The Imprint of Galaxy Formation on X-ray Clusters

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It is widely believed that structure in the Universe evolves hierarchically, as primordial density fluctuations, amplified by gravity, collapse and merge to form progressively larger systems. The structure and evolution of X-ray clusters, however, seems at odds with this hierarchical scenario for structure formation. Poor clusters and groups, as well as most distant clusters detected to date, are substantially fainter than expected from the tight relations between luminosity, temperature and redshift predicted by these models. Here we show that these discrepancies arise because, near the centre, the entropy of the hot, diffuse intracluster medium (ICM) is higher than achievable through gravitational collapse, indicating substantial non-gravitational heating of the ICM. We estimate this excess entropy for the first time, and argue that it represents a relic of the energetic winds through which forming galaxies polluted the ICM with metals. Energetically, this is only possible if the ICM is heated at modest redshift (z<2) but prior to cluster collapse, indicating that the formation of galaxies precedes that of clusters and that most clusters have been assembled very recently.

Recent numerical work has unveiled a remarkable similarity in the structure of galaxy clusters formed through hierarchical clustering: properly scaled, the dark matter density profiles of virialized clusters are nearly identical. The scaling prescription is simple. Coeval clusters have approximately the same characteristic density, $M/r^3 = \text{constant}$, where $M$ and $r$ are the characteristic mass and radius of a cluster. The mass profiles of all clusters are then similar once radii are scaled to a “virial” radius, $r_v \propto (GM/r)^{1/2}$. Baryons in galaxy clusters contribute a minority of the total mass, and are found in a hot, diffuse, X-ray bright intracluster medium at a temperature, $T$, which indicates the depth of the potential well; $T \propto GM/r \propto r_v^2$. If gas traces mass, scaled X-ray surface brightness profiles are also expected to be similar. Furthermore, a simple scaling is expected between X-ray luminosity, $L_X$, and temperature. Assuming that the emission is dominated by bremsstrahlung, $L_X \propto M_{\text{gas}}^2 R^{-3} T^{1/2}$, or $L_X \propto f_{\text{gas}}^2 T^2$, where $f_{\text{gas}} = M_{\text{gas}}/M$ is the gas mass fraction.

X-ray clusters deviate substantially from this simple scaling, and the observed $L_X:T$ relation is considerably steeper than $T^2$. Two main interpretations are usually considered: either the gas fraction is systematically higher in hotter clusters, or the spatial distribution of the gas deviates systematically from the similarity profile in clusters of different temperature. A simple example of the latter is provided by the “preheated ICM” model, wherein the entropy of the gas in all clusters is raised at early times to levels comparable to those reached through gravitational collapse. This entropy “floor” imposes a maximum central density for the ICM which increases roughly as $T^{3/2}$ and therefore affects cooler clusters more severely, reducing their X-ray luminosities and steepening the $L_X:T$ relation relative to the similarity scaling.

In order to investigate the nature of this similarity breaking, we have extracted X-ray surface brightness profiles from ROSAT observations of 25 systems spanning a factor $\sim 15$ in temperature, from rich clusters to small groups. The sample is restricted to systems with reasonably regular X-ray morphology and good estimates of X-ray temperature from the GINGA or ROSAT satellites. The profiles are then scaled so that
they would coincide if obeying similarity, and are shown in Figure 1. (Details of the scaling procedure are given in the caption.) Profiles are colour-coded according to system temperature. Systems with $T > 4$ keV (shown in blue) have on average similar profiles and show no strong trend with temperature, whilst cooler systems (green and red) have profiles that become progressively shallower and less centrally concentrated. This is especially noticeable outside the centre, where cooling flows dominate and the profiles of most systems steepen ($r \lesssim 0.05 r_e$). Deviations in the scaled profiles persist out to radii where cooling timescales greatly exceed the age of the universe, so it seems unlikely that radiative effects are responsible for this result.

The trends in Figure 1 are clearly inconsistent with simple variations in overall baryon fraction (which would result in profiles similar in shape, but shifted vertically with $T$), but are in good agreement with the predictions of the “preheated ICM” model described above. However, one can imagine other effects which would lead to a reduction in central gas densities. For example, non-thermal pressure support (e.g. by magnetic fields) or a failure in the similarity of the underlying gravitational potentials. The unmistakable signature of preheating is a rise in the entropy of the gas. Magnetic support, for example, would actually reduce the entropy, since it would weaken the shocks which heat the gas as the cluster potential develops.

