INVESTIGATING HEATING AND COOLING IN A SAMPLE OF CLUSTERS

R. J. H. Dunn and A. C. Fabian

Institute of Astronomy, Cambridge, UK

ABSTRACT

We select clusters from the Brightest 55 sample which have a short central cooling time and a large central temperature drop as these require some form of heating. 20 clusters meet this requirement, of which at least 14 contain clear bubbles. The median radius out to which the bubble power can offset the X-ray cooling is $0.98r_{\rm cool}$. Using these average values for the clusters with bubbles, the expected size of bubbles in the clusters in the B55 sample which contained a central radio source was calculated. The expected sizes are very similar to the observed radio source lobes in the cases where they are resolved.

Key words: Clusters; Heating; Radio Bubbles.

1. INTRODUCTION

Since the discovery of strong X-ray emission in clusters of galaxies, the thermal plasma which makes up the Intra-Cluster Medium (ICM) has been known to be cooling. As the temperature of the gas falls, it would lose pressure support unless it flows inwards to the centre of the gravitational potential. Such a flow is known as a cooling flow.

However, with the advent of *Chandra* and *XMM-NEWTON*, little X-ray cool gas was found; the cooling flow problem. Cooling appears to terminate at around 1/3 of the virial temperature e.g. Peterson et al. 2001. Various mechanisms have been proposed by which the cool gas could be heated, including thermal conduction, but this doesn't appear to work for clusters below $5\,{\rm keV}$ (Voigt & Fabian, 2004). Active Galactic Nuclei (AGN) have been observed at the centre of many clusters. In some clusters there are decrements in the X-ray emission which anti-correlate spectacularly with the extended radio emission. These holes in the X-ray emission have been interpreted as bubbles of relativistic plasma, blown by the AGN. Ghost bubbles, ones without ${\rm GHz}$ radio emission, have also been discovered, and these are thought to be rising buoyantly up through the ICM. Deep images of the Perseus and Virgo Clusters (Fabian et al., 2003; Forman et al., 2003) show pressure waves which are a mechanism by which the energy contained within the bubble could be transferred to the ICM.

Studying a large sample of clusters would be useful in providing a concept of what an "average" cluster was as many recent studies have concentrated on clusters which are abnormal – the brightest, hottest, closest and morphologically most interesting. Then with the properties for an average cluster the processes occurring at the centres of clusters would be clearer, especially the heating processes. An extension of this cluster survey to higher redshift would allow the study of the evolution of heating processes as clusters continue to form.

2. SAMPLE SELECTION

The sample of clusters from which our subset was taken was the Brightest 55 (B55) sample from Edge et al. (1990), which was further analysed by Peres et al. (1998) using *ROSAT* data. It is a $2-10\,{\rm keV}$ flux-limited sample of X-ray clusters which are all close enough to have been imaged at sufficient resolution by the previous generation of X-ray instruments. From this sample we looked at those clusters which had a short central cooling time ($t_{\rm cool} \leq 3\,{\rm Gyr}$) and a central temperature drop such that $T_{\rm centre}/T_{\rm outer} < 1.2$ as these are the clusters which are most likely to require some form of heat source to stem cooling.

Out of the 55 clusters, 23 have a short $t_{\rm cool}$ and 21 have a central temperature drop. 20 clusters have both and as such require some form of heating. Of these 14 (almost 75%) have clear X-ray depressions (Dunn et al., 2005). Of the remaining six clusters required heating but containing no clear bubbles, five have radio emission from their core. AWM7 is the only cluster in the sample which requires some form of heating to offset the X-ray cooling but has neither bubbles nor a central radio source. This proportion of clusters containing bubbles matches that from Eilek (2004) and Marković et al. (2004) who selected their clusters using mass deposition rate and the size of the central cluster galaxy.

Table 1. Cluster Sample

Bubbles	Radio		No Radio
Heating	Heating	No Heating	Heating
2A0335+096*	A496	3C129.1	AWM7
A85	A2204†	A399	
A262	PKS0745-191†	A401	
A426		A576	
A478		A754	
A1795		A1644	
A2029		A1650	
A2199		A3112	
A2597		A3391	
A4059		Klem44	
Centaurus			
Cygnus A			
Hydra A			
M87			
MKW3s*			

* These clusters do not have *c*lear bubbles but the X-ray decrements have been interpreted as such.
† These clusters are above $z = 0.1$.

