CLUSTERS OF GALAXIES: DIAGNOSTIC TOOLS FOR COSMOLOGY

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Abstract

Clustersones of galaxies can be used for very different kinds of cosmological tests. I review a few of the methods: determination of cluster masses and dark matter content, metal enrichment and its connection to the origin of the intra-cluster gas, and the dynamical state of clusters. The progress in the different fields expected from observations with the new X-ray satellites XMM and Chandra is pointed out.

1 Introduction

In recent years clusters of galaxies have been shown to be excellent diagnostic tools for cosmological research. They provide a variety of different ways to determine cosmological parameters like the mean density Ω of the universe, the baryon density Ω_{baryon}, the cosmological constant Λ or the Hubble constant \( H_0 \). Galaxy clusters are special for several reasons. (1) They are the largest bound structures in the universe. With sizes of a few Mpc and masses around \( 10^{15} M_\odot \) they constitute already a considerable fraction of the universe. (2) They are closed systems. As no matter can leave the cluster potential well the mix of baryons and non-baryons should be representative for the universe as a whole. (3) The crossing time – the time it takes a galaxy to move from one end of the cluster to the other – is of the order of a Hubble time. Therefore the information of the formation process is not completely wiped out, but there are still traces left, which provide insights into the early universe. (4) Clusters
are observable out to large redshifts. Comparison of properties of distant and nearby clusters therefore yields information about evolutionary effects, which are predicted to be different in different cosmological scenarios. They can be used as tracers for the mass distribution in the universe, which is another quantity to constrain cosmological models.

2 Cluster components

Clusters of galaxies consist of various components. Clusters were first discovered as associations of hundreds to thousands of galaxies. These galaxies are not at rest in the potential well, but move around with velocities of the order of 1000 km/s. The galactic mix of morphological types of galaxies in clusters differs from the mix in the field (Dressler 1980): in clusters an excess of elliptical galaxies is visible, which is an indication of interaction. This interaction can be between galaxies or between galaxies and another component: the intra-cluster gas.

This gas fills all the space between the galaxies. The density of the gas is relatively low with $10^{-2} - 10^{-4}$ particles per cm$^{-3}$, but the temperature is high at $10^{7} - 10^{8}$ K. Such high temperatures are in good agreement with the depth of the potential wells of clusters. Gas with these specifications emits thermal bremsstrahlung in the X-ray range, which makes it a particularly interesting cluster component because we can observe it with X-ray satellites. These observations provide spatial information about the morphology of the clusters as well as spectral information which can be used to determine gas temperatures. The X-ray spectra also show lines which correspond to metallicities of about one third of the solar value (Fukazawa et al. 1998). This is an indication that the gas cannot be only of primordial origin, but at least part of it must have been processed in cluster galaxies and expelled later from the galaxy potential wells.

Another interesting component is relativistic particles. Their presence can be inferred from radio observations of their synchrotron emission.

These different components can be used to determine cosmological parameters in different ways. In the following I present a selection of particularly interesting methods.

3 Cluster masses, baryon fraction and dark matter

The mass fraction of the intra-cluster gas is not negligible. It makes up about 10 - 30 % of the total cluster mass. Compared to that the mass in the galaxies is much smaller, about 3 - 5 %. The major fraction of the mass is not visible and is therefore called dark matter. Hence measurements of the total mass of the clusters indirectly yield information on the amount and the distribution of the dark matter (for an example see the mass profile of the Virgo cluster in Fig. 1).

The total mass of clusters can be measured in different ways.

- The X-ray emitting gas can be used as a tracer of the cluster potential. The depth and the shape of the potential well can be determined from X-ray observations alone via the temperature and density gradient of the intra-cluster gas with the assumption of hydrostatic equilibrium.
A second method is based on the gravitational lensing effect: light from galaxies behind clusters is deflected by the large mass of the cluster, so that we see distorted images of these galaxies. The giant arcs (strong lensing) as well as the statistical distortion of all background objects (weak lensing) can be used for the mass determination (Wambsganss 1998; Hattori et al. 1999; Mellier 1999).

The third and oldest method uses optical spectroscopic observations and determines the mass from the velocity distribution of cluster galaxies with the assumption of virial equilibrium.

