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Implications of the central metal abundance peak in cooling core clusters of galaxies

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Abstract. Recent XMM-Newton observations of clusters of galaxies have provided detailed information on the distribution of heavy elements in the central regions of clusters with cooling cores providing strong evidence that most of these metals come from recent SN type Ia. In this paper we compile information on the cumulative mass profiles of iron, the most important metallicity tracer. We find that long enrichment times (≥5 Gyr) are necessary to produce the central abundance peaks. Classical cooling flows, a strongly convective intracluster medium, and a complete metal mixing by cluster mergers would destroy the observed abundance peaks too rapidly. Thus the observations set strong constraints on cluster evolution models requiring that the cooling cores in clusters are preserved over very long times. We further conclude from the observations that the innermost part of the intracluster medium is most probably dominated by gas originating predominantly from stellar mass loss of the cD galaxy.

Key words. clusters of galaxies – cooling flows – supernovae – chemical evolution

1. Introduction

Since the discovery of the iron emission line in the thermal spectra of the intracluster Medium (ICM) in clusters of galaxies (Mitchell et al. 1976), the abundances of the heavy elements in the ICM received much attention and provided insights into the star formation history in the cluster volumina. The large amount of iron implied that the cluster galaxies must have lost a large fraction of the iron produced during their star formation histories to the ICM. The total iron mass in the ICM is in fact larger than the total iron mass in all cluster galaxies. Attempts to model the production of the observed iron masses on the basis of the observed present day stellar population have shown that such models have to make maximizing assumptions like a top heavy IMF in early epochs of star formation to increase the number of historic SN II (Arnaud et al. 1992; Elbaz et al. 1993) or an increased rate of type Ia supernovae in the past (Renzini et al. 1993).

In this paper we concentrate on the implications of the heavy element abundances in the central regions. With the ASCA satellite observatory which provided the first possibility of spatially resolved spectroscopy of the cluster ICM it was found that some clusters with cD galaxies had a strong increase in the metal abundance towards the center (Fukazawa et al. 1996, 2000; Matsumoto et al. 1996; Matsushita et al. 1998; Ikebe et al. 1999). With similar results from BeppoSAX DeGrandi & Molendi (2001) and DeGrandi et al. (2003) showed that these iron abundance peaks are a signature of so-called cooling flow clusters, cluster with a very peaked X-ray surface brightness profile and thus a high central gas density, which we term cooling core clusters in this paper. Again with observational data from ASCA, Finoguenov et al. (2000) could derive abundance profiles of Fe and Si and could show that the central regions in those clusters with metal abundance peaks where strongly enriched in iron while the bulk volume of the clusters outside the central region had an iron-to-silicon ratio close to the yields of SN type II. This implies that the central excess seen in cooling core clusters is most probably due to enrichment by SN type Ia in the cD galaxies.

Now with the improved capabilities of the XMM-Newton satellite observatory as well as with the Chandra observatory, more detailed information on the origin, the metal source distribution, and the ICM transport history can be obtained. In this paper we compile information on the central element abundance profiles from four nearby clusters observed with XMM and interpret the results. We discuss the origin of the X-ray emitting gas in terms of the enrichment by supernovae type Ia and whether it should be considered to be the interstellar medium of the central galaxy or the cluster ICM. We calculate the time it takes to produce the Fe abundance peak and

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discuss the implications of the implied large enrichment times for the cluster evolution history.

Throughout the paper we use a Hubble constant of $h_{70} = 1$ where $h_{70} = H_0/70$ km s^{-1} Mpc^{-1}. The other cosmological parameters play not significant role at the relevant distances. The Virgo distance is assumed independently of H_0 as 17 Mpc.

