Gas in Groups and Clusters of Galaxies

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Abstract. Groups and clusters contain a large fraction of hot gas which emits X-ray radiation. This gas yields information on the dynamical state and on the total mass of these systems. X-ray spectra show that heavy elements are present in the gas. As these metals must have been produced in the cluster/group galaxies and later transported into the gas, the metallicity is a good tracer for the transport processes. Several possible processes, that transport gas from the small potential wells of the galaxies into the clusters and groups, are discussed.

Keywords:

1. Gas properties

Clusters and groups of galaxies do not only contain galaxies but all the space between the galaxies is filled with hot gas. This gas is also often referred to as intra-cluster medium (ICM) or intra-group medium (IGM). The high temperature of the gas of 1 -10 keV is in good correspondence with the depth of the potential wells of groups and clusters (see Table 1). According to the shallower potential of groups also the temperature is lower in groups ($\approx$ 1 keV) compared to clusters (3-10 keV). The gas is almost fully ionised and has very low densities of $10^{-2} - 10^{-4}$ cm^{-3} decreasing outwards. It is optically thin. In the spectra of both, groups and clusters, lines of heavy elements have been detected corresponding to metallicities of about 0.2 to 0.4 in solar units. These metals indicate that the gas cannot be of purely primordial origin, but part of it must have been previously the inter-stellar medium (ISM) in galaxies and then it must have been transported from the galaxies into the ICM and IGM, respectively, by certain processes. The processes will be discussed in the next section.

Gas with such properties emits thermal bremsstrahlung in the X-ray range (see Table 1). Therefore groups and clusters are currently studied extensively by the X-ray observatories XMM and CHANDRA. While in almost all of the clusters X-ray emission has been found, the X-ray emission from groups is somewhat harder to detect due to their lower luminosity. So far in about 50% of the nearby groups X-ray emission has been found.

Table I. Properties of the gas in cluster and groups of galaxies.

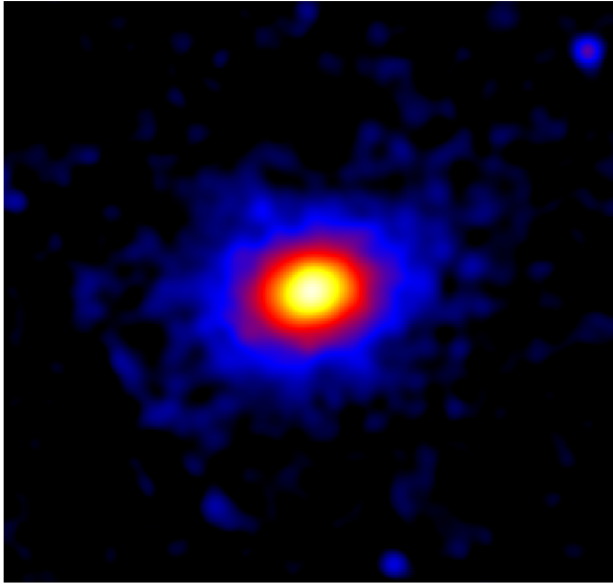|	Clusters	Groups
Temperature	3-10 keV	≈ 1 keV
Extent	few Mpc	0.1-1 Mpc
Metallicity	0.2-0.4 solar	0.2 solar
X-ray luminosity	10^{43-45} erg/s	10^{42-43} erg/s

Figure 1. CHANDRA image of the cluster RBS797 (from Schindler et al. 2001). The cluster looks well virialised with a very regular surface brightness distribution.

