of a corona in a relaxed cluster, given the fact that coronae, starting from the first objects observed, the BCGs in the Coma cluster [12], seem to be generally associated with merging subclusters.
CAVITIES, FILAMENTS AND COLD FRONTS IN NGC 5044

The galaxy group NGC 5044 is one of the brightest groups in X-rays: our estimate, using the new Chandra and XMM data, for the bolometric X-ray luminosity within $r_{500} = 443h_{70}^{-1}$ kpc is $1.05 \pm 0.06 \times 10^{43}h_{70}^{-2}$ erg s$^{-1}$. An H$\alpha$ nebula is present in the core of NGC 5044 showing an extended filamentary structure [e.g., [13]]. NGC 5044 is also remarkable because Spitzer data show extended cold dust emitting at 70 $\mu$m and extended 8 $\mu$m excess (likely arising from PAH, polycyclic aromatic hydrocarbon, molecules) extending out to several kpc and spatially coincident with the H$\alpha$ emitting nebulosity and the brightest soft X-ray emission [14]. As proposed in Temi et al. [14], current evidence is consistent with an internal origin of this dust, which has been buoyantly transported from the galactic core out to several kpc into the hot X-ray emitting gas following an AGN outburst. Because of its short lifetime ($\sim 10^7$ yrs) to sputtering destruction by thermal ions, this dust is a spatial tracer of extremely transient events. A two-dimensional analysis of the Chandra and XMM data available at that moment [see [15]] has revealed the wealth of structures present in the core of this object. The Chandra image (see Fig. 1 left panel) shows two depressions in surface brightness and multiple filamentary structures, some of them connected to the presence of the cavities. The temperature map of the inner 10 kpc reveals that the filament spatially coincident with the H$\alpha$ and dust filament is cooler than any other region on the map. Therefore the Chandra data show the impact of the energy release from the AGN on the hot X-ray emitting gas, reinforcing the scenario proposed in Temi et al. [14]. However it is remarkable that a pair of cavities close to the nuclear source are lacking extended high frequency radio emission. This is contrary to what is generally observed in particular in clusters of galaxies. They also strengthened the association of dust, H$\alpha$ and soft X-ray emission (see Fig. 1 right panel): the presence of the cavity in the North likely explains the origin of the N H$\alpha$ filament. X-ray filaments are present at both sides of the cavities,
but only the ones with the presence of dust are showing optical emission and cooler X-ray emission. Temi et al. \cite{14} showed that the cospatiality of these features can be explained as the result of dust-assisted cooling in an outflowing plume of hot dusty gas: dust can cool buoyant gas to $10^4$ K, which emits the optical emission lines observed. It is unfortunate that the deep Hα observation of Caon et al. \cite{13} is affected by a CCD defect in the southern region co-spatial to the X-ray cavity; we have obtained IFU observations at the VLT to map in detail the Hα emission in NGC 5044.

At 31 kpc and 67 kpc two surface brightness discontinuities have been detected, confirmed to be a pair of cold fronts by the spectral analysis. The widely accepted scenario for the presence of cold fronts in relaxed cool core systems is that they are due to sloshing of the cool gas in the central gravitational potential, which is set off by minor mergers/accretions \cite{16}. This is also suggested by the peculiar velocity of the brightest galaxy NGC 5044 with respect to the mean group velocity \cite{17}. NGC 5044 is the first relaxed group for which sloshing cold fronts have been discussed in close similarity to the ubiquitous ones detected in relaxed clusters.

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