Heating of Gas in Galaxy Groups and Clusters

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Abstract. Was the diffuse gas in galaxy groups and clusters heated at high redshift before it entered a massive halo, or was the heating produced inside collapsed objects by SNII accompanying normal star formation? We compare here two radically different models corresponding to the two scenarios described above. Our results indicate that internal heating by SNII works better than the extreme version of external heating that we adopt in reproducing the observed $L - T$ and entropy $- T$ relations.

1. Introduction

In a simple universe governed only by gravity, the bremsstrahlung luminosity of galaxy clusters would scale as $L \propto T^2$, where $T$ is the gas temperature (Kaiser 1986). However, the observed relation is steeper, $L \propto T^3$ or $L \propto T^4$ (e.g. Arnould & Evrard 1999; Helsdon & Ponman 2000). Other relations, notably the one between entropy and temperature, also show deviation from self-similarity (Lloyd-Davies, Ponman, & Cannon 2000; Mohr, Mathiesen, & Evrard 1999).

These discrepancies can be explained if gas in clusters experienced some non-gravitational heating before (or when) it flowed into the cluster halo (Kaiser 1991; Evrard & Henry 1991). However, there is no general consensus about the details of the heating process.

Here we compare two pictures for the heating that have been proposed by a number of authors in recent years: the external heating scenario, in which the gas is heated at high redshifts, before it enters massive halos, and the internal heating scenario, in which the energy is injected when some or most of the gas is already inside a massive halo. In this latter case we assume that the sources of energy are SNII explosions. The motivation for considering SNII heating a viable form of heating is the success of our models in reproducing the evolution of ISM in NGC 4472 (Brighenti & Mathews 1999a). NGC 4472 is a giant elliptical at the center of a subcluster in Virgo, consistent with being the remnant of a galaxy group, probably stripped of the outer regions when it entered the Virgo cluster. We showed that SNII heating was able to reproduce the gas density and temperature profiles (and therefore also the entropy profile).
2. The Simulations

We use a modified version of the hydrocode ZEUS (Stone & Norman 1992) and we assume spherical symmetry. The code follows two fluids: a normal, collisional gas, and a collisionless fluid which represents the dark matter. Our groups and clusters evolve from a single top-hat perturbation in a $\Lambda$CDM universe ($\Omega_0 = 0.3$, $\Lambda = 0.7$, $h = H_0/(100 \text{ km/s Mpc}) = 0.725$, $\Omega_b = 0.037$). The dark matter accumulates in a Navarro, Frenk, & White (1996) halo by design. We consider a set of three objects with different virial masses (at the present time):

- $M_{\text{vir}} = 4.7 \times 10^{13} \text{ M}_\odot$: “the group”;
- $M_{\text{vir}} = 2.2 \times 10^{14} \text{ M}_\odot$: “the poor cluster”;
- $M_{\text{vir}} = 1.2 \times 10^{15} \text{ M}_\odot$: “the rich cluster”;

We focus here mainly on groups, since lower mass system are more sensitive to heating, and our models, by ignoring the complex merging events, are anyway less appropriate to describe the formation and evolution of large clusters.

**External pre-heating.** We assume an extreme form of preheating: at very high redshift, $z_h = 9$, we reset everywhere the gas density to the mean baryon density, $\rho = \bar{\rho}_b (z = 9)$. At that epoch, the temperature is raised to some constant level $T_h$. We consider 4 levels of heating: $T_h = 10^4, 5 \times 10^6, 10^7, 3 \times 10^7 \text{ K}$, corresponding to $1.3 \times 10^{-4}, 0.65, 1.3, 3.9 \text{ keV/particle}$. These amount of heating is characterized by the numbers 1 to 4 respectively, in our nomenclature. The entropy parameter $S = T/n_e^{2/3}$ corresponding to these levels of heating, which depends on the heating epoch $z_h$ through $n_e$, is $S = 0.025, 0.25, 0.75, 2.5 \text{ keV cm}^2$.

Gas is allowed to cool and to dropout of the flow. This last process is modeled in the usual way (e.g. Sarazin & Ashe 1989) adding a sink term in the continuity equation $\dot{\rho}_d = -q\rho/t_{\text{cool}}$ with $q = 1$.