2. Origin of the metal abundance peak

Recent XMM-Newton observations of M 87 (Böhringer et al. 2001; Matsushita et al. 2002, 2003a; Molendi & Gastaldello 2001; Gastaldello & Molendi 2002) have yielded radial abundance profiles for the M 87 halo region in the center of the Virgo cluster of the seven elements, O, Mg, Si, S, Ar, Ca, Fe. This provides a finger print of the origin of the metals. Since O and Mg are essentially only produced by SN II, the observed flat central O abundance profile is a strong further confirmation of the dominant SN Ia contribution to the central abundance peak. In an analysis by Finoguenov et al. (2002) using in one approach e.g. the oxygen abundance profile to separate the SN II and SN Ia products it was shown that SN II contributed only about 10% to the central iron abundance, corresponding to abundance values of 0.1 to 0.15 in solar units. The contribution by SN Ia yields an Fe abundance of at least 1 in solar values. The SN II abundance contribution in the center of Virgo can also be compared to the iron abundances in the outer regions of clusters, where SN II enrichment dominates (Finoguenov et al. 2000; DeGrandi & Molendi 2001) with typical iron abundances of about 0.2 of the solar value. Here some contribution comes also from SN Ia. Therefore, we conclude that very roughly a fairly homogeneous distribution of iron with an abundance of at least 0.15 solar prevails in these clusters.

3. Iron mass contained in the abundance peak

To further explore the origin of the central abundance peaks we calculate the total iron mass profiles, $M_{\rm Fe}(\leq r)$, for the clusters Virgo, Centaurus, Perseus, and A1795 from the gas mass profiles and the Fe abundance profiles as given by Matsushita et al. (2003, 2004), Churazov et al. (2003), Ikebe et al. (2003; see also Tamura et al. 2001), respectively. These abundance profiles for the central 200 kpc are shown in Fig. 1 with abundances given in solar units based on the solar Fe abundance quoted by Feldman (1992). Similar results are also reported from the analysis of Chandra observations showing very good consistency with the results used here (Sanders et al. 2003; Sanders & Fabian 2002; Ettori et al. 2002). For the Virgo and Centaurus cluster we use the abundances derived for the multi-temperature models. The higher abundances found for the two- and three temperature modeling only matter for the very central regions in these two clusters. The gas mass profiles were also compared to other previous results (e.g. Reiprich & Böhringer 2002) and were found to be in good agreement.

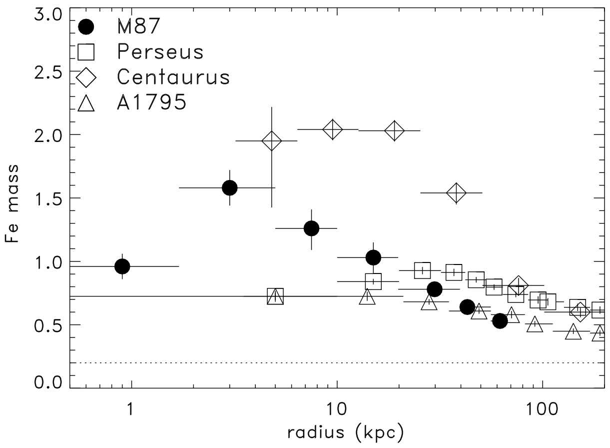

Fig. 1. Iron abundance profiles measured in the four nearby galaxy clusters, M 87/Virgo, Perseus, Centaurus, and A1795. The data are taken from Matsushita et al. (2003), Churazov et al. (2003), Matsushita et al. (2004), Tamura et al. (2001), respectively. The values are in solar units based on the solar abundance of iron quoted by Feldman (1992). The dashed line shows the iron abundance with a value of ~0.2 solar, observed on large scale in clusters and assumed to come mostly from SN II enrichment before cluster formation.

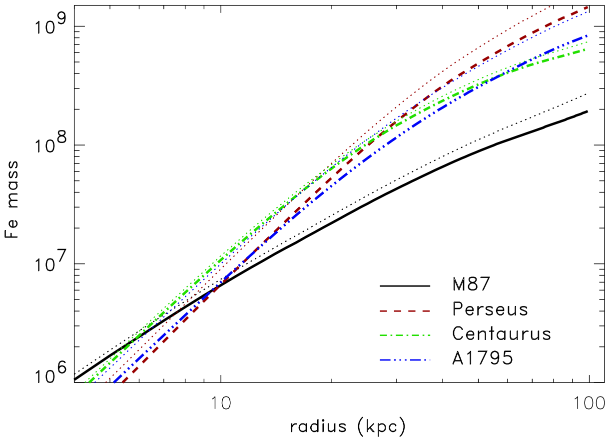

Fig. 2. Cumulative iron mass profiles in the centers of four nearby galaxy clusters. The thin dotted lines show the total iron mass and the thick lines show the iron mass in the central excess where a mean abundance of 0.15 solar was subtracted.

