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Feedback from intra-cluster supernovae on the ICM in cooling flow galaxy clusters

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Abstract. We study the effect of heating and metal enrichment from supernovae (SNe) residing between galaxies on the Intra-Cluster Medium (ICM). Recent observations indicate that a considerable fraction (∼20%) of the SN Ia parent stellar population in galaxy clusters is intergalactic. By considering their effect on the relaxed progenitors of cooling flow clusters we propose that intra-cluster SNe can act as a distributed heating source which may influence the initial stages of the formation of cooling flows. We investigate the increase in cooling time as a function of the energy input supplied by SNe and their assumed spatial distribution, and conclude that intra-cluster SNe represent a heating source which in some clusters can cause a delay of the formation of cooling flows. This would imply that some cooling flows are younger than previously thought. We also discuss the impact that a large population of intra-cluster SNe could have on the chemical evolution of the ICM in cooling flow clusters.

Key words. supernovae: general – galaxies: clusters: general – X-ray: galaxies: clusters – cooling flows

1. Introduction

In the central regions of clusters of galaxies the gas density is often high enough that the radiative cooling time due to X-ray emission is shorter than the Hubble time. Therefore, without any balancing heating mechanisms, the gas should cool down and flow slowly inwards in order to maintain the hydrostatic equilibrium. Recent X-ray observations with *Chandra* and *XMM-Newton* (e.g. David et al. 2001; Johnston et al. 2002; Peterson et al. 2003 and references therein) have altered this simple picture of a steady cooling flow (for a review of the standard cooling flow model see Fabian 1994). The lack of observations of cooler gas represent an open question which is often referred to as the so called *"cooling flow problem"*. This topic is still lively debated and has recently triggered the development of a variety of theoretical models.

There are two main approaches to solve this problem. The first solution is that the gas does cool, but we do not observe it. Different possibilities have been investigated in this context, including absorption (Peterson et al. 2001; Fabian et al. 2001), inhomogeneous metallicity (Fabian et al. 2001; Morris & Fabian 2003), and the emerging of the missing X-ray luminosity in other bands, like ultraviolet, optical and infrared (due to mixing with cooler gas/dust, Fabian et al. 2001, 2002a; Mathews & Brighenti 2003), and radio (due particle re–acceleration, Gitti et al. 2002, 2004). The second solution is that an additional heating mechanism which balances the cooling is acting in the intra-cluster medium (ICM). Proposed heating mechanisms include heating through processes associated with relativistic AGN outflows (e.g., Rosner & Tucker 1989; Tabor & Binney 1993; Churazov et al. 2001;

Brüggen & Kaiser 2001; Kaiser & Binney 2002; Ruszkowski & Begelman 2002; Brighenti & Mathews 2003), electron thermal conduction from the outer regions of clusters (Tucker & Rosner 1983; Voigt et al. 2002; Fabian et al. 2002b; Zakamska & Narayan 2003), continuous subcluster merging (Markevitch et al. 2001), and contribution of the gravitational potential of the cluster core (Fabian 2003). In general, proposed heating sources face problems with the spatial distribution of the heating rate necessary to balance the cooling, which is a crucial requirement for a successful model. The further possibility of combining these two approaches has been investigated in the context of the moderate cooling flow model (Soker 2001, 2004), in which the heating does not completely balance cooling and the gas cools at lower rates, leading to a better agreement with the recent observations.

In this letter we discuss a novel approach in the context of the heating scenario – we consider intra-cluster supernovae as an energy source to delay the formation of cooling flows in relaxed clusters. The effect of heating by supernovae (SNe) in cooling flows has already been studied in previous works (e.g., Brighenti & Mathews 2003; McNamara et al. 2003), although the contribution of intra-cluster SNe has never been included. The existence of such a population of supernovae (SNe) is suggested by recent observations showing evidence of an intra-cluster stellar population (ICSP) in nearby clusters, which is also predicted by *N*-body simulations (e.g. Napolitano et al. 2003, and references therein). Feldmeier et al. (1998) found many intra-cluster planetary nebulae in the Virgo cluster while Theuns & Warren (1997) found the same for the Fornax cluster. Arnaboldi et al. (2003) used planetary nebulae in the Virgo

cluster as a tracer for the diffuse intra-cluster light and determined limits for the total luminosity of the ICSP. They find an amount of 10–40% of the total stellar population. Furthermore, a population of red giant stars in the Virgo cluster was discovered with HST observations (Ferguson et al. 1998) and even direct evidence for intra-cluster SNe was found (Gal-Yam et al. 2003). In general, these observations indicate that the ICSP consists of an old stellar population, therefore only SNe type Ia should occur there due to their long evolution time.