**Internal heating.** In this series of models, heating is assumed to be the result of star formation occurring inside the group or cluster. Thus, we need to assume a schematic scenario for star formation in these systems. At $z_s = 3$ (2 Gyr after the big-bang) we form stars from cooled gas (conserving baryons) and release SNII energy inside the accretion shock radius $r_{\text{sh}}(z_s)$. All the gas inside $r_{\text{sh}}$ is assumed to get the same amount of energy per unit mass. Te total amount of energy released is $E_{\text{SN}} = \nu \eta_\text{Salpeter} E_0 (M_*/M_\odot)$, where $\eta_\text{Salpeter} \sim 0.007$ is the number of SNII per unit solar mass predicted by a stellar population with a Salpeter IMF, $E_0 = 10^{51} \text{ erg}$ is the kinetic energy released by a single SNII and $M_*$ is the total mass of stars. The parameter $\nu$ controls the amount of heating (i.e. the number of SNII). We consider 4 models with $\nu = 0.5, 1, 2, 4$, labeled with numbers 1 to 4, in analogy with the external heating models.

In more familiar units, SNII inject $\sim 2.4\nu \text{ keV/particle}$ to the gas inside $r_{\text{sh}}$ at $z_h$. This is consistent with the global value $0.22 \text{ keV/particle}$ which is derived assuming a global star formation efficiency $M_*/M_\text{baryon} = 0.1$ (Fukugita, Hogan, & Peebles 1998) and assuming that the SNII energy is shared among all the baryons. In our models, instead, SNII heat only the central part of clusters, similar to the models proposed by Loewenstein (2000). In these models the hydrodynamic equations are modified to take into account the mass and energy injected by stars and SNIa of the central, dominant galaxy. Full details about the simulations can be found in Brighenti & Mathews (2001).
3. Results

3.1. The $L - T$ relation

After evolving to the current time, $t = 13$ Gyrs, the location of our models can be compared with observed clusters in the $L - T$ plot as shown in Fig. 1. In general, heating has a little effect on the emission weighted temperature (heated clusters are not hotter!). Paradoxically, models with maximum heating are always the coolest. Instead, the luminosity generally decreases as heating increases, a result of the lower mean gas density. Groups, having lower virial temperatures, are more affected by the heating, while rich clusters are quite insensitive to it.

The left panel of Fig. 1 shows the results for the external heating scenario. Models “1” without heating nicely follow the self-similar prediction $L \propto T^2$. The group model with maximum heating (model “4”) lies among the observed groups, and the series of models “4” follows a relation $L \propto T^3$, similar to the observed one. However, it requires that $\sim 3.9$ keV/particle are dumped in the gas, or that an entropy floor $S \sim 750$ keV cm$^2$ is established at $z_h = 9$. The energy budget needed is a function of $z_h$. If $z_h = 5$, $\sim 1$ keV/particle is sufficient to decrease the luminosity of groups to the observed level.

The internal heating models are less sensitive to the amount of energy injected (right panel of Fig. 1) and they tend to lie near the upper envelope of the observed $L - T$ data, where strong cooling flows are dominated by a massive central galaxy as we have assumed. Groups models with $\nu \geq 1$ have X-ray properties consistent with observed groups, provided the efficiency of SNII heating is high (we assumed efficiency = 1). However, it is likely that a significant fraction of the SNII energy is lost by radiation, and a more realistic constraint may be $\nu \geq 2 - 3$. 

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**Figure 1.**  Bolometric X-ray luminosity vs. emission weighted temperature for *external heating* (left) and *internal heating* (right) models. Small symbols are data: open squares, crosses and open circles are from Helsdon & Ponman (2000), Arnoud & Evrard (1999) and Allen & Fabian (1998) respectively. Big circles, squares and triangles are models for groups, poor clusters and rich clusters. Labels 1 → 4 indicate the heating level (see text).
Figure 2. External heating. Left: $S = T n^{-2/3}$ evaluated at $0.1 r_{\text{vir}}$ versus emission weighted temperature (open circles). The size of the symbols increases with the amount of heating. Data (filled squares) are taken from Lloyd-Davies et al. (2000). Right: $S(r)$ profiles for group models. Models 1→4 are represented with solid, dotted, short-dashed and long-dashed lines respectively. The dot-dashed line is the observed profile for group NGC 2563.

3.2. The $S-T$ relation

The behavior of entropy for external heating models is illustrated in Fig. 2. In the left panel we compare the entropy evaluated at $r = 0.1 r_{\text{vir}}$ with the data of Lloyd-Davies et al. (2000). The series with maximum heating (models “4”, indicated with the largest circles), which fits best in the $L-T$ plot, has a much larger entropy than observed groups and poor clusters. Models “3” (which requires $\sim 1.3$ keV/particle) may be the best compromise.

The difficulty for external heating models to simultaneously fit the $L-T$ and $S-T$ relations is also illustrated by the radial entropy profiles (right panel of Fig. 2). The computed group entropy profiles are compared with the observed profile of NGC 2563 group (dot-dashed line; Trinchieri, Fabbiano, & Kim 1997); see also the profiles in Lloyd-Davies et al. (2000). Real groups have entropy profiles that increase monotonically with radius, while for model “4” $S$ is uniform and model “3” shows a flat entropy core for $r < 300$ kpc. This behavior is due to the inefficiency of radiative cooling in the low density cores of these strongly heated groups.

