Heating and Cooling in the Perseus Cluster Core

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1 Introduction

It is well known that the radiative cooling time of the hot X-ray emitting gas in the cores of most clusters of galaxies is less than $10^{10}$ yr (Fig. 1). In many clusters the gas temperature also drops towards the centre. If we draw a causal connection between these two properties then we infer the presence of a cooling flow onto the central galaxy (e.g.\cite{8}). High spectral resolution XMM-Newton data \cite{25}\cite{33} and high spatial resolution Chandra data, e.g. \cite{1}, show however a lack of X-ray emitting gas below about one third of the cluster virial temperature. The explanation is that some form of heating balances cooling. The smoothness and similarity of the cooling time profiles and the flatness of the required heating profiles all indicate that we must seek a relatively gentle, quasi-continuous (on timescales $< 10^8$ yr), distributed heat source. The likely such source is the central black hole and its powerful jets which create bubble-like cavities in the inner hot gas (\cite{5}, see \cite{24} for a review).

Fig. 1. Heating and cooling properties of the intracluster gas in the cores of 16 X-ray bright clusters \cite{7}. (Left) radiative cooling times and (Right) heating rate required per kpc to balance cooling.
Fig. 2. Status of the cores in clusters from the Brightest 55 sample with Chandra data [7]. Objects in the column on the left show clear bubbles, those in the 2 centre columns have a central radio source and the one on the right has no reported radio source at the centre. Heating is defined as required if the central cooling time is less than 3 Gyr and the central temperature drop exceeds a factor of two.

We briefly review the general heating and cooling statistics in an X-ray bright sample of cluster before we discuss the detailed situation in the Perseus cluster, the X-ray brightest cluster in the Sky. The Chandra count rate from the Perseus cluster is twice that of any other cool core cluster (the Virgo and Centaurus clusters come next) and the total exposure, of almost 1 Ms, is almost twice as long (compare with 500 ks for Virgo and 200 ks for Centaurus). In many ways therefore the Perseus cluster data are the best, and possibly unique, for determining the details of the energy flow in a cluster core.

2 General conclusions from the Brightest Clusters

Here we summarize the general situation in low redshift clusters using the Chandra analysis of the Brightest 55 sample from [7]. The results, where relevant, are in agreement with the earlier ROSAT analysis of [23]. Fig. 2 lists 30 sources of which only one (AWM7) does not have a radio source associated with the central galaxy. 14 of them have clear bubbles and another 5 have possible bubbles or interaction between the radio source and the hot gas. Only 10 out of the 30 do not need any heating (i.e. either the central cooling time exceeds 3 Gyr, see Fig. 2, and/or any central temperature drop is less than a factor of two).
Fig. 3. Frequency histogram of the clusters tabulated in Fig. 2. Black shading indicates that clear bubbles are seen; grey means that there is a plausible radio source at the centre [7].

Fig. 4. An approximate estimate of the total energy emitted within the cooling radius over 13 Gyr plotted versus cluster temperature [13]. The accreted black hole mass, assuming a radiative efficiency of 0.1, is also shown. The results reduce roughly as (time)$^2$, so drop by 7 if a cluster age of only 5 Gyr is assumed. The accreted masses are then still considerable (up to $3 \times 10^9 M_\odot$).
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The common occurrence of bubbles in the clusters which require heating means that the duty cycle of bubbling is between 75 and 90 per cent – the jets are ‘on’ most of the time. Such a mechanism satisfies the quasi-continuous requirement.

The steep abundance gradient observed in many clusters requires that the heating mechanism be relatively gentle and not produce much turbulence \[27\][18]. The relatively smooth and similar cooling time profiles support this.

The energy requirements are considerable (Fig. 4 from [13]). The \(PdV\) work done by the bubbles on the surrounding gas is nevertheless of the right order of magnitude \[2\][26][7]. It appears inescapable that the central radio source is pumping energy into the intracluster gas at roughly the required level. What is not clear from a general study of clusters, albeit the brighter ones, is how that energy is distributed on the right spatial scale to balance radiative cooling. Gas is not piling up at any particular radius or temperature. An even more challenging issue is how the feedback required for a tight heating / cooling balance operates.

Highly energetic events, such as inferred for Hydra A \[22\], whilst spectacular, are not typical of the norm. They also dump most of their energy well beyond the cooling region.

3 The Perseus Cluster

The Perseus cluster, A 426, is the X-ray brightest cluster in the Sky. The X-ray emission is sharply peaked on the cluster core, centred on the cD galaxy NGC 1275. Jets from the nucleus of that galaxy have inflated bubbles to the immediate N and S, displacing the ICM \[3\][11]. Ghost bubbles devoid of radio-emitting electrons, presumably from past activity, are seen to the NW and S. The radiative cooling time of the gas in the inner few tens of kpc is 2–3 hundred Myr, leading to a cooling flow of a few \(100\, M_\odot\, \text{yr}^{-1}\) if there is no balancing heat input. Energy from the bubbles or the bubble inflation process is a likely source of heat but the energy transport and dissipation mechanisms have been uncertain.

