Chin. J. Astron. Astrophys. Vol. 3 (2003), **Suppl.**, 97–104
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

Keys to Cosmology – Clusters of Galaxies

Sabine Schindler ⋆
Institut für Astrophysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

Abstract We review several aspects of clusters of galaxies and their application to cosmology. We present first results of numerical simulations of the dynamics of the intra-cluster gas and of different interaction processes between cluster galaxies and the intra-cluster gas. In particular metallicity maps are very useful to determine the importance of the different interaction processes. Also mass determination methods and possible sources for uncertainties in the measurements are shown.

Key words: galaxies: clusters: general, interactions, cosmological parameters, dark matter, X-rays: galaxies: clusters, hydrodynamics

1 INTRODUCTION

Clusters of galaxies are very versatile tools for various types of analyses. They can be used to determine cosmological parameters as well as physical processes on large scales and extreme environments. Out of this large field we select here mass and dark matter measurements, determination of the dynamical state and the investigation of the interaction between the cluster galaxies and the intra-cluster gas.

2 MASS DETERMINATION AND DARK MATTER

As clusters of galaxies are large structures which can be regarded as being representative for the universe as a whole their ratio of baryonic matter to dark matter is a crucial number. Dark matter makes up about 80% of the total cluster mass, with the total cluster mass being determined by different methods.

One of the methods uses X-ray observations. The X-ray emitting gas traces the total cluster potential and hence traces the total cluster mass. With this mass determination one finds the following mass fractions: mass in galaxies 3%–5%, mass in the intra-cluster gas 15%–20%.

For the X-ray mass determination two assumptions are required: hydrostatic equilibrium and spherical symmetry. Tests with a sample of X-ray clusters together with analytical models showed that even if clusters are not spherically symmetric, but elongated the determination of total masses and gas mass fractions is quite reliable (Piffaretti et al. 2003). Only if projected clusters masses are calculated, which are used for the comparison with masses from gravitational lensing, differences in the mass of spherical and elongated clusters, respectively, can be seen (see Fig. 1). Therefore part of the observed discrepancies between X-ray masses and lensing masses (e.g. Seitz et al. 1996; Schindler et al. 1998) can come from these projection effects.

⋆ E-mail: `Sabine.Schindler@uibk.ac.at`

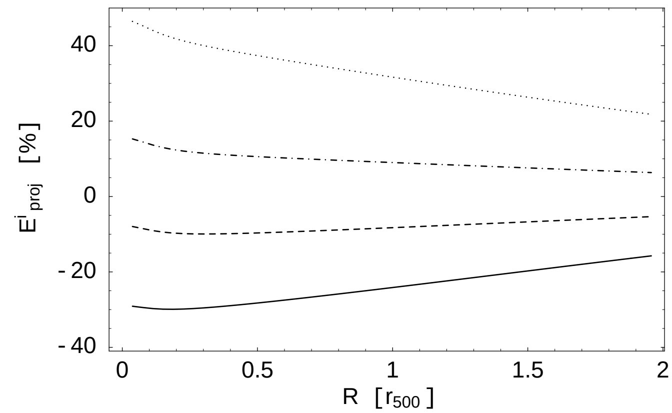

Fig. 1 The relative errors $E^i_{proj}(R)$ for the projected mass estimates in a cluster plotted versus the radius for 4 triaxial models: compressed along the line of sight (dotted line), prolate (dash-dotted line), oblate (dashed line) and elongated along the line of sight (solid line). Negative relative errors imply underestimates of the mass, if spherical symmetry is assumed. This is the case if the cluster is elongated. Overestimates are found for compressed clusters. Therefore an elongation along the line of sight can contribute to resolve the discrepancy between X-ray and lensing mass (from Piffaretti et al. 2003).

The second assumption, hydrostatic equilibrium, was tested by hydrodynamic simulations and found to be a valid assumption for relaxed i.e. non-merger clusters (Evrard et al. 1996; Schindler 1996). Clusters in the process of a major merger are obviously not in hydrostatic equilibrium and therefore the mass determination can easily be wrong by a factor of two.