Internal heating group models fall nicely among the observations in the $S-T$ plane (Fig. 3), regardless of the heating parameter $\nu$. Strong radiative cooling regulates the entropy in the central regions to have similar values for all adopted $\nu$. Radial entropy profiles are also consistent with observations (Fig. 3, bottom panel), although our models are somewhat denser overall with slightly lower $S(r)$.

3.3. Baryon fractions and cooling times

Models experiencing external preheating at very early times differ from those heated internally by SNII in several other respects. Notably, it appears that
internal heating removes baryons more efficiently than preheating at $z_h = 9$. We find for preheated groups that the baryon fraction at $r_{\text{vir}} \sim 900 \text{ kpc}$ is $f_b \sim 0.11$ for model “3”, almost equal to the cosmic baryon fraction assumed, 0.123. Only for the maximally preheated model “4”, is the baryon fraction significantly lower than the cosmic one: $f_b \sim 0.07$.

Groups heated internally by SNII have low baryon fraction even when a Salpeter IMF is assumed ($\nu = 1$): $f_b \sim 0.075$ ($f_b \sim 0.055$ for $\nu = 2$). The fraction of mass in gas at $r_{\text{vir}}$ is $\sim 0.04$ and $\sim 0.03$ for $\nu = 1$ and $\nu = 2$, respectively.

A further distinction between external and internal heating models is the central cooling time which, if lower than the age of the system, may indicate the presence of a cooling flow. We find that models with preheating strong enough to fit observations in the $L-T$ plot (models 3 and 4 in Fig. 1) never develop cooling flows (or, more precisely, never have $t_{\text{cool}} < \text{age}$), contrary to many observed groups and clusters. All internal heating models, instead, develop strong cooling flows. In particular, group models have $\dot{M} \approx 1 - 10 \, M_\odot \, \text{yr}^{-1}$.

4. Heating-enrichment connection

Both the external and internal heating scenarios seem to require more energy than that provided, via SNII, by the observed stellar content with a Salpeter IMF. A reasonable requirement may be $\sim 1 \text{ keV/particle}$ (a value consistent with most models proposed in recent years). SNII also produce metals, so we should ask: is the number of SNII needed to heat the gas consistent with the number of SNII necessary to produce the metal content of the universe?

A Salpeter IMF (from 0.1 to 100 $M_\odot$) produces $\sim 0.007$ SNII per $M_\odot$ of stars formed. Assuming a global star formation efficiency $\Omega_\star/\Omega_{\text{baryon}} = 0.1$ (Fukugita et al. 1998), we get $\epsilon \sim 0.22\nu \text{ keV/particle}$. Thus, to generate $\sim 1$ keV/particle we need $\nu \sim 5$.

The present day universe has a global iron abundance $<Z_{\text{Fe}}> \sim 0.3 - 0.4$ solar meteoritic units (Renzini 1997). Assuming again $\Omega_\star/\Omega_{\text{baryon}} = 0.1$ with an average Fe yield per SNII $<y_{\text{Fe}}> \sim 0.1 \, M_\odot$ (e.g. Gibson, Loewenstein, & Mushotzky 1997), the averaged metallicity produced by all SNII is $<Z_{\text{Fe}}>_{\text{SNII}}$.
0.053\(\nu\) solar. To make the observed metallicity, a high SNII production efficiency is needed: \(\nu \sim 5 - 6\) (this value would be reduced somewhat if SNIa contribute a significant fraction of iron). Thus, it appear that both heating and cosmic metallicity may be produced by a stellar population with \(\nu \approx 5\). The agreement between these two estimates of \(\nu\) supports SNII as the source of non gravitational heating. However, it should be noted that such a large production of SNII may be inconsistent with the chemical evolution of ISM in elliptical galaxies (Brighenti & Mathews 1999b).

5. Conclusions

*External heating* models fit the data in the \(L - T\) plot provided the preheating is sufficiently strong: \(\sim 1 - 4\) keV/particle, depending on \(z_h\). However, successful models in the \(L - T\) plane have entropies that exceed observed values (a cautionary note: we are well aware that our models are approximate, and it’s possible that less extreme preheating scenarios may overcome the problems pointed out by the present work). The competing models with *internal heating* by SNII fit the whole set of X-ray observations better and more plausibly, but they likely require a production of energy per unit of stellar mass larger than that based on a Salpeter IMF. This may not be a severe demand since the cosmic metallicity itself requires such a higher number of SNII per unit of stellar mass.

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