16

AGN Feedback and Gas Enrichment in Clusters of Galaxies

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We examine deep *Chandra* observations of the nearby Perseus and Centaurus galaxy clusters to examine AGN feedback and enrichment of the intracluster medium. We show evidence of 100 Myr of activity by the central nucleus in Perseus, generating shocks, bubbles and sound waves, heating the cluster core. Despite the AGN activity there exist 10^9 solar masses of $\sim 5 \times 10^6$ K gas embedded in an intracluster medium 5 to 10 times hotter than it. Transport properties of the intracluster medium are likely to be important. We observe and map the distribution of metals in the Centaurus cluster, and show that Type II supernova enrichment is important in even the core of this cluster. It has been relatively undisturbed for 8 Gyr with a close heating/cooling balance.

§1. Introduction

Deep X-ray observations by modern telescopes, such as *Chandra*, *XMM-Newton* and *Suzaku* are revealing a great deal about the nature of Active Galactic Nucleus (AGN) feedback in clusters of galaxies and how the intracluster medium (ICM) is enriched. We examine the evidence for AGN heating in the Perseus galaxy cluster, and examine the enrichment of the intracluster medium in the Centaurus cluster.

1.1. Cooling and heating

The X-ray surface brightness profile from the centres of many clusters of galaxies is steeply peaked. The primary emission mechanism is bremsstrahlung emission from the hot (few 10⁷ K), tenuous (~ 10^{-4} to 10^{-2} cm⁻³) ICM. If the mean radiative cooling time (the ratio of the thermal energy of the gas to its luminosity) is measured as a function in of radius in a sample of clusters,¹⁾ they tend to show almost identical profiles, decreasing to less than 10^9 yr in the inner 30 kpc. In addition, the temperature of the gas in the very centres is typically between 2 and 3 times lower than in the outskirts.²⁾

In the absence of heating and in steady state, there should be a deposition of mass out of the X-ray band at rates of 10–1000 s of solar masses per year. This is known as a *cooling flow*.³⁾ It has been found using high resolution X-ray spectroscopy that there is a deficit of cool X-ray emitting gas in many clusters of galaxies.⁴⁾ If there are large mass deposition rates, the Fe XVII lines, in particular, should be strong. These lines are weak or missing.

The obvious source of heat to prevent cooling is the central AGN which lies at the centre of each galaxy cluster. Most galaxy clusters which require heating show evidence for recent or current AGN activity.⁵) There are some issues relating to heating by the central AGN. Firstly, heating needs to be distributed over a roughly 100 kpc region⁶) and requires most of the accretion power of the central black hole.⁷)

AGN Feedback and Gas Enrichment in Galaxy Clusters



Fig. 1. Pressure map of the core of the Perseus cluster after subtracting average at each radius. Darker regions have lower thermal pressure.



Fig. 2. Filtered image of the Perseus cluster showing the surface brightness ripples or sound waves.







Fig. 4. Mass map of ~ 0.5 keV X-ray emitting gas $(left)^{9}$ with H α image of the same region (right).¹²⁾

1.2. Intracluster medium enrichment

The intracluster medium in galaxy clusters is typically enriched to a third of the solar metallicity, with those clusters traditionally known as cooling flow clusters (relaxed, with peaked surface brightness distributions) showing peaked metallicity gradients.⁸⁾

Studying the distribution of metals in galaxy clusters provides information about how the central AGN mixes the ICM, how stellar processes enrich it, and the relative fractions of different types of supernova.

J. S. Sanders

§2. AGN heating in the Perseus cluster

The affect of the central AGN in the Perseus cluster on the surrounding intracluster medium can clearly been seen by examining a map of the pressure of the gas from a long 900-ks *Chandra* observation (Fig. 1).⁹⁾ Around each of the radio lobes of 3C 84 lies a high pressure rim. This corresponds to a weak shock.¹⁰⁾ The nonthermal gas in the radio lobes displaces the thermal gas, leading to a depression in the pressure map. There are an apparent chain of low pressure regions (including the so-called fossil bubbles, no longer associated with radio emission) extending down to the south of the cluster, and perhaps to the north. These would represent 100 Myr of activity by the central AGN.⁹⁾

Surrounding the centre of the cluster are a set of quasi-spherical ripples in the intracluster medium. These are seen by using an unsharp mask image of the cluster^{9),10)} or using a high-pass Fourier filter¹¹⁾ (Fig. 2). A surface brightness profile and residuals from a model show these features are approximately sinusoidal¹¹⁾ (Fig. 3). The surface brightness is closely related to the density of the gas, so these are ripples in density and therefore pressure. They are apparently sound waves propagating through the intracluster medium,⁹⁾ with periods of approximately 10^7 yr. The power carried by these waves appears to be of a similar magnitude to that required to balance radiative losses.¹¹⁾

Despite the energetic processes of the central AGN, there is evidence for cool gas in the Perseus cluster. Surrounding the central galaxy is a massive and spectacular line emitting nebula.¹²⁾ There is filamentary X-ray emission coincident with the nebula. The mass of this X-ray emitting material was mapped⁹⁾ (Fig. 4), giving a total mass of 10^9 solar masses at around 0.5 keV.



Fig. 5. Metallicity maps of the core of the Centaurus cluster in iron, silicon and sulphur.



Fig. 6. Fraction of SN Ia enrichment from O/Fe, Si/Fe, S/Fe and Mg/Fe ratios using APEC model. These results are to the east and west of the core, and uses XMM-Newton data at larger radii.

AGN Feedback and Gas Enrichment in Galaxy Clusters

§3. Enrichment of Centaurus

The Centaurus cluster is a nearby galaxy cluster that is highly enriched to ~ 1.5 times solar.^{13),14)} The distribution of iron, silicon and sulphur was mapped using a long 200-ks *Chandra* observation of the cluster (Fig. 5).¹⁴⁾ The metals are distributed inhomogeneously on ~ 5 kpc scales.

By comparing the ratios of different elements to iron as a function of radius, to the values expected from models of supernova, the fraction of Type Ia relative to Type II enrichment can be computed (Fig. 6).¹⁴⁾ The values are relatively consistent between the different elements. They indicate there is significant Type II enrichment in the core (~ 30 per cent). There was either a massive initial burst of star formation, or a continuous rate of ~ 5 solar masses per year. Either scenario requires the cluster to have been undisturbed for 8 Gyr, and a close heating cooling balance.

§4. Conclusions

In order for the sound waves to heat the core of Perseus their energy must be dissipated. This requires that a process such as viscosity is present to convert the sound energy into local thermal energy. The linear nature of the filaments (Fig. 4) argues that viscosity is present to damp turbulent motion on small scales. It is almost certain that magnetic fields are required to maintain the emission line and X-ray nebula in the hot intracluster medium, in order for conduction to be suppressed. All of these point to the importance of the transport properties of the ICM to explain the cooling flow phenomenon.

The Centaurus results show that we can learn a great deal about the star formation and enrichment processes in clusters of galaxies. It shows that in at least some objects, there are stable heating/cooling balances, and massive past or steady continuous star formation.

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