Another possible source for the discrepancy between X-ray and lensing masses found in some clusters can be non-thermal pressure. While in the centre of clusters neglecting the non-thermal pressure from cosmic rays and magnetic fields can lead to a significant mass underestimate (Colafrancesco et al. 2003), we found that in the outer parts, where the mass is usually determined, the non-thermal pressure from magnetic fields is negligible (Dolag & Schindler 2000). Only if the clusters are in the process of merging, their magnetic field can temporarily be so strongly enhanced that a mass underestimate down to 50% can be found.

A second way to determine the mass is gravitational lensing. Light from background galaxies is deflected by the huge mass of a cluster. Therefore the images of these background galaxies are distorted and show up as arcs (= strong lensing). The arcs are very thin and typically very faint structures. Under non-ideal observing conditions (e.g. bad seeing) they are easily dispersed and disappear into the background. Even under ideal conditions they are not easy to detect, because they are often just above the background level. To remove the noise and make faint structures better visible usually smoothing is applied. Unfortunately in the case of such thin structures as arcs the smoothing procedure often leads to a dispersion of the few photons so that the arcs are not detectable. To prevent this dispersing we have developed an algorithm that automatically smooths only along the arcs and not perpendicular to them, by so-called “anisotropic diffusion” (see Fig. 2, Lenzen et al. 2004). The subsequently applied source finding procedure extracts all the information from the sources necessary to distinguish arcs from other sources. This new algorithm is much more efficient in finding gravitational arcs than existing source detection algorithms because it is optimised just for this purpose. Results obtained with the algorithm will be presented soon.

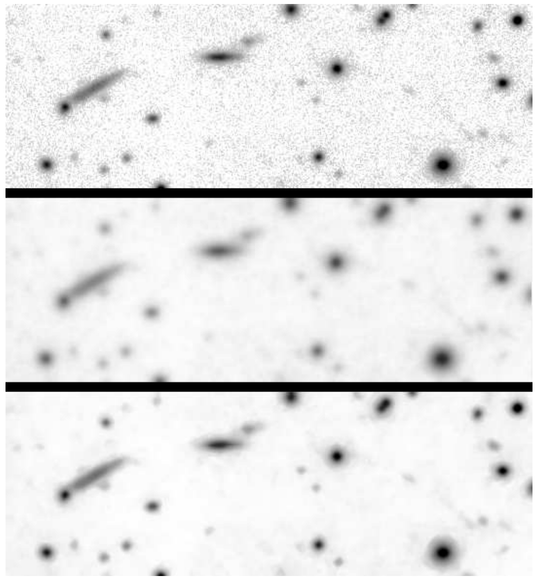

Fig. 2 Comparison of different smoothing methods. Top: original image. Middle: Image smoothed with a Gaussian filter. Bottom: Image smoothed with the newly developed algorithm of anisotropic diffusion. In the Gaussian filtered image (middle) the edges are not well preserved, i.e. the arcs get dispersed, while anisotropic dispersion (bottom) maintains the edges and reduces the noise at the same time (from Lenzen et al. 2004).

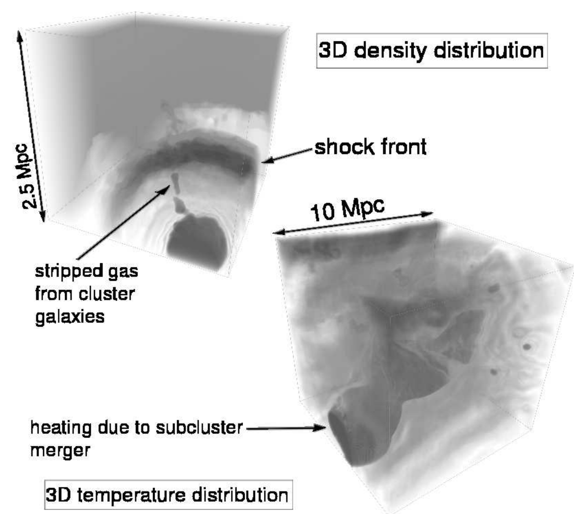

Fig. 3 Density and temperature distribution of the intra-cluster gas. Mergers of subclusters lead to shock fronts (left) and to heated regions in particular between the subclusters just before the collision (right). Note the different scale of the two images (Visualisation by W. Kapferer).