$H_0 = 50$ km s^{-1} Mpc^{-1} is used throughout the paper.

2. Feedback from intra-cluster SNe

2.1. Heating rate

As discussed in the Introduction, our approach to the cooling flow problem is to consider an energy source to delay the evolution of relaxed clusters (hereafter progenitor clusters) to cooling flow clusters. In the ideal case, a heating source which is able to supply the energy lost to X-rays on the same timescale of the emission process would completely prevent the formation of cooling flows. Note that this approach is different from a scenario stopping cooling flows after they have long been established. Here we suggest that intra-cluster SNe may contribute to that heating source. Indeed, their rate is not triggered by cooling flows themselves and therefore, contrarily to other heating sources (e.g. AGNs), intra-cluster SNe can act also in the progenitor clusters. Four main reasons support our general idea: 1) new observations show that a considerable fraction (~20%) of the SN Ia parent stellar population in clusters is intergalactic (Gal-Yam et al. 2003); 2) SNe exploding in the ICM can heat the ambient medium very efficiently and their metal rich material will be ejected directly into the ICM; 3) intra-cluster SNe provide a distributed heating source; 4) SN heating can act over a long period of time.

To investigate whether intra-cluster SNe can have a significant impact on the evolution of the progenitor clusters, we compare the energy lost by these clusters in a Hubble time with the energetics of SN heating. One way to estimate the X-ray emission of the progenitor clusters is to start from observations of cooling flow clusters and extrapolate the fit of the surface brightness in the outer regions (regions out of the cooling radius are unaffected by the cooling flow) to the center. Note that this results in a flat density distribution in the central region of the cluster. In particular, by adopting the density distribution derived in this way and the cluster temperature observed outside the cooling region, we determine the X-ray luminosity up to a certain radius by integrating over the X-ray emissivity. X-ray luminosities are multiplied by 10^{10} years to compare them with the SN heating provided in a Hubble time. To get an impression of the importance of this effect we give here two examples. Values are derived in the central 130 kpc. Input parameters are in brackets. 1. Perseus cluster ($T = 6.2$ keV, core radius: $r_c = 280$ kpc, $\rho(0) = 4.05 \times 10^{-3}$ cm^{-3}, $\beta = 0.87$; Churazov et al. 2003): $L_X \sim 6.8 \times 10^{43}$ erg/s or $\sim 2.1 \times 10^{61}$ erg in 10^{10} years. 2. Centaurus cluster ($T = 3.4$ keV, $r_c = 110$ kpc, $\rho(0) = 2 \times 10^{-3}$ cm^{-3}, $\beta = 0.66$; values were derived from

Allen & Fabian 1994 and Sanders & Fabian 2002): $L_X \sim 1.4 \times 10^{43}$ erg/s or ~4.4×10^{60} erg in 10^{10} years.

The energetics of SN heating can be estimated from the central abundance peak observed in cooling flow clusters. Various authors argued that most of the central iron abundance is produced by SN Ia (e.g. Böhringer et al. 2004) therefore we calculate the heating due to SN Ia by assuming an iron production of 0.7 $M_\odot$ per SN (e.g. Renzini et al. 1993). As most of the energy from SNe exploding into the thin hot ICM will be transformed into thermal energy, a typical SN Ia will deposit a total energy of the order of ~10^{51} erg in the ICM (a detailed discussion on SN remnants in hot thin environments can be found in Dorfi & Völk 1996). On this basis Sasaki (2001) already proposed intra-cluster SNe as a possible extra energy source in clusters. By adopting the iron excess found by Böhringer et al. (2004) in the central 130 kpc[1] we derive the number of SNe necessary to produce it and then, by knowing the energy injected per SN, we calculate the total energy provided. For the two examples we find: 1. Perseus cluster: ~2.4×10^9 $M_\odot$ Fe, ~3.4×10^9 SNe Ia leading to a total heating of ~3.4×10^{60} erg. 2. Centaurus cluster: ~1.4×10^9 $M_\odot$ Fe, ~2×10^9 SNe Ia leading to a total heating of ~2×10^{60} erg. This corresponds to ~16% (Perseus) and ~45% (Centaurus) of the energy emitted in X-rays by the progenitor clusters. So, while in Perseus the effect is not so important, in the case of Centaurus the additional heating by SNe may be significant. In general, the importance of the effect will depend on the particular cluster.