Many cluster masses have been determined in the three ways. In some clusters there is agreement between the mass derived with the different methods, in other clusters there are discrepancies typically with the following relation

\[ M_{X\text{-ray}} \approx M_{\text{velocity dispersion}} \lesssim M_{\text{weak lensing}} \lesssim M_{\text{strong lensing}} \]  \hspace{1cm} (1)

with differences sometimes as high as a factor of 2-3 between X-ray and strong lensing mass. These discrepancies have studied extensively and several possible explanations for them have been suggested:

- Observational uncertainties in the X-ray observations by ROSAT and ASCA have been found by numerical simulations to be the main error source in the X-ray
mass so far (Evrard et al. 1996; Schindler 1996).

- Non-equilibrium configurations, as are the case in merging clusters, can lead to severe under- as well as overestimation of X-ray masses.
- Projection effects: lensing is sensitive to all the mass along the line-of-sight, i.e. if there are mass concentrations in the back- or foreground they are included in the lensing mass. The X-ray mass determination is only sensitive to the potential well filled with hot gas and measures therefore only the cluster mass.
- Multi-phase medium (gas of different temperatures and densities in pressure equilibrium), as is assumed to be present in cooling flows, can lead to underestimation of the mass if only a single temperature is used for the mass determination (Allen 1998).
- Magnetic fields have also been suggested to be the reason for the discrepancy. In the X-ray mass determination only thermal pressure is taken into account. If there were in addition considerable magnetic pressure this would lead to an underestimation of the mass. With magneto-hydrodynamic simulations, though, we have shown that the effect of magnetic fields on the mass determination is essentially negligible (Dolag & Schindler 2000; Fig. 2).

The ratio of visible to total mass is a measure for the baryon fraction $\Omega_{\text{baryon}}$. Current measurements are in contradiction with primordial nucleosynthesis for $\Omega = 1$ (White et al. 1993), which is therefore one of the important hints for a low $\Omega$ universe.

The relative distribution of gas and dark matter within a cluster gives also useful information on physical processes occurring in clusters. The fact that the gas is more extended than the dark matter – an effect which is stronger for the less massive clusters (see Fig. 3) – can be explained by additional (non-gravitational) heating processes, which are more efficient in less massive clusters (Schindler 1999; Ponman et al. 1999). This gives in principle hints on when and how the heat is produced and hence information about cluster formation. But for stringent conclusions better data are required (see Fig. 3).

The relatively large range found for the gas mass fraction does not only reflect the large observational uncertainties, but there are really large variations in the gas mass fraction of individual clusters (Ettori & Fabian 1999; Schindler 1999; see Fig. 4). These large variations, which span an order of magnitude in extreme cases, have some implications for cluster formation. If all the clusters had originally the same small gas mass fraction and all the differences came later by different amounts of gas released by the cluster galaxies, larger metallicities in clusters with high gas mass fraction would be expected. But this is not observed. Therefore the difference must be caused at least partially by the primordial distribution of baryonic and non-baryonic matter.

The new X-ray and optical facilities will certainly soon clarify many of these questions. Chandra and XMM with their improved spatial and spectral resolution will provide very accurate measurements of cluster masses and hence the amount and the distribution of dark matter.
Figure 2: Ratio of true and X-ray mass for 4 different magnetic field strengths as seen in magneto-hydrodynamic simulations (Dolag et al. 1999). The bold lines are averaged profiles over 18 model configurations, while the thin lines show the corresponding standard deviation. Hardly any dependence of the mass estimate on the magnetic field strength is visible (from Dolag & Schindler 2000).

4 Metal enrichment and the origin of the intra-cluster gas

Spectroscopic X-ray observations of clusters show metal lines which correspond to metallicities around 0.3 in solar units (Fukazawa et al. 1998). This indicates that the gas cannot be purely of primordial origin. Instead it must have been processed in the cluster galaxies, at least partially, and then have been expelled from the galaxies’ potential wells into the intra-cluster gas. The amount of this processed intra-cluster material is not negligible, but equals or even exceeds (Mushotzky 1999) the amount of metals in the galaxies themselves. There has been much speculation about the processes responsible for the transport of gas from within the galaxies into the intra-cluster gas and two mechanisms emerged as probable: galactic winds (De Young 1978) and ram-pressure stripping (Gunn & Gott 1972). Light can be shed on which mechanisms operate by measuring metallicity gradients and metallicity evolution.