The matter density of the universe Ω_m can be determined with mass determinations of galaxy clusters in two ways. One possibility is to measure total mass and baryonic mass and assume that the ratio between the two is representative for the universe as a whole. This methods yields values around $\Omega_m \approx 0.3$ (Ettori et al. 2003, Castillo-Morales & Schindler 2003). Another way is to determine the mass function which yields similar results (Rosati et al. 2002, Reiprich & Böhriger 2002). In the latter method one must be careful with selection effects and source confusion (see Gil-Merino & Schindler 2003).

3 DYNAMICAL STATE

The dynamical state of clusters depends sensitively on the matter density and slightly also on the dark energy. Therefore the determination of the dynamical states of many clusters is another independent way to constrain cosmological parameters.

As from observations one can obtain only snapshots of the cluster evolution, it is ideal to use numerical simulations to learn how different dynamical states appear in X-ray images or temperature maps. Therefore we perform hydrodynamic simulations of the intra-cluster medium in a collaboration between University of Innsbruck (Domainko, Kapferer, Kimeswenger, Mair, Schindler, van Kampen), University of Edinburgh (Mangete, Ruffert) and Max-Planck-Institut für Gravitationsphysik (Benger). We use a grid code (Piecewise Parabolic Method, Colella & Woodward 1984) with multiply nested grids (Ruffert 1992).

Preliminary results of the simulations are shown in Figs. 3 and 4. Subcluster mergers lead to numerous shocks, which are moving outwards. The shocks appear in the temperature as well as in the density distribution as steep gradients. It is possible that particles, which are responsible for the radio haloes in several clusters, are accelerated to relativistic energies in these shocks (Giovannini & Feretti 2002).

Even before the collision of subclusters the gas is heated. The gas between the two subclusters is compressed and therefore it is heated. Hence a hot region between the subclusters is visible in the temperature map of the intra-cluster gas. For more information, images and films see http://astro.uibk.ac.at/astroneu/hydroskiteam/index.htm.

Such a feature of a heated region is e.g. observed in the cluster CL0939+4713 (De Filippis et al. 2003). The X-ray image shows (apart from several point-like sources) two extended subclusters. The temperature map clearly shows a hot region between the two subclusters as it is expected for the early stage of an (almost) central collision (see Fig. 5).

4 INTERACTION BETWEEN GALAXIES AND THE INTRA-CLUSTER GAS

Until recently galaxies and the intra-cluster gas have been treated mostly independently. But in the last years a lot of examples of interaction between these two components have been found. The evidence does not only come observations of galaxies in several wavelengths, but also from observations of the intra-cluster gas, in particular of the metal abundances. As the metal content of the intra-cluster gas is on average roughly one third of the solar value, i.e. the total amount of metals in the intra-cluster gas is about the same as in all galaxies together, a lot of gas must have been transported from the galaxies into the intra-cluster medium. Several transport processes have been suggested: ram-pressure stripping (Gunn & Gott 1972), galactic winds (De Young 1978), galaxy-galaxy interaction, jets from AGN and others. A closer look at the different metal enrichment processes is therefore very important for the understanding of cluster formation and galaxy evolution. So far numerical simulations including only some of the processes gave quite discordant results on the efficiency of the different processes (e.g. Cen & Ostriker 1999; Aguirre et al. 2001; Metzler & Evrard 1994, 1997). To improve on this we have

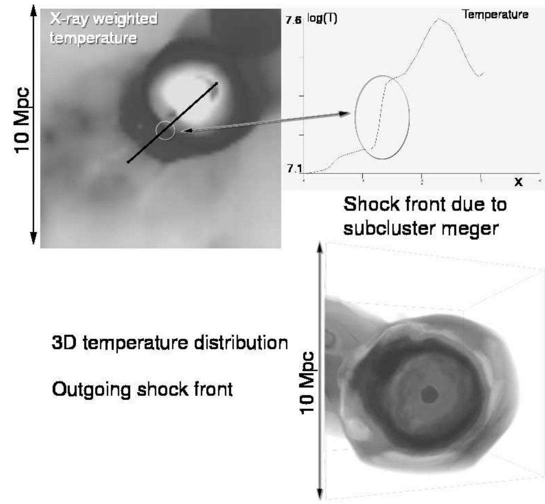

Fig. 4 Shocks emerging from subcluster mergers are seen as steep gradients in the temperature distribution. Top: Temperature map as it would appear in an X-ray observation of a cluster shortly after a collision. For a quantitative view a trace through the shock is shown on the right. Bottom: 3D view of an outgoing shock after the collision of subclusters (Visualisation by W. Kapferer).