The results in Fig. 2 show as thin dotted lines the total Fe mass profiles and as solid lines the profiles for the iron abundance excess, where an ubiquitous Fe abundance of 0.15 of the solar value was subtracted. As shown in Fig. 2 the widely distributed Fe component (which we assume to come from an early enrichment by mainly SN II mostly before the formation of the cluster) is truly a minor fraction inside a radius of 50 kpc. (If the very central ICM inside 10 kpc originates only from stellar mass loss as argued below, the thick lines underestimate the recently produced Fe mass by a very small amount.) We note that the iron masses in the abundance excess are quite large. Inside 10 kpc, a radius that is for example of the order of the scale radius of the giant elliptical galaxies, we find that the Fe masses span a narrow range from about 6 to 10×10^6 $M_\odot$. At a radius of 50 kpc, where in terms of the total stellar light the central galaxy is still completely dominant, M 87 features a smaller Fe mass of about 10^8 $M_\odot$ while the more massive clusters show values in the range 3 to 5×10^8 $M_\odot$. The smaller Fe mass in the M 87 halo is due to the smaller total gas mass concentrated around M 87 compared to that of the larger clusters. Also M 87 is the least luminous central galaxy in this sample.

4. ISM or ICM?

It may be to some extent semantic to distinguish the interstellar medium of the central galaxy from the intracluster medium, since in X-ray images we observe one continuous hot gaseous halo trapped in the common potential well of the central galaxy and the cluster. It has a very smooth surface brightness distribution and temperature profile showing no break, which could lead us to draw a boundary between two distinct media. Therefore the distinction has to be made on the basis of the composition.

We take M 87, which has by far the best data, as a study case and concentrate on the inner 10 kpc. We find a total gas mass of about $2 \times 10^9\ M_\odot$, which can be replenished by stellar mass loss, taking a rate as proposed by Ciotti et al. (1991, of about $2.5 \times 10^{-11}\ L_B$ – assuming a galactic age of 10 Gyr) in about 2−3 Gyrs. Also the total iron mass of about $6 \times 10^6\ M_\odot$ can be produced by the SNIa rate of 0.15 SNU (Cappelaro et al. 1997, 1999) and stellar mass loss from the stellar population of M 87 (contributing about 40%) in this time. Furthermore as shown by Matsushita et al. (2003) the Mg abundance in the very center approaches that of the stellar population. Taking these three facts together the gaseous halo of M 87 and its composition in the inner 10 kpc can very well be explained by stellar mass loss, that is an ISM nature, if it has been produced without disturbance in the last 2−3 Gyrs. The cooling time of this gas is less than 2 Gyrs, however, and the mass loss by a traditional cooling flow would be an important sink for this medium with losses faster than the replenishment by stellar mass loss. Since this traditional cooling flow picture with large mass deposition rates is not supported by the recent XMM-Newton and Chandra observations (e.g. Tamura et al. 2001; Peterson et al. 2003; Böhringer et al. 2002), this also implies that the gas is not cooling at the maximal allowed cooling rate. Therefore the gas in the central region can be considered as ISM and the neighbouring region outside as a mixture of ISM and ICM.

5. Enrichment ages for cD halos in galaxy clusters

For the further understanding of the enrichment and transport processes in these environments we introduce the concept of enrichment time of the central ICM. We take the excess iron abundance as the enrichment tracer. We assume that Fe is introduced into the ICM by input from SNIa explosions and by stellar mass loss from a stellar population heavily enriched in Fe. The enrichment time, $t_{\rm enr}$, is calculated by means of the formula

$$t_{\rm enr} = M_{\rm Fe} \times \left[L_B \left(SR\ 10^{-12} L_{B\odot}^{-1} \eta_{\rm Fe} + 2.5 \times 10^{-11} L_{B\odot}^{-1} \gamma_{\rm Fe}\right)\right]^{-1}$$

where L_B is the galaxy blue luminosity inside r, SR is the SN Ia rate in SNU, $\eta_{\rm Fe}$ is the iron yield per SN Ia ($0.7\ M_\odot$), and $\gamma_{\rm Fe}$ is the mean iron mass fraction in the stellar winds (2.8×10^{-3}) for a mean stellar iron abundance of about 1.6. The light profile of the central galaxies was obtained from Giraud (1999) for M 87, from Schombert (1988) for NGC 1275, and we used the generalized model from Schombert (1986) together with the total luminosity for the central galaxies of Centaurus (NGC 4696) and A1795. The value for the total luminosity of A1795 was taken from the *I*-band observation of Johnstone et al. (1991).