Metallicity gradients can indicate what mechanism prevails, because the different
mechanisms expel the gas with different radial distribution. Differences in the distribution of iron and $\alpha$-elements give information on the type of supernovae the metals origin from and hence on different enrichment time scales. So far, in several clusters hints for radial metallicity gradients have been detected (e.g. Finoguenov et al. 1999; De Grandi & Molendi 1999a; Irwin & Bregman 2000) from observations with ASCA and BeppoSAX, but again for more detailed results we have to wait for XMM and Chandra.

The time evolution of cluster metallicities is another obvious way to investigate different processes, because they are expected to have different time dependencies. Observations of clusters out to $z \approx 0.5$ did not show any significant evolutionary effects (Mushotzky & Loewenstein 1997). Observations of high redshift clusters out to $z \approx 1$ (Schindler 1999) are consistent with this result, but are very restricted due to large errors. In particular XMM with its high sensitivity will provide exact metallicity measurements for many distant clusters, which will give important clues on cluster formation and galaxy formation.

### 5 Dynamical state

The dynamical state of clusters, whether already relaxed or still consisting of merging subclusters, offers another way to measure $\Omega$ as different scenarios predict different
evolution times (Richstone et al. 1992). While in some clusters the unrelaxed state is already obvious in the X-ray images (e.g. in Abell 1437, see Fig. 5), for most clusters the dynamical state is not so easy to determine. It has been shown in numerical hydrodynamic simulations, that the dynamical state can be characterised best by taking into account not only the distribution of the X-ray emission but by comparing it also with the temperature distribution (Schindler & Müller 1993). Inhomogeneities in the temperature distribution arise in clusters during mergers: shock fronts emerge before and after the collision, which show up as temperature gradients. Also heated gas between two subclusters can be observed before the core passage. From ASCA and BeppoSAX observations coarse temperature maps have been produced (Markevitch et al. 1998; De Grandi & Molendi 1999a, b; Irwin et al. 1999), but the capabilities for spatially resolved spectroscopy of the new X-ray instruments on XMM and Chandra promise well resolved temperature maps.

Of particular interest for the determination of the dynamical state is the comparison of X-ray observations with observations in other wavelengths. The spatial distribution as well as the velocity distribution of the galaxies obtained from optical observations yield complementary information about the morphology and kinematics. Radio emission can provide additional hints in two different ways. (1) The relative velocity between radio galaxies and the intra-cluster gas can be inferred from the orientation and the shape of radio tails, so that the kinematics perpendicular to the line of sight can be estimated. (2) Diffuse, extended radio emission, which is not associated with a particular galaxy – radio halos and relics – can be an indication of a recent
Figure 5: ROSAT/HRI image of the cluster Abell 1437. The emission of the cluster is strongly elongated in SW-NE direction and the cluster centre in X-rays does not coincide with the optical position – both indications of a cluster in which subclusters are in the process of merging (from Schindler 2000). The point source in the NE is probably not connected with the cluster.

merging process (Giovannini et al. 1999; Feretti et al. 2000), because the shock waves emerging during the collision of subclusters can reaccelerate particles to relativistic energies, so that they emit synchrotron radiation.

6 Conclusions

Clusters of galaxies can be used for very different types of cosmological tests. In particular observations with the new X-ray satellites launched recently, XMM and Chandra, will provide a large step forward in several respects. The unprecedentedly high spatial resolution of Chandra (1") provides detailed X-ray images to investigate cluster morphology and derive very accurate profiles. The high sensitivity of XMM makes it the ideal instrument to find and study distant galaxy clusters in order to investigate evolutionary effects. Improved spectral resolution allows for much better temperature and metallicity measurement. And – very importantly – XMM and Chandra are capable of performing spatially resolved spectroscopy with high accuracy, which is necessary for temperature maps, mass determination and metallicity distributions. The combination of these data with observations in other wavelengths will open new horizons in
cosmology.

7 References

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