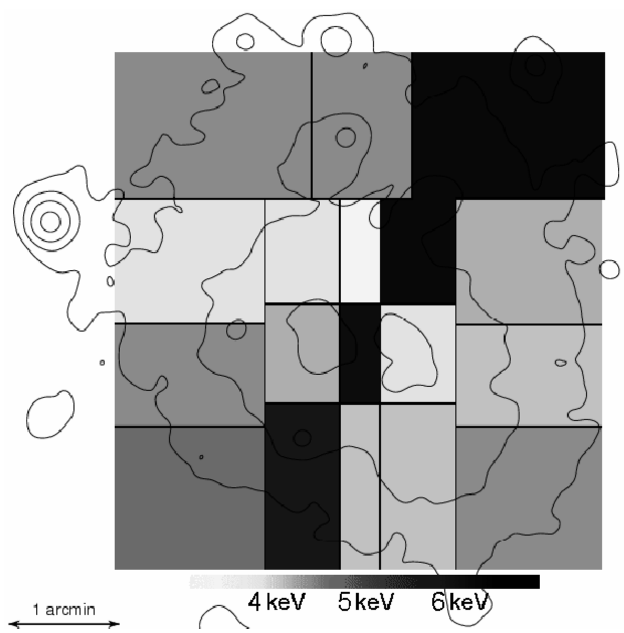

Fig. 5 XMM observation of the cluster CL0939+4713. The contours show the X-ray surface brightness distribution. Superposed on it is the temperature map in grey scales with the hotter gas being darker. Between the two subclusters is a hot region which implies that they are approaching each other (from De Filippis et al. 2003).

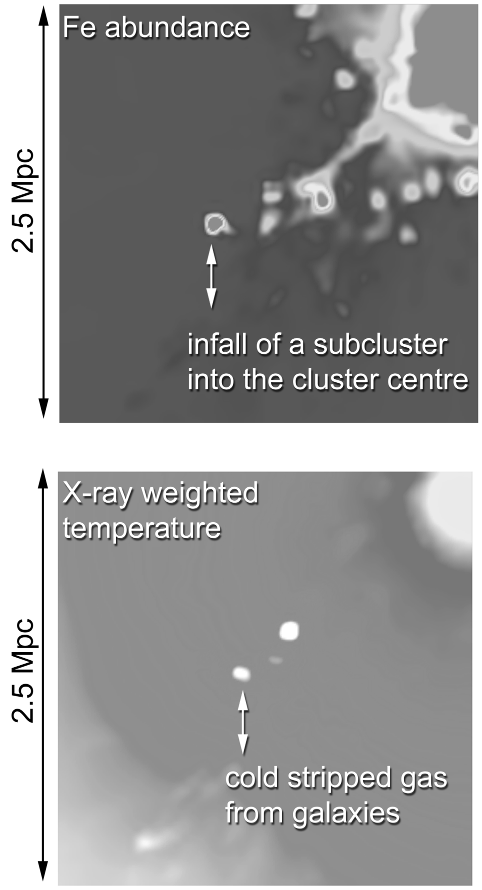

Fig. 6 As galaxies and subclusters fall onto the centre of a cluster they feel more and more pressure of the intra-cluster gas. At some point this can lead to ram-pressure stripping. The galaxies lose their cool, metal-enriched gas to the intra-cluster gas. Here we show the distribution of the iron abundance and the temperature in a simulated cluster. The centre of the cluster is in the upper right corner. Top: regions of high iron abundance are visible, where subclusters and galaxies have been stripped. Bottom: the cool gas stripped off galaxies is visible for a while in the temperature map. It is surrounded by the hotter intra-cluster medium (Visualisation by W. Kapferer).

started a comprehensive project. We use the hydrodynamic simulations mentioned above and include all possible enrichment processes. We calculate simulated metallicity maps for direct comparison with observations.