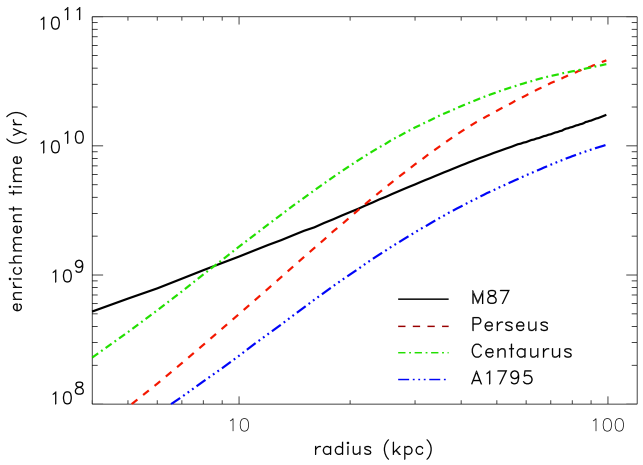

Fig. 3. Enrichment ages of the central iron abundance peak in the four galaxy clusters, M 87/Virgo, Centaurus, Perseus, and A1795. The enrichment times were calculated on the basis of a SN Ia rate of 0.15 SNU (Capellaro et al. 1999) and an additional contribution by stellar mass loss.

Figure 3 shows the derived enrichment times. While inside 10 kpc the enrichment times are typically less than 2 Gyrs, the times become quite large at the 50 kpc radius. While for A1795 and M 87 we find about 5 and 9 Gyrs the enrichment times exceed the Hubble time for Centaurus and Perseus. The relatively short time for A1795 comes as a consequence in the calculations of the very luminous central galaxy.

Alternatively, we can adopt an increased SN Ia rate, $R(t)$, in the past as assumed in e.g. Renzini et al. (1993), often modeled by a power law behavior

$$R(t) = R_0 \left(\frac{t}{t_0}\right)^{-s}.$$

We explore two models with $s = 1.1$ and 2 ($t_0 = 13$ Gyr). The latter model has a more extreme exponent than used in Renzini et al. which is here meant to represent a bracketing solution. The so determined enrichment times are shown in Fig. 4. The most important contribution now is happening at the earliest times, which results in a flattening of the curves. At a radius of 50 kpc the different examples converge to a narrow age span of 5−9 (6.4−11) Gyr, with the exception of A1795 which yields about 3.5 (3.9) Gyrs for the $s = 2$ ($s = 1.1$) model. We therefore conclude that unless the supernova rate for SN Ia increases in the past we cannot explain the production of the iron peak, but we do net get further constraints for the parameter s other than it needs to be at least close to one.

DeGrandi et al. (2003) also discuss in detail the origin of iron abundance peaks in the centers of clusters, taking a different look at this phenomenon, however. While we have concentrated here on the inner region of the abundance peak and on the

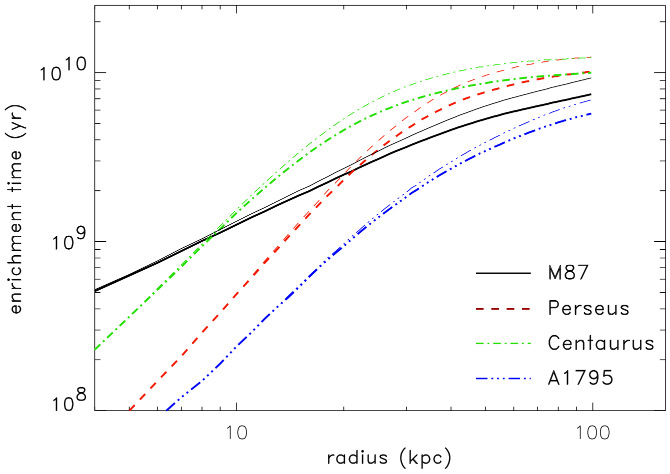

Fig. 4. Enrichment ages of the central iron abundance peak in the four nearby galaxy clusters for the case of a steeply increasing SN type Ia rate in the past (the thick lines are for an evolutionary exponent $s = 2$ and the thin lines for $s = 1.1$.).

recent enrichment by SN Ia (motivated by the abundance pattern described in Sect. 2), these authors describe the total iron mass of the central abundance excess streching over a range of at least 200−300 kpc. Consequently they find higher values for the excess iron mass, typically $1{-}4 \times 10^9\ M_\odot$. To explain the creation of this abundance peak, they investigate the total iron ejection of the central galaxy over its lifetime based on the modeling of Pipino et al. (2002) including both supernovae type II and type Ia and find that the total iron production is sufficient to account for the observed central excess. This is covering a much larger time span including the early epoch of SN II enrichment which lays mostly before the formation of the cluster. It also implies a different element composition for the large scale abundance peak than we find for the innermost part.