Bîrzan et al. (2004) found that 16 out of 80 clusters in the *Chandra* archive contained bubbles, however their sample contained all clusters, and not just those which are likely to require some form of heating.

Two clusters which require heating but do not have clear bubbles are 2A0335+096 and MKW 3s. 2A 0335+096 has a complicated lumpy core and so contains X-ray depressions, however they do not have much radio emission associated with them. Mazzotta et al. (2003) interpreted these depressions as bubbles and so this cluster is included with the "bubbled" clusters. MKW 3s also has features in the X-ray emission which may be bubbles, though they are a long way out in the cluster (Mazzotta et al., 2002). This cluster is also added into the sample of clusters containing clear bubbles, making 16.

In addition to the clusters which require heating, those clusters in B55 sample which contain a central radio source were also analysed. This adds another 10 clusters into the sample, making 30 in total; 16 have bubbles, 13 have a radio source (of which 10 do not have a short central cooling time *and* a central temperature drop) and AWM7. The total sample is shown in Table 1.

3. BUBBLE ANALYSIS

Using archive data the publicly available dataset with the longest exposure time was obtained for all the clusters in the sample. Standard reprocessing and deprojection was performed, obtaining radial temperature, density and pressure profiles as well as the heating required per annulus to offset the X-ray cooling.

For the clusters containing clear bubbles the energy in the bubbles was determined using the $4pV$ work done, where the factor of 4 is $\gamma/(\gamma-1)$ for a relativistic gas. Using the sound speed timescale for the young active bubbles, and the buoyancy timescale for the ghost bubbles the power deposited by the bubble in the ICM was calculated. A comparison of the bubble power to the heating required per annulus gives the median radius out to which the bubbles offset the X-ray cooling as $0.98 r_{\rm cool}$, where $r_{\rm cool}$ has been calculated for a cooling time of $3\,{\rm Gyr}$.

There is a large spread in the distance out to which the bubble power can offset the cooling – almost $4 r_{\rm cool}$ for A2052, but only $0.08 r_{\rm cool}$ for Centaurus. The spread of the fraction of heat supplied within $r_{\rm cool}$ is also large – $10.5\times$ for Cygnus A, but only $0.03\times$ for Centaurus. Therefore, in order for the bubbles to offset all of the X-ray cooling, on average the AGN have to be active for a large proportion of the time. Some bubbles are sufficiently powerful to provide more heating than required by the X-ray cooling in the region of the cluster currently analysed.

3.1. Perseus

The radio source at the centre of the Perseus Cluster (3C84) has a complicated "S" or "Z" shaped morphology. Dunn et al. (2005) explain this with the central regions of the source containing two pairs of bubbles – an inner and an outer pair. If these bubbles are treated separately then the power supplied by the bubbles goes up by $1.4\times$. This increases the radius out to which the X-ray cooling is offset by the bubbles from $75\,{\rm kpc}$ to $100\,{\rm kpc}$ $(1.3 r_{\rm cool})$.

4. BUBBLE PREDICTIONS

The clusters which do not contain clear bubbles were reprocessed and deprojected in the same way, and profiles for the heating required per annulus to offset the X-ray cooling were obtained. The median value for the radius out to which an average bubble offsets the X-ray cooling in the clusters with bubbles were used to calculate the power an average bubble placed at the centres of the clusters with no bubbles would have to produce. In the assumption that all of the bubbles are young and as such expanding at the sound speed, the size of an "average" bubble corresponding to that cluster was calculated. AWM7 was included in this analysis even though it does not appear to contain a central radio source.

Table 2. Bubble Expectations

Cluster	Expected Bubble Radius (kpc)	Observed Radio Radius (kpc)
3C129.1	1.72	2.6×2.6
A399	2.53	
A401	1.44	
A496	2.43	
A576	0.50	
A754	0.78	
A1650	3.61	
A1644	2.32	
A2204	8.46	5.1×4.6
A3112	5.98	
A3391	2.63	$\sim 20 \times 30$
AWM7	3.39	None
Klem44	3.44	
PKS0745	7.61	$9.2 \times 6.0^{*}$

* full dimensions of the amorphous radio source.
Radio source present in the cluster unless specified.