With 200 ks Chandra exposure we discovered both cool gas and shocks surrounding the inner bubbles as well as quasi-circular ripples in the surrounding gas which we interpreted as sound waves generated by the cyclical bubbling of the central radio source. Related features have been seen in the Virgo cluster \[15\][16]. The NW ghost bubble has a horseshoe-shaped Hα filament trailing it which shows the streamlines in the hot gas. (The velocities along the filament are reported by \[20\] and are consistent with the streamline hypothesis.) On this basis we concluded that the ICM is not highly turbulent and thus that viscosity (and possibly conduction) is high enough to dissipate the energy carried by the sound waves \[9\][10]. Such an energy transport and dissipation mechanism is roughly isotropic and can thereby provide the required gently distributed heat source \[29\][30][31][28][12]. The energy flux in
Fig. 5. Full 900 ks Chandra image of the centre of the Perseus cluster with red, green and blue representing soft, medium and hard X-rays within the Chandra band [14].

Fig. 6. Left: unsharp-mask image showing the ripples, Right: profile of the raw data to the E with deviations from a simple beta-model fit to that profile.
Fig. 7. Perseus pressure maps. Left: with radio overlay, Centre: showing that the high pressure regions are thick and circular around the radio bubbles, Right: pressure difference map showing a series of outer bubbles and channels to S and N.

Fig. 8. Temperature, density and pressure profiles in a 30 deg wide sector to the NE of the Northern bubble. The position of the edge of the higher pressure ring (the shock front) is marked by a dashed line.
the sound waves seen equals the energy required to balance cooling within a radius of about 100 kpc.

A ripple is presumably made each time a new bubble grows. Close to the bubble the amplitude must be high so a shock is likely to form, which could dissipate so much of the energy that there is little left for significant sound waves and would overheat the innermost regions [17][21]. We now have 900 ks of good Chandra data and can see the details of what is happening here. The ripples (Fig. 6) have an amplitude of ±5 per cent or less (a level probably not detectable in any other cluster). Pressure maps show a thick high pressure rim to the bubbles (Fig. 6) with a sharp outer edge (best seen to the NE in Fig. 5). We measure the density jump at this edge as 40%. If the gas has an adiabatic index of 5/3 this should lead to a temperature rise from 4 to 5 keV. No such temperature jump is seen. Indeed the gas temperature, if anything, drops slightly across the edge [14]. (The sharp edge appears all round the bubbles so it is not a cold front.)

Observationally it seems that the violent pumping action of bubble growth does not lead to excessive heating of the innermost regions and allows sound waves to propagate outward, where the energy can be dissipated by viscosity and conduction in a more distributed manner, as required. The lack of a temperature jump is puzzling, but can be understood if energy is spread by thermal conduction [14].

4 Multiphase effects and cooling

The central galaxy in the Perseus cluster, NGC 1275, is surrounded by a spectacular filamentary optical nebulosity (see [6]). This is detected in the emission from molecular hydrogen [19] and CO [32] implying temperatures ranging from several 100 to several 1000 K. Soft X-ray emission is seen coincident with the filaments requiring a significant mass of gas at 0.7 keV (Fig. 9). There is also OVI emission detected by FUSE indicating gas at \( \sim 5 \times 10^5 \) K [4]. Assuming that this last emission is typical and attributing it all to cooling, then the cooling rate in the central 6 kpc is \( \sim 30M_\odot\text{yr}^{-1} \) [4]. The cooling rate implied at 1 keV by Fig. 9 is also only about 10 M\( \odot \) yr\(^{-1} \). Some mixing, conduction etc could affect these estimates but it would be difficult to argue for any simple cooling flow over the central region exceeding about 10% of that deduced by the hotter X-ray emitting gas, in the absence of heating. The heating / cooling balance in the Perseus cluster core, as is the case in most such objects, must be tightly controlled.

5 Discussion

Heating by the repetitive formation and growth of bubbles has the quasi-continuous form required to balance radiative cooling. The deep imaging of
the Perseus cluster core reveals the sound waves produced and shows that the inner shock is isothermal. More work is required to understand this, but electron conduction is a plausible explanation.

A major remaining problem is how the necessary tight feedback is achieved. Just how does the central accretion rate adjust to make heating balance cooling over a $\sim 100$ kpc radius region?

6 Acknowledgements

We thank Robert Dunn and others for collaboration. ACF thanks the Royal Society for support.
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