6. Implications for cluster cooling flows

Turning again to the classical cooling flow picture, we can with the given observed parameters and with the known mass deposition profiles calculated in the classical way for cooling flow models (e.g. Allen et al. 2001) determine the iron mass loss rate from the ICM due to mass deposition for a steady state situation and the given abundances. The derived iron depletion times inside a radius of 50 (10) kpc are smaller by factors of 1 (2), 6 (1), 6.5 (8), 1.5 (0.3) compared to the enrichment times for M 87, Perseus, Centaurus, and A1795, respectively. Therefore it seems very difficult to sustain the very large central iron concentrations in the frame of the classical cooling flow model with large mass deposition rates. Reduced mass deposition rates suggested by recent observations (e.g. Petersen et al. 2003) would not strongly affect the above enrichment picture, however.

7. Implications for other ICM transport histories

The long enrichment times also put constraints on any disturbances of the central regions of the clusters. A first disturbance could be provided by the proposed heating models of cooling core regions by AGN. If e.g. the heating model by bubbles of relativistic plasma from radio lobes, as proposed by Churazov et al. (2000, 2001), leads to a large convective motion covering the full cooling core region, gas could be transported around in a circle in a few Gyr. This would tend to flatten the observed steep abundance profiles. Numerical simulations as performed e.g. by Brüggen (2002) where the effect of buoyantly rising bubbles was studied in the presence of tracer particles show that the convection induced in the ambient gas by the relativistic plasma bubbles may be more "differential", such that individual gas parcels are only dragged along for shorter distances. Only such a gentle motion would be consistent with the observed gas profiles. Other proposed heating mechanisms for cooling cores, not relying on convection, like heating by viscous sound or weak shock waves (Fabian et al. 2003; Ruszkowski et al. 2003; Forman et al. 2003) would not affect the steep observed abundance gradients.

Finally the observations also put strong constraints on the effects of cluster mergers on the cooling cores of clusters. Traditionally cluster mergers are believed to destroy cooling flows (e.g. McGlynn & Fabian 1984). Allen et al. (2001) has calculated cooling flow ages on the basis of the comparison of the spectroscopically inferred mass flow rates with those rates determined from the surface brightness distribution and finds cooling flow ages of the order of a few to several Gyr. This is consistent with the merger frequency expected to be a few Gyr (e.g. Schuecker et al. 2001). The above analysis suggests that the cooling cores are in general older than the time to the last major merger. This implies that most mergers may not destroy the cooling cores. Specificly, more rare merger configurations with roughly equal mass partners and both with dense cores may be required for an effective cooling core disruption and the cooling core clusters we see today may never have suffered from such an event, while clusters like e.g. Coma have. The difficulty of disrupting the cluster core by a merger was also pointed out by Churazov et al. (2003) in a different context. For a formation scenario for cooling cores which is alternative to cooling flow models see also Motl et al. (2003). The enrichment ages also provide a lower limit on the age of the central region of the cluster, but a definitive age estimate has to await a more precise picture of the enrichment history to develop.

8. Summary and conclusions

The large metal abundance excesses in cooling core regions of clusters of galaxies indicate that large enrichment times are necessary to create them. For the four examples studied here, the Virgo, Perseus, Centaurus, and Abell 1795 clusters, we find enrichment times of about 4−10 Gyrs for the central 50 kpc radius region. Thus we conclude that the dense cooling cores in clusters are very persistent phenomena. These studies can easily be expanded to a larger sample of clusters to test if these conclusions hold in general. But since very similar abundance gradients are observed for most cooling core clusters we expect that this will be the case. A more detailed study of the abundance ratios of several tracer elements will also provide more detailed information on the enrichment history by the different SN types as well as on the possible secular evolution of the SNIa.

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