Note that the complete compensation of the energy loss would be in disagreement with the observations which show that the ICM – at least at some level – does cool.

In the previous estimate we did not discriminate between the iron contribution by galactic and intra-cluster SNe. Even though the distinction between the remote envelopes of the cD galaxy and the ICSP may simply be a matter of semantics (Gal-Yam et al. 2003), we stress that the fraction of iron produced by intra-cluster SNe will be significantly higher than 20%, as a substantial part of the iron produced by galactic SNe will remain in their host galaxies. SNe explosions associated with the cD galaxy stellar population will also contribute to that heating (McNamara et al. 2003; Wise et al. 2004). The SN rate for SN Ia might be even higher in the past by a factor of 10 (Renzini et al. 1993) which will also have an important impact on the time dependence of the problem.

In our model we consider a single phase ICM of the progenitor cluster so the X-ray emission, which is $\propto \rho^2$, is mainly a function of the distance r. The density distribution $\rho(r)$ is described by a β profile (Cavaliere & Fusco-Femiano 1976). Different distributions of SN heating rate are described with King profiles with variable exponent which can be written in a similar way as the β model:

$$H_{SN}(r) = \frac{H_{SN}(0)}{[1 + (r/r_c)^2]^{3\beta_{SN}/2}}. \tag{1}$$

Here $H_{SN}(r)$ is the radial dependence of the SN heating rate, r_c is the core radius and β_{SN} controls the outer slope of this distribution.

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[1] Quantities were scaled accordingly to the value of H_0 adopted.
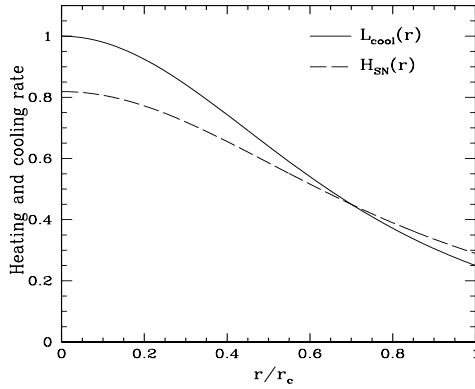
Fig. 1. An example of the spatial distribution for intra-cluster SN heating rate and cooling rate due to X-ray emission. Both profiles are normalized to the same total energy when integrated over the core region of the cluster. The units on the *y*-axis are in arbitrary linear scale. For the cooling profile a β model for the density with a β_ρ of 0.66 is chosen, while for the SNe distribution a King profile with $\beta_{SN} = 1$ is used.
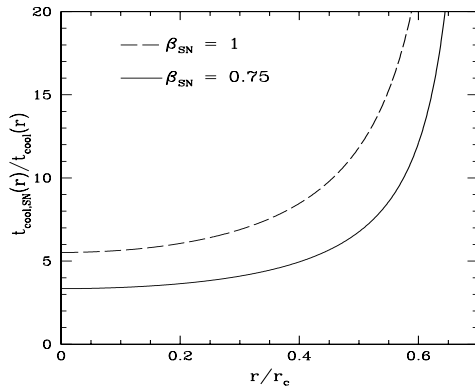
Fig. 2. The radial dependence of the introduced cooling time in units of the cooling time t_{cool}. The two curves correspond to different β_{SN} for two different SN distributions.

In order to investigate the effect of intra-cluster SNe on cooling flows, we introduce the cooling time $t_{cool,SN}$ which takes into account the heating contribution from these sources:

$$t_{cool,SN}(r) = \frac{E_{th}(r)}{L_X(r) - H_{SN}(r)} \qquad (2)$$

where E_{th} is the thermal energy of the ICM, L_X is the X-ray luminosity and H_{SN} is that of Eq. (1).

Because of its dependency on the square of the density, the X-ray emission will be more peaked towards the cluster center with respect to the SN heating rate. By normalizing such that the total energy input due to SN heating (integrated over the cluster core region) balances the total X-ray luminosity (as an ideal case where heating balances cooling), this means that for any realistic density and SNe distribution the energy loss due to cooling is more efficient than the SN heating rate near the cluster center whereas the SN heating rate dominates at bigger radii (see Fig. 1).

The radial dependence of our defined cooling time is shown in Fig. 2, where we plot $t_{cool,SN}(r)$ as a fraction of the cooling time $t_{cool}(r)$ calculated without the heating contribution.