Finally, the first observed metallicity maps are available because the X-ray satellites XMM and CHANDRA have sufficiently high sensitivity and provide the possibility for spatially resolved spectroscopy. Therefore the evolution of metals in the intra-cluster gas as well as the spatial distribution can be measured now and be compared with simulations. While is was thought previously, that only the cluster centre has metallicity different from the rest of the

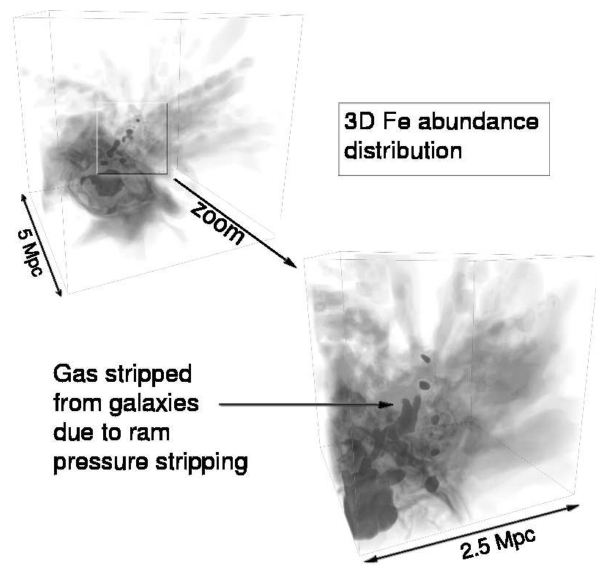

Fig. 7 3D distribution of the iron abundance in the ICM after the ISM has been stripped off the galaxies. Two different scales (5 Mpc and 2.5 Mpc) are shown (Visualisation by W. Kapferer).

cluster, recently in a number of clusters variations in the overall metallicity distribution have been found (Perseus cluster: Schmidt et al. 2002, A2199: Johnstone et al. 2002, A3558 and 3C129: Furuzawa et al. 2002, A1060: Yamasaki et al. 2002, A3671: Hudaverdi et al. 2002, 2A0335+096: Tanaka et al. 2002, AWM7: Furusho 2002, Cl0939+4713: De Filippis et al. 2003).

First results of the simulations are shown in Figs. 6 and 7. The simulations shown here include so far only ram-pressure stripping. While many other simulations have concentrated on the effect of the stripping on the galaxies (Abadi et al. 1999; Mori & Burkert 2000; Quilis et al. 2000; Vollmer et al. 2001; Schulz & Struck 2001; Toniazzo & Schindler 2001; Otmianowska-Mazur & Vollmer 2003), we concentrate here on the effects of the stripping process on the intra-cluster gas.

The gas that is stripped off the galaxies is visible not only in the metallicity maps of the intra-cluster gas, but also in the temperature maps, because this gas is cooler than the surrounding intra-cluster medium. It takes a while for the gas from the galaxies to mix with the intra-cluster gas. Sometimes one can see even shock waves passing over these cool regions and the cool gas is not heated up immediately. Also the metallicity distribution is not expected to be homogeneous shortly after the stripping, because the gas is not mixed immediately. This expectation is indeed supported by the metallicity variations observed in the metallicity maps mentioned above. In the simulations we see the highest stripping rate and hence the highest metallicities in regions where subclusters fall onto the main cluster.

For more information on the simulation method, first results in form of images and films see http://astro.uibk.ac.at/astroneu/hydroskiteam/index.htm.

Acknowledgements This work is supported partly by the Austrian Science Foundation FWF, Project P15868, and by the EU Exchange Programme "Training and Research on Advanced Computing Systems" (TRACS) between Innsbruck and Edinburgh.

