AWM 4 and MKW 4 - two very different poor clusters observed with XMM

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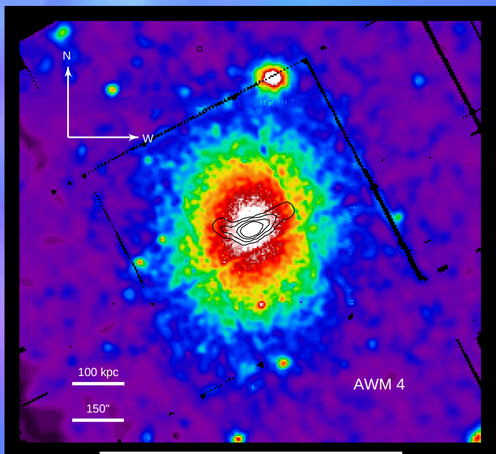


Adaptively smoothed mosaiced image of AWM 4, based on images from the EPIC PN, MOS 1 and MOS 2. The image was smoothed with the SAS task ASMOOTH, using a signal-to-noise ratio of 10. Ignoring the distortions caused by the PN chip gaps, the halo is quite regular with no sign of substructure. The black contours in the centre of the image show the radio source associated with the dominant galaxy, and are based on VLA first 20 cm data. The source north of the cluster is a bright background AGN.

Introduction

MKW 4 and AWM 4 are fairly relaxed poor clusters, originally identified in the Morgan et al.(1975) and Albert et al.(1977) surveys. Each is dominated by a giant elliptical or cD galaxy, surrounded by ~50 (MKW 4) or ~30 (AWM 4) other galaxies. Previous observations by *Einstein*, *ASCA* and *ROSAT* have shown these systems to have large X-ray halos, extending out to >150 kpc (Dell'Antonio et al. 95). Both systems lie on the $L_X : T_X$ and $M : T_X$ relations for clusters (Sanderson et al 03). Given their apparently undisturbed state, and the large mass concentrations associated with their central galaxies, these clusters are potentially excellent sites to observe cooling at the lower end of the cluster mass range. We have used *XMM* to observe these systems, in order to determine whether they host cooling flows and to model the current state of their halos.

Images and halo structure

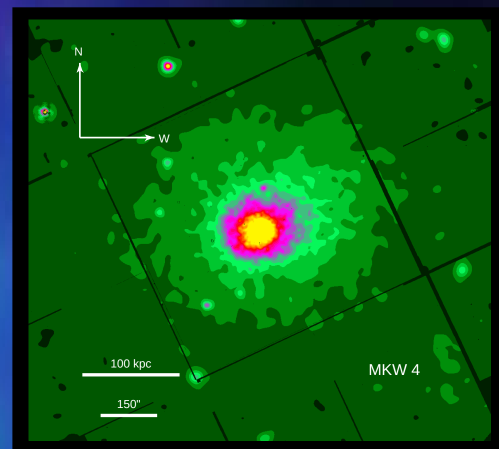
The two clusters were observed by *XMM-Newton* for ~14 ksec (MKW 4) and ~17 ksec (AWM 4) respectively. Smoothed images from the EPIC cameras can be seen to the left and right.

- AWM 4 (left) is, as expected, very regular with little substructure. The halo is well described by two beta models with a common centre.
- MKW 4 (right) is more complex. Surface brightness modelling showed that the halo is not well described by a combination of beta models, owing to structure along a NW-SE axis. The halo extends further to the NW than in any other direction, and to the SE there is excess surface brightness between 10 and 30 kpc from the core. **This excess does not take the form of a sharp edge, and there is no significant change in temperature or hardness across it.** We model the halo based on the NE and SW quadrants.

Central galaxies

The dominant galaxies in MKW 4 and AWM 4 are NGC 4073 and NGC 6051 respectively. Both are highly luminous and ~1.5 magnitudes brighter than the second ranked galaxies in the clusters.

- NGC 4073 shows evidence of a past merger. It has a kinematically decoupled core and the spectroscopic age of the stellar population is ~7.5 Gyr. It is the larger of the two galaxies, with Log L_B=11.01 $L_\odot$.
- NGC 6051 hosts an active nucleus, which although not detected in the X-ray or optical, is revealed by a large scale radio feature extending from the galaxy core. The contours overlaid on the X-ray image to the left show the scale of the radio jets. The optical luminosity of NGC 6051 is L_B=10.76 $L_\odot$.