2. Gas distribution, dynamical state and mass determination

Two examples of X-ray emission from clusters of galaxies are shown in Figs. 1 and 2. The cluster RBS797 (Fig. 1) has a very regular shape on this scale with a somewhat elongated structure. This is a typical relaxed cluster. The cluster CL0939+4713 (Fig. 2) has a very different, irregular morphology. In the XMM image one can distinguish clearly two main subclusters. These subclusters show even some internal structure. Obviously the cluster is not in an equilibrium state, but there are still some structures visible that are in the process of falling into the cluster. So already the X-ray morphology contains a lot of information about
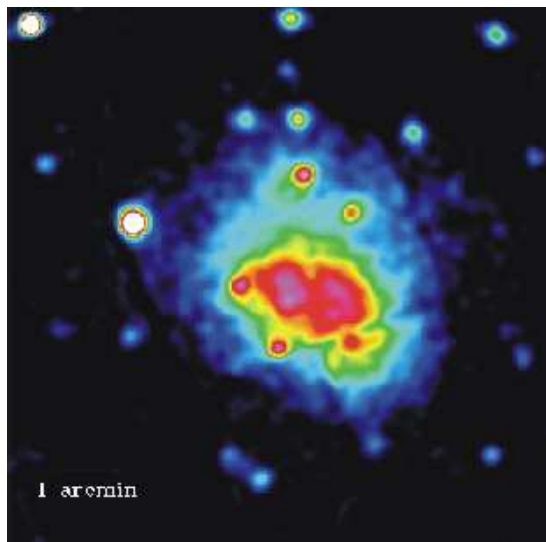
Figure 2. XMM image of the cluster CL0939+4713 (from De Filippis et al. 2002). Two subclusters are visible with even some internal structure indicating that the cluster is in a merger process.

the dynamical state of the cluster. But X-ray spectroscopy tells even more. In Fig. 3 the temperature distribution of the gas in CL0939+4713 is shown. There is a hot region between the two subclusters which is an indication that the subclusters are approaching each other – just as it is expected from hydrodynamic simulations (Schindler & Müller 1993; Ricker & Sarazin 2001; Ritchie & Thomas 2002): when two subclusters start to merge the gas between them is compressed and heated, so that a hot region is produced. Therefore we conclude that this cluster in the beginning of a major merger process (De Filippis et al. 2002).

Also groups show extended emission coming from the IGM as it can be seen e.g. in HCG16 (Belsole et al. 2002) or in HCG90 (Longo et al. 2002). In groups the extended emission from the IGM is not so dominant as in clusters. One can usually see different components in the X-ray emission. Apart from the extended IGM also more compact components caused by galaxies and other sources can be seen.

The mass of the ICM and IGM is not negligible compared to the other components. Table 2 gives an overview of the mass fraction of gas, galaxies and dark matter in groups and clusters, respectively. In clusters there is always considerable more mass in the gas than in the galaxies, while in groups the mass in the galaxies usually exceeds the mass in the gas. Both systems have in common that most of the mass is in form of dark matter. This shows how important mass determination
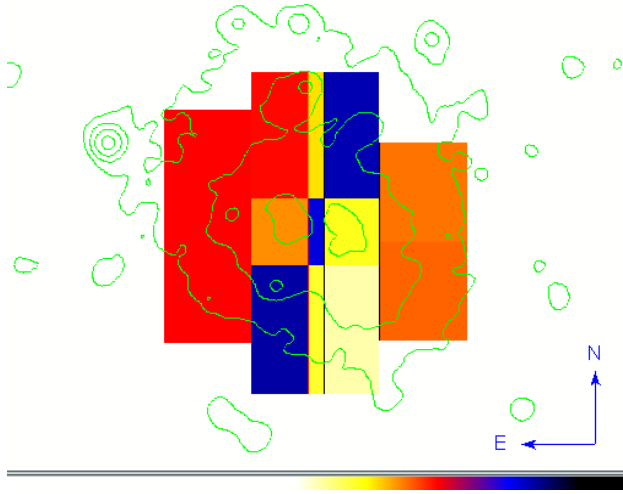
Figure 3. Temperature map of the cluster CL0939+4713 (from De Filippis et al. 2002). The temperature is increasing from yellow over orange and red to blue. The contours show the same surface brightness distribution as in Fig. 2. Between the two subclusters a region of hot gas is visible indicating that the subclusters are approaching each other.

Table II. Mass fraction of the different components in clusters and groups of galaxies

	Clusters	Groups
Galaxies	3-5%	3-20%
Gas	15-20%	2-10%
Dark matter	rest	rest

is. When the total mass of the system can be measured and the visible components are subtracted, the amount and distribution of the dark matter can be inferred.