To explore this, we have fitted simple isothermal models to the X-ray emission profiles in order to derive profiles of the “entropy”, $S(r) = T/n_e^{2/3}$, for all systems. The fits exclude any central excess arising from a cooling flow, and employ the widely-used isothermal $\beta$-model to derive $n_e(r) = n_e^0 [1 + (r/r_{\text{core}})^2]^{-3/2}$. Figure 2 shows the entropy of the gas at a fiducial radius of $0.1 r_e$, just outside the cooling flow-dominated region. If the gas profiles were similar, the entropy at a fixed fraction of $r_e$ would be directly proportional to the temperature (solid line). Cool ($T < 4$ keV) clusters clearly have entropies higher than achievable through gravitational collapse alone. The presence of large cores in the entropy profiles of a small sample of galaxy groups and clusters has been noted previously. Here we see that this is part of a systematic trend whereby low mass systems progressively depart from the self-similar scaling, and that at $T \sim 1$ keV the entropy appears to converge to a characteristic floor value of $\sim 100 \, h^{-1/3} \, \text{keV cm}^2$.

What processes are potentially able to establish this trend? Cooling flows will remove low-entropy gas from the centre allowing higher entropy material to flow inwards. However, an effect of the magnitude seen can only be obtained if the amount of gas removed by the cooling flow is a substantial fraction of the ICM, which seems unlikely. Moreover, substantial loss of gas to cooling flows, or large systematic variations in galaxy formation efficiency, are inconsistent with the fact that the gas fraction within $r_e$, and the metallicity of the ICM, are roughly independent of the temperature of the system. It is clear from the observed metal content of the ICM that galaxies have polluted their surroundings with substantial quantities of metal-rich gas. The strong galactic winds responsible for this pollution are thus the most natural mechanism available to heat the ICM. In hot clusters the gravitational collapse of the system generates entropies in excess of the floor value established by galaxy winds, but in cooler systems it is preserved during collapse, and prevents the gas from collapsing to high central densities.

The energy requirements of the preheating mechanism can be assessed by considering the Coma cluster, the best studied nearby rich cluster, although the argument applies equally to smaller systems. The total stellar mass in galaxies in Coma is $\sim 10^{13} h^{-1} M_\odot$ and therefore the total energy available from supernovae is $\sim 10^{52} h^{-1} \, \text{erg}$ (assuming 1 SN event per 100 $M_\odot$ of stars formed). Since the gas mass in the ICM is $\sim 5.5 \times 10^{13} h^{-5/2} M_\odot$, these supernovae can raise the ICM temperature by $\sim 0.4 \, h^{3/2}$ keV. Hence SN can only raise the entropy, $T n_e^{2/3}$, to the observed floor value of $\sim 100 \, h^{-1/3} \, \text{keV cm}^2$ if $n_e < 2.5 \times 10^{-4} h^{11/4} \, \text{cm}^{-3}$, a value well below the electron density at our fiducial radius of $r = 0.1 r_e$ in Coma. In other words, dumping all of the available supernova energy into the ICM of Coma today would be insufficient to heat the denser inner regions to the desired entropy floor. The problem is even more acute at higher redshift, since the density of the Universe, and that of all collapsed clumps, is higher then. This simple analysis implies that the gas in the ICM cannot be in collapsed, overdense systems at the time of preheating. The formation of galaxies must therefore precede the collapse of the cluster as a whole, validating the basic tenet of the hierarchical clustering paradigm.

When did this heating occur? Assuming that the gas is uniformly distributed throughout the Universe at the time of preheating, the density limit gives a strict upper limit on the preheating redshift, $z_{\text{prech}} \lesssim 10$. In practice, density variations and reductions in heating efficiency reduce this redshift limit. An entropy
of $100h^{-1/3}$ keV cm$^2$ is approximately the value baryons would have at present if they were spread uniformly throughout the Universe at the mean density inferred from models of cosmic nucleosynthesis and heated to a temperature of 30,000 K. The entropy of the Ly-$\alpha$ forest gas observed in QSO spectra (the dominant baryonic component of the Universe at $z \sim 2$), is almost an order of magnitude smaller, since the temperatures are of the same order but the density of the Universe at $z \sim 2$ is a factor of $\sim 30$ greater. If, as expected, winds from forming galaxies affect cluster and field environments alike, observations of the Ly-$\alpha$ forest imply that $z_{\text{preh}} > 2$, consistent with the low redshift at which the global star formation rate in the universe appears to have peaked.