Under these assumptions we find that the SN heating rate will not prevent the cluster center from cooling, but it will
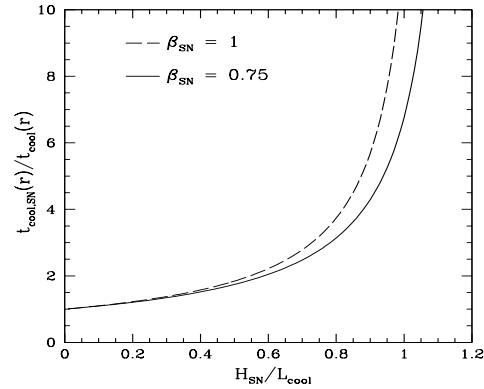
Fig. 3. The delay of the cooling process relative to an undisturbed formation of a cooling flow. On the x axis the fraction of total heating energy in units of the total energy loss due to cooling is shown. The two curves correspond to different β_{SN} for the SN distributions. Results are given for a radius of 0.5 core radii. For the density distribution $\beta_\rho = 0.66$ is chosen.

lengthen the timescale on which the gas cools. The importance of this effect can vary from cluster to cluster, depending on the energy input supplied by SNe and their assumed spatial distribution. To show this, we plot the increase in cooling time for various parameters (Fig. 3). For example, by assuming $\beta_{SN} = 1$ a total SNe heating rate corresponding to a fraction ~0.6 of the total X-ray luminosity would produce a factor of 2 increase in cooling time, which can be very important for the outers parts of a cluster core (Fabian et al. 2003).

As a result of these considerations, we conclude that intra-cluster SNe can provide an extended heating input into the ICM. The significance of this additional heating depends on the particular cluster, as we showed in two different examples, and in some cases it may cause a delay of the cooling process. This would imply that some cooling flows are younger than previously thought, as already argued by several authors (e.g. Allen et al. 2001; Johnston et al. 2002).

2.2. Iron enrichment

In Sect. 2.1 we estimated the SN heating from the observed iron masses in the central regions of cooling flows. We point out that the observed iron masses might be lower limits to the total amount of iron produced, because some of the iron might be deposited by fueling the central AGN and star formation (McNamara et al. 2003). This would mean that the energy injected might be higher than estimated from the iron mass.

Another consequence of the presence of a large population of intra-cluster SNe could be that of producing a metallicity gradient in the ICM of cooling flow clusters, which is an alternative view to the scenario where the central abundance peak originates from the stellar population of the cD galaxy (Böhringer 2004). Indeed, a gas flow passing SN explosions will be loaded with iron thus resulting in a central abundance peak when moving towards the cluster center. Different distributions of SNe and gas density will lead to a similar effect. We stress that metallicity gradients are in fact observed in cooling flow clusters (e.g., De Grandi & Molendi 2001), even though a

more detailed model with various enrichment processes (ram-pressure stripping, galactic winds, etc.) would be required in order to compare directly the predicted metallicity gradient with that observed.

Finally, we note that material from SNe exploding in between the galaxies will eject the iron directly into the ICM. Therefore, the remnants of intra-cluster SNe may end up as highly enriched bubbles in the ICM and this could result in rapid cooling of the highly enriched material (Fabian et al. 2001; Morris & Fabian 2003).

3. Conclusions

In this paper we investigate the feedback from intra-cluster SNe on the ICM in cooling flow clusters. By considering their effect on the relaxed progenitors of cooling flow clusters we suggest that intra-cluster SNe represent a heating source for the ICM: the significance of this additional heating depends on the particular cluster and in some cases it may cause a delay of the formation of cooling flows. In general the proposed scenario does not solve the cooling flow problem, so another heating mechanism is needed (e.g. AGNs). However, since intra-cluster SNe can act as a distributed heating source once the cooling flow has started, they may represent an interesting complement to heating models which consider central AGN activity. Intra-cluster SNe might also have a remarkable impact on the chemical evolution of galaxy clusters and explain the presence of metallicity gradients in cooling flows. Recent observations of a population of intra-cluster SNe (Gal-Yam et al. 2003) and the high efficiency of SN heating rate in an ambient hot, thin medium support our general idea. Numerical simulations show that the ICSP originates from tidal debris caused by galaxy-galaxy and galaxy-cluster interaction (Napolitano et al. 2003). One important open question in connection with the model is: will tidal interaction between galaxies disrupt or enhance the SN Ia formation mechanisms? Gal-Yam et al. (2003) conclude that the intra-cluster SN Ia rate should be comparable to the SN rate found in galaxies. The critical points for our model are the spatial distribution of the SNe and the SN rate, which both strongly influence the heating scenario. More observations of the ICSP and a more detailed modelling are required in order to reach a better understanding of this problem.

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