There are different ways to determine masses, one of them is the X-ray method. With two assumptions – spherical symmetry and hydrostatic equilibrium – the X-ray emitting gas can be used as a tracer for the total potential. Only the gas density and the gas temperature are required for this method, which can both be measured from X-ray observations.

With the gas density also the gas mass is known. The ratio between gas mass and total mass is the gas mass fraction. In Fig. 4 the gas mass fraction is plotted versus the radius. We find that the gas mass fraction
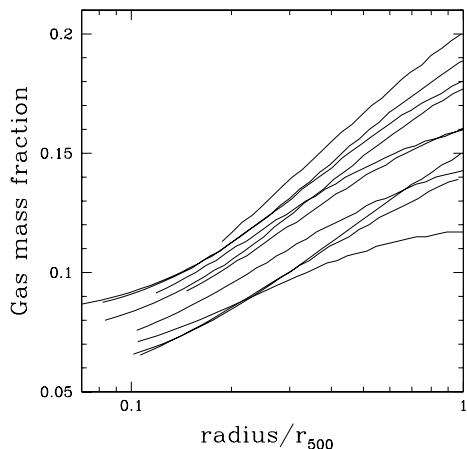
Figure 4. Gas mass fraction versus radius. For all the clusters the gas mass fraction increases with radius, i.e. the gas distribution is more extended than the dark matter distribution (from Castillo-Morales & Schindler 2002).

is not constant but is increasing with radius (Schindler 1999; Castillo-Morales & Schindler 2002) . That means that the gas is more extended than the dark matter. Obviously, there is not only gravitational energy from the collapse present but there must be additional heating processes at work like e.g. supernova-driven winds. Also interesting is the question whether the gas mass fraction is changing with time. In Fig. 5 the gas mass fraction is shown for nearby and distant cluster samples. So far no significant evolution is detectable.

The gas mass fraction can also be used to derive an upper limit on the matter density of the universe Ω_m. Assuming that the matter accumulated in a cluster is representative for the universe as a whole, the ratio between the mass in baryons and the total mass $M_{gas}/M_{tot} \approx f_{gas}$ should be the same as Ω_{baryon}/Ω_m. As an upper limit for Ω_{baryon} can be determined from primordial nucleosynthesis to be about 0.06 (for $H_0 = 50$ km/s/Mpc) one finds $\Omega_m \approx 0.3 - 0.4$ in units of the critical density.

3. Interaction between ISM and ICM/IGM

The ICM and the IGM show metal lines in the X-ray spectra. These metals cannot have been produced in the gas, but they must have been produced in the galaxies and subsequently transported from the
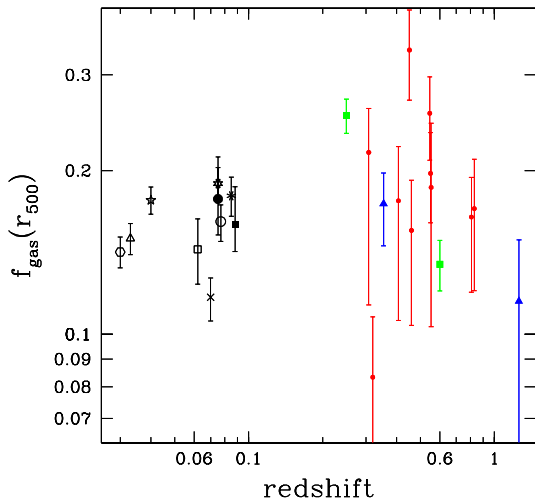
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Figure 5. Gas mass fraction versus redshift. With the current data not significant evolution of the gas mass fraction in clusters is visible (from Castillo-Morales & Schindler 2002).

galaxies into the ICM/IGM by certain processes like e.g. ram-pressure stripping, galactic winds, galaxy-galaxy interaction or jets from active galaxies. The metallicity is the best indicator for finding out which of these processes are most important. Of special interest is the distribution of metals. So far there are only few examples of measured metallicity variations in real 2D maps and not only profiles. In CL0939+4713 we find different metallicity in the different subclusters (De Filippis et al. 2002). In the Perseus cluster also clear metallicity variations were found (Schmidt et al. 2002). 1D profiles are not very useful in this context because photons from regions in the cluster which are very far apart are accumulated in the same spectrum.