Adaptively smoothed mosaiced image of MKW 4, based on images from the EPIC MOS cameras. The image was smoothed with the SAS task ASMOOTH, using a signal-to-noise ratio of 10. The elongation of the halo towards the NW can be seen.

Three-dimensional models

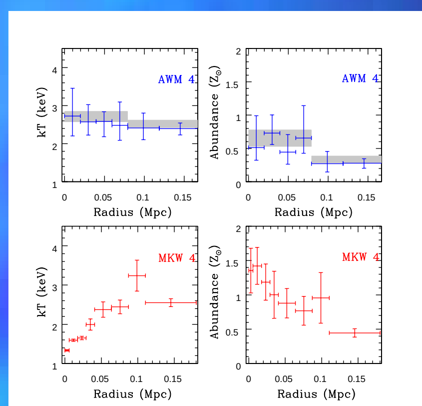
Based on our surface brightness fits and deprojected temperature profiles, we have generated three-dimensional models of the the halos and potential wells of the two clusters. Comparing the profiles of properties such as mass, density and entropy for AWM 4 and MKW 4 highlights several noteworthy features.

- The temperature profiles of the two systems are quite different, but the peak temperature of MKW 4 is very similar to the average temperature of AWM 4.
- Although the two clusters have quite different structures, their total mass profiles are very similar outside the core regions.

⇒ The two clusters are have **similar total masses**, with the difference in the core probably caused by the **different masses of the dominant galaxies**.

- MKW 4 has a larger total mass and a larger mass of gas in its core regions than AWM 4. The gas fraction of AWM 4 is very low out to ~40 kpc, where it begins to rapidly increase. In the outer regions the situation is reversed, and AWM 4 has a considerably larger gas fraction than MKW 4.
- MKW 4 has a relatively short cooling time in the core (~5×10^8 yr), and the inner halo contains very low entropy gas. In AWM 4, gas entropy is significantly higher, and the cooling time is relatively long, even at very small radii.

⇒ While MKW 4 has a cool core, and may be developing towards a cooling flow, **the core of AWM 4 has likely been heated.** The gas fraction profile suggests that the inner halo has been "puffed up" by the injection of energy, which is also responsible for the isothermal temperature profile.



Deprojected temperature and abundance profiles of the two clusters. Symbols represent 90% error regions. Fitting was carried out using the *XSPEC* PROJCT model, and assuming the emission arises from an absorbed MEKAL model. Hydrogen column was fixed at the galactic value. The grey regions in the AWM 4 plots (upper panels) show fits with bins tied together to form inner and outer region. Note that the temperature difference is still not significant.

Temperature and Abundance profiles

Using elliptical annuli, we extracted radial spectra for MKW 4 and AWM 4 and used these to model the deprojected temperature and abundance profiles, and the projected abundances of Fe, Si and S.

Deprojected profiles

- **The deprojected temperature profiles of the two clusters are quite different**. MKW 4 has a strong decline in temperature toward the core, with kT falling from ~3 keV to ~1.4 keV. On the other hand, **AWM 4 is apparently isothermal**, with a possible trend for temperature to increase in the core.
- The abundance profiles are more similar, with abundance increasing in the cluster cores. However, **It is clear that MKW 4 is more metal-rich than AWM 4**.

⇒Cooling has been effective in MKW 4 but not in AWM 4.

- Steady state cooling flow spectral models produce very poor fits in MKW 4, and models such as CEVMKL only produce acceptable fits if **the contribution from gas at low temperatures is minimal**. High resolution RGS spectra show evidence for the OVII line, but no lower energy species.

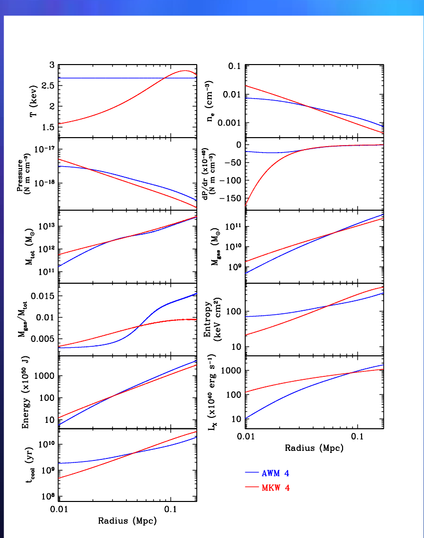
⇒Although MKW 4 is cooling, there is little or no gas at temperatures cooler than 0.5 keV.

