CLUSTERS OF GALAXIES IN X-RAYS

S. Schindler

Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead L14 1LD, UK

ABSTRACT X-ray observations of clusters at different redshifts are presented and compared. For the nearest cluster – the Virgo cluster – we show a comparison of the galaxy distribution and the distribution of the intra-cluster gas. Although the Virgo cluster has such an irregular structure, it seems that within each of the subclusters some kind of equilibrium has already established. X-ray observations of distant lensing clusters reveal very different properties. The large range of X-ray properties without any obvious correlation between them shows that cluster evolution is complex, i.e. not every cluster is evolving in the same way. A comparison of nearby clusters and distant clusters shows that there is no clear trend with time in any of the X-ray properties, which favours a low $\Omega$ universe.

KEYWORDS: clusters of galaxies; X-rays; evolution

1. WHY ARE X-RAY OBSERVATIONS OF GALAXY CLUSTERS INTERESTING?

Galaxies are not the only observable component in clusters, but there is hot gas between the galaxies. The gas is an important component as its mass amounts to about 5 times the mass in the galaxies. The temperature of the gas is typically between 2 and 10 keV so that it is emitting thermal bremsstrahlung in