Apart from the metallicity distribution also the evolution of the metallicity is interesting. As soon as enough XMM and CHANDRA observations of distant clusters are available we can compare the metallicities in these clusters with those of nearby clusters. This is another way of distinguishing between the enrichment processes as different processes have different time dependence. In addition element ratios can be derived, e.g of Fe and α-elements to get information on the different types of supernovae that have contributed to the metal enrichment.

Various processes have been suggested for the transport of gas from the galaxies to the ICM/IGM. 30 years ago Gunn & Gott (1972) suggested ram-pressure stripping: as the galaxy moves through the cluster and approaches the cluster centre it feels the increasing pressure of the intra-cluster gas. At some point the galaxy is not able anymore to retain its ISM. The ISM is stripped off and lost to the ICM and with it all its metals. Many numerical simulations have been performed to investigate this process, first 2D models (Takeda et al. 1984; Gaetz et al. 1987; Portnoy et al. 1993; Balsara et al. 1994). With increasing computing power also more detailed 3D models could be calculated (Abadi et al. 1999; Quilis et al. 2000; Vollmer et al. 2001; Schulz & Struck 2001; Toniazzo & Schindler 2001). In Fig. 6 such a simulated stripping process is shown for an elliptical galaxy.

Another possible process is galactic winds e.g. driven by supernovae (De Young 1978). Also for this process simulations have been performed on order to see whether only winds can account for the observed metallicities. The results were quite discordant as the following two examples show. Metzler & Evrard (1994, 1997) found that winds can account for the metals, while Murakami & Babul (1999) concluded that winds are not very efficient for the metal enrichment. In the simulations of Metzler & Evrard quite steep metallicity gradients showed up which are not in agreement with observations.

A third possible process is galaxy-galaxy interactions, like tidal stripping or galaxy harassment. Also during these interactions a lot of ISM can be lost to the ICM and IGM. This process is very likely more efficient in groups of galaxies, because in these systems the relative velocities are smaller and therefore the interaction timescales are longer. The ram-pressure stripping on the other hand is probably less efficient in groups because not only the pressure of the IGM is lower than that of the ICM, but also the velocities are smaller. This is also very important as the stripping is about proportional to $\rho_{gas}v^2$.

A forth possible mechanism is jets emitted by active galaxies. These jets can also carry metals. Fig. 7 shows the interaction of jets with the ICM as it was discovered by X-ray observations. In the cluster RBS797 minima in the X-ray emission have been detected in a CHANDRA observation (Schindler et al. 2001). The X-ray depressions are arranged opposite with respect to the cluster centre. It is very likely that the pressure of the relativistic particles in the jets push away the X-ray gas. Preliminary radio observations with the VLA confirm this hypothesis.