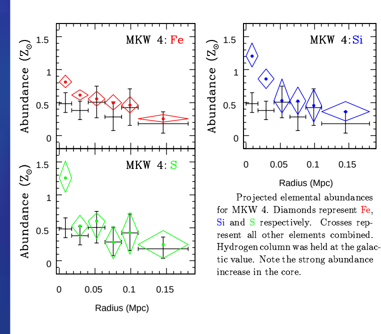
- The isothermal profile of AWM 4 suggests that some process must be heating the gas. As there is no sign of a sub-cluster merger, it seems likely that the AGN activity in NGC 6051 is responsible for heating the cluster core and preventing cooling.

Elemental abundances

- In MKW 4, there are clear central peaks in the abundance of Fe, Si and S. These are consistent with ~50% of the metal enrichment in the cluster core arising from SNIa.
- In AWM 4, the uncertainty of the fitted parameters is somewhat larger, but there is **no significant difference in the abundances of the individual elements**.

⇒This suggests that the gas in AWM 4 has been mixed by the same process responsible for heating the core.





Projected elemental abundances for MKW 4. Diamonds represent Fe, Si and S respectively. Crosses represent all other elements combined. Hydrogen column was held at the galactic value. Note the strong abundance increase in the core.

Heating in MKW 4

MKW 4 is similar to a number of systems observed by *Chandra* and *XMM* in that although its halo contains gas at a range of temperatures, there is no evidence of cooling below ~0.5 keV. NGC 4636 (Xu et al. 2002), M87 (Sakelliou et al. 2002) and NGC 5044 (Tamura et al. 2003) all show this behaviour, with minimum temperatures of 0.5-0.6 keV. Given this minimum temperature in MKW 4, it seems likely that the halo has been heated in the past and is now in the process of cooling and re-establishing a cooling flow. This heating could have been caused by some dynamical event, such as a sub-cluster merger, or by AGN activity.

- We calculated the time required for an isothermal halo to cool to the point where its temperature profile would match that which we observe. In the cluster core, this cooling timescale is ~200 Myr. This is quite comparable to the activity cycle of an AGN, but very dissimilar to the spectroscopic age of the dominant galaxy.

⇒MKW 4 is likely to have been heated by an AGN which is currently quiescent.

We note that the temperature profile of MKW 4 is not well described by either the "universal" temperature profile for relaxed clusters of Allen et al.(2001) or by models in which cooling is balanced by conduction (Voigt et al 2002).

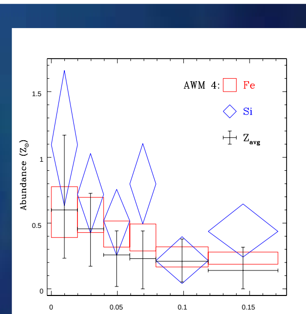
⇒MKW 4 is not in a stable state and is likely to cool further.

Heating in AWM 4

AGN heating is also likely responsible for the isothermality of AWM 4. Taking the unlikely possibility that the isothermal temperature profile we observe is a stable, long term feature of the system, an energy input of at least ~10^{43} erg s^{-1} is required to balance the X-ray emission from the central 100 kpc. If, as is more likely, AWM 4 once had a temperature profile much like that of MKW 4, ~9×10^{58} erg would be needed to heat it to its current state. **This is equivalent to an AGN injecting ~3×10^{43} erg s^{-1} for 100 Myr.**

⇒Even considering efficiency factors, it is realistic to assume AWM 4 has been heated by AGN activity.

This AGN activity is also the probable cause of the gas mixing we infer from the abundance profiles.



Projected elemental abundances for AWM 4. All symbols correspond to 90% error regions, and hydrogen column was held fixed at the galactic value. Although abundance rises toward the core, there is no significant difference between the abundances of Fe, Si and the other elements ($\mathbf{Z}_{avg}$).

Conclusions

AWM 4 and MKW 4 appear to be very similar clusters with two major differences:

1) AGN activity: While AWM 4 is currently being heated by the AGN in NGC 6051, there is no ongoing AGN activity in NGC 4073, and gas in the core of MKW 4 has been able to cool.

2) Galaxy mass: NGC 6051 is considerably less massive than NGC 4073, leading to a less steeply peaked mass profile in the core of AWM 4.

We therefore conclude that the differences between the two clusters are probably caused by differences in their dominant galaxies, and the fact that the central AGN are at different phases of their activity cycle.

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