We can also estimate the typical propagation velocity of the winds, $v_w$, by noting that one galaxy can perturb a volume of order $(4\pi/3)(v_w/100\text{ km s}^{-1})^3 h^{-3} \text{ Mpc}^3$ in a Hubble time. Since the mass in the Coma cluster has been collected from a volume a few hundred times this, whilst its optical luminosity is approximately that of 200 galaxies like the Milky Way, most of the ICM in Coma could have been preheated by winds blowing at $v_w > 100$ km s$^{-1}$. Such velocities lie comfortably within the range allowed by winds observed in galaxies which are actively forming stars.

The results presented above demonstrate the dramatic influence that forming galaxies have on their surroundings. In the case of rich clusters, which account for $\sim 10\%$ of galaxies, preheating by galaxy winds will substantially modify the evolution of the X-ray luminosity and temperature functions, and will result in a luminosity-temperature relation which is independent of redshift, in good agreement with current compilations of X-ray data. In poor clusters and groups, the entropy floor will have more dramatic effects, and may reduce the baryon fraction within the virial radius below the universal value.

For the majority of galaxies which, like the Milky Way, are not located in virialised groups or clusters, preheating will largely prevent gas from collapsing into their potential wells, leaving the bulk of the baryons in the Universe in a currently undetectable high entropy sea. Inhibiting the collapse of baryons into galaxies after preheating robs them of their main source of fresh fuel and may explain the precipitous drop in the global star formation rate of the universe since $z \sim 1$. In this scenario, most baryons are distributed between galaxies at temperatures $T \sim 30,000 \delta^{2/3}$ K, where $\delta$ is the gas overdensity relative to the universal average. This explains why most galaxies lack the prominent X-ray halos observed in rich clusters. In the halos of galaxies like the Milky Way, where the virial temperature is $\sim 0.1$ keV, gas densities cannot exceed a few times the universal average, and would only be detectable through absorption studies of highly ionized species of metals such as Si in the ultraviolet spectra of background sources. Only in “hotter” systems, such as massive ellipticals, galaxy groups and clusters, can baryons achieve densities high enough to shine profusely and be easily detected.

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Figure Captions

Fig.1 — Scaled X-ray surface brightness profiles are overlaid to show departures from similarity in galaxy systems of different temperatures. ROSAT PSPC images in the 0.4-2 keV band of the 25 systems (A262, A478, A496, A548S, A665, A1060, A1413, A1651, A1689, A1795, A1837, A2142, A2163, A2199, A2218, AWM4, AWM7, MKW3, MKW4, HCG62, HCG94, HCG97, NGC533, NGC2300, NGC4261) were extracted from the public archive, corrected for the effects of vignetting and obscuration by detector support structures, and background flux subtracted. Point sources were removed, and X-ray surface brightness profiles constructed relative to the centroid of the remaining diffuse emission (making due correction for areas removed). Mean temperatures for each system are taken from GINGA and ROSAT observations −28. These are used to compute virial radii, \( r_v = 0.57(T/\text{keV})^{1/2} h^{-1} \text{Mpc} \). The X-ray profiles have been converted from ROSAT count rates to bolometric X-ray intensities using a hot plasma code, and have been scaled by \( T^{1/2}(1+z)^{9/2} \Lambda(T) \) to allow for self-similar scaling with mass and cosmic density evolution [\( \Lambda(T) \) is the temperature dependence of the hot plasma emissivity], and by \((1+z)^{-4}\) to correct for cosmological dimming. The profiles are colour-coded by system temperature. Similarity appears to hold for hot \((T > 4 \text{ keV})\) systems, but large systematic deviations are noticeable in cooler systems.

Fig.2 — The gas “entropy” (defined as \( S = T/n_e^{2/3} \), where \( T \) is the mean temperature and \( n_e \) is the electron number density) at a fiducial radius \( r = 0.1 \ r_v \) is shown as a function of temperature for the 25 systems in our sample. Entropies are computed by fitting isothermal-\( \beta \) models to the surface brightness profiles shown in Figure 1. Error bars indicate 90% confidence levels in temperature, and span the variation in entropy from 0.05 to 0.2 \( r_v \). The solid line shows the similarity relation obtained from numerical simulations including non-radiative gas dynamics, \( S(0.1 \ r_v) \sim 45 (T/\text{keV}) (f_{\text{gas}}/0.06)^{-2/3} h^{−4/3} \text{keV cm}^2 \), where Hubble’s constant is \( H_0 = 100 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \). The numerical results depend only weakly on the assumed cosmological model, and provide a very good match to the central entropy of hot \((T > 4 \text{ keV})\) systems for \( f_{\text{gas}} \approx 0.06 h^{-3/2} \). However, poor clusters and groups have apparently been heated to higher entropy than achievable through gravitational collapse.