Simulations with different enrichment processes were also performed on cosmological scales. Also here quite discordant results have been found as the two following examples show. Gnedin (1998) found that galactic winds play only a minor role, while galaxy mergers eject most
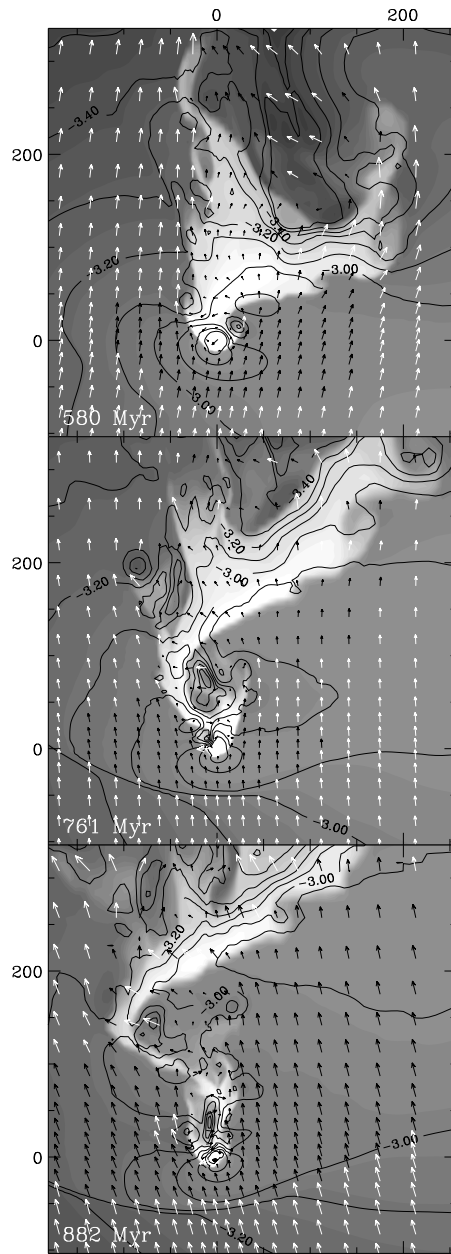
Figure 6. Gas density (grey scale) and pressure (contours) of a galaxy moving down-wards towards the cluster centre. The arrows show the Mach vectors (white when $M > 1$, black otherwise). The gas of the galaxy is stripped due to ram pressure (from Toniazzo & Schindler 2001).
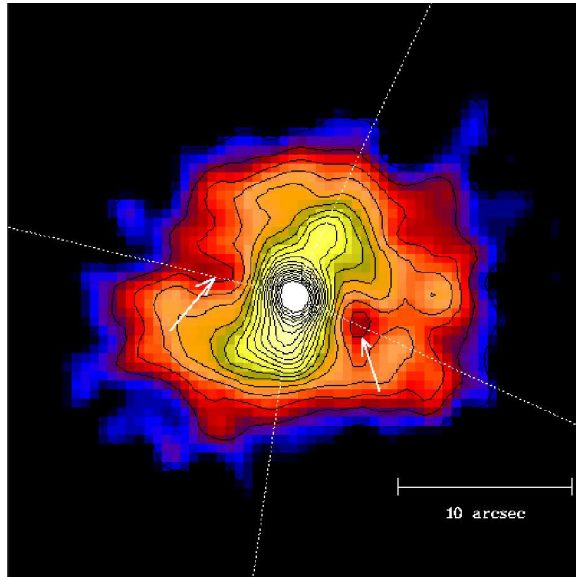
Figure 7. CHANDRA image of the central part of the cluster RBS797 (from Schindler et al. 2001). There are depressions in the X-ray emission which are located opposite to each other with respect to the cluster centre (see arrows). These depressions can be explained by an active galaxy in the centre of the cluster, which has two jets. The pressure of the relativistic particles in the jets push away the X-ray gas resulting in minima in the X-ray emission.

of the gas. In contrary to these results Aguirre et al. (2001) concluded that winds are most important and ram-pressure stripping is not very efficient. The reason for these differences are probably the large ranges in scale that are covered by these simulations, from cosmological scale down to galaxy scales. Therefore only a small number of particles are left for each single galaxy and hence galaxies are not well resolved. This can be the reason for the discordant results.

In order to clarify this we are currently performing comprehensive simulations, which include the different enrichment processes.

4. Summary

So far the picture of the interaction between ICM/IGM and the ISM is not very clear. There are many different processes possible that can transport gas from the galaxies to the ICM/IGM: ram-pressure stripping, galactic winds, galaxy-galaxy interaction, jets from active galaxies and maybe even more. It is not known yet, which of the processes is most efficient, what the time variations are and how much it depends on other parameters like e.g. the mass of the cluster/group.

The best property to test these different processes is the metallicity. The distribution and the time evolution of the metals are now finally measurable with high accuracy with the X-ray satellites XMM and CHANDRA, so that we will soon get answers on the importance of the different enrichment processes.

Acknowledgements

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