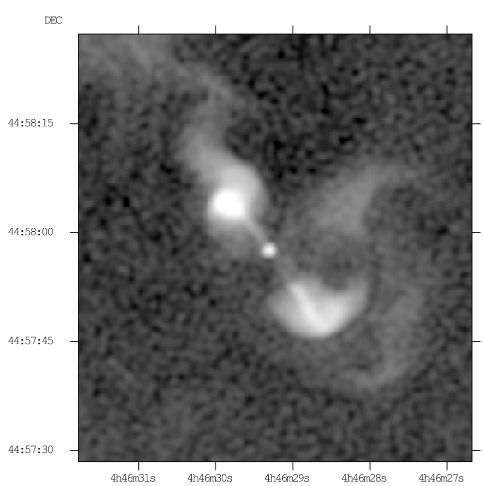

Figure 1. The 5 GHz *radio emission from 3C129.1*

For three of the clusters VLA Radio images show bi-lobed morphologies, very similar to those radio sources in clusters which do show clear bubbles (see Fig. 1); in two of these cases the sizes match very well (see Table 2). These are only average bubbles and so although for A3391 the expected size is much smaller than what is observed, this is not a problem given the range in supplied heating calculated for the clusters with bubbles. The two highest redshift sources (A2204 and PKS 0745-191) along with the others have expected bubble sizes which are only a few *Chandra* pixels in radius and so may not be clearly obvious in short exposure times, especially if their contrast is small. PKS 0745-191 is an amorphous radio source and so describing the interaction of the radio source with the ICM with bubbles may not be correct.

5. FUTURE PROSPECTS

This analysis assumed that the energy contained within the bubble is $4pV$. If the energy is just pV then on average the heating supplied by the bubble is not going to be enough to stem the X-ray cooling. The analysis also assumes that all of the energy within the bubble is transferred to the ICM where it can stem the cooling. However is this reasonable?

It has been shown that the inflation of the bubbles can produce sound waves in the gas (Fabian et al., 2003). These waves can dissipate some of their energy as heat as they travel out in the cluster. However this is going to occur over a much longer timescale than that of the bubble creation.

The bubbles have been assumed to be travelling at the sound speed as there are no strong shocks observed in the rims surrounding them, in fact the rims can contain the coolest gas in the cluster. However, as the jets that create the bubbles are expected to be relativistic then the early expansion of the bubbles would be expected to be supersonic. The buoyancy rise-time for the bubbles was used for the ghost bubbles. For further discussions of the timescales involved see Dunn et al. (2005).

Although the bubbles are created at a rate corresponding to the power described above, the energy they contain is unlikely to be liberated over the same time period as this would imply that the bubbles would dissipate very quickly and so ghost bubbles of the size and scale observed would not be seen. If the bubbles are, on the whole, providing the heating for the central regions of the cluster then if the bubbles dissipate their energy over a longer time, and so larger volume of the cluster, the AGN would have to be active for a large proportion of the time.

This is only a relatively small sample – 16 clusters with bubbles and 14 clusters without. A larger sample, work on which is underway, would improve the confidence in the results. Extending the sample to higher redshifts would also show the evolution of heating and cooling processes over time.

6. CONCLUSIONS

Out of the Brightest 55 sample, 20 clusters require some form of heating. Of these at least 14 (75%) contain clear bubbles. The bubbles in these clusters, as well as those in two more which have less obvious X-ray depressions, can offset the cooling from X-ray emission out to $0.98r_{\rm cool}$ (median). The 14 clusters which do not have bubbles, of which 10 do not require heating given our selections, all but one contain a central radio source. The average bubbles expected in these clusters are such that with short exposures they may not have been seen as yet. However the sizes match the observed bi-lobed morphologies seen in three of the cluster radio sources.

ACKNOWLEDGEMENTS

We thank Jeremy Sanders and Roderick Johnstone for technical support and interesting discussions during the course of this work. RJHD and ACF acknowledge PPARC and The Royal Society respectively.

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