References

Abadi, M.G., Moore, B., Bower, R.G., 1999, MNRAS, 308, 947
Aguirre, A., Hernquist, L., Schaye, J., Katz, N., Weinberg, D.H., et al. 2001, ApJ, 561, 521
Castillo-Morales, A., Schindler S., 2003, A&A, 403, 433
Cen, R., Ostriker, J.P., 1999, ApJ, 519, L109
Colafrancesco, S., Dar, A., De Rujula, A., 2003, submitted to A&A, astro-ph/0304444
Colella P., Woodward P.R., 1984, JCP, 54, 174
De Filippis, E., Schindler, S., Castillo-Morales, A., 2003, A&A, 404, 63
De Young, D.S., 1978, ApJ, 223, 47
Dolag, K., Schindler, S., 2000, A&A 364, 491
Ettori, S., Tozzi, P., Rosati, P., 2003, A&A 398, 879
Evrard, A.E., Metzler, C.A., Navarro, J.N. 1996, ApJ, 469, 494
Furusho T., 2002, Proceedings of the Japan-German workshop on "Galaxies and Clusters of Galaxies", Shuzenji, Japan, http://www-x.phys.metro-u.ac.jp/docs/workshop/cluster-2002-10-29/proceedings/
Furuzawa A., Morishita T., Hudaverdi M., Tanaka T., Takahashi S., et al., 2002, Proceedings of the Japan-German workshop on "Galaxies and Clusters of Galaxies", Shuzenji, Japan, http://www-x.phys.metro-u.ac.jp/docs/workshop/cluster-2002-10-29/proceedings/
Giovannini G., Feretti, L., 2002, in "Merging Processes in Galaxy Clusters", Astrophysics and Space Science Library, Feretti L., Gioia I.M., Giovannini G. (eds.), Kluwer, p.197
Gil-Merino R., Schindler, S., 2003, A&A, 408, 51
Gunn, J.E., Gott, J.R.III, 1972, ApJ, 176, 1
Hudaverdi M., et al., 2002, Proceedings of the workshop on "Galaxies and Clusters of Galaxies", http://www-x.phys.metro-u.ac.jp/docs/workshop/cluster-2002-10-29/proceedings/
Johnstone, R.M., Allen S.W., Fabian A.C., Sanders, J.S., 2002, MNRAS 336, 299
Lenzen, F., Schindler, S., Scherzer, O., 2004, A&A Letters 416, L391
Metzler, C.A., Evrard, A.E., 1994, ApJ, 437, 564
Metzler, C.A., Evrard, A.E., 1997, astro-ph/9710324
Mori, M., Burkert, A., 2000, ApJ, 538, 559
Otmianowska-Mazur, K., Vollmer, B., 2003, A&A, 402, 879
Piffaretti, R., Jetzer, Ph., Schindler, S., 2003, A&A 398, 41
Quilis, V., Moore, B., Bower, R., 2000, Science, 288, 1617
Reiprich, T., Böhringer, H., 2002, ApJ, 567, 716
Rosati, P., Borgani, S., Norman, C., 2002, ARA&A 40, 539
Ruffert M., 1992, A&A 265, 82
Seitz C., Kneib J.-P., Schneider P., Seitz S., 1996, A&A 314, 707
Schindler, S. 1996, A&A, 305, 756
Schindler, S. et al. 1998, A&A, 338, 843
Schmidt, R. W., Fabian, A. C., Sanders, J. S., 2002, MNRAS 337, 71
Schulz, S., Struck, C., 2001, MNRAS, 328, 185
Toniazzo, T., Schindler, S., 2001, MNRAS, 325, 509
Vollmer, B., Cayatte, V., Balkowski, C., Duschl, W. J., 2001, ApJ, 561, 708
Tanaka T., Hudaverdi M., Akimoto F., Furuzawa A., Tawara Y., Yamashita K., 2002, Proceedings of the Japan-German workshop on "Galaxies and Clusters of Galaxies", Shuzenji, Japan, http://www-x.phys.metro-u.ac.jp/docs/workshop/cluster-2002-10-29/proceedings/
Yamasaki N.Y., Furusho T., Ohashi T., 2002, Proceedings of the Japan-German workshop on "Galaxies and Clusters of Galaxies", Shuzenji, Japan, http:// www-x.phys.metro-u.ac.jp /docs/workshop/cluster-2002-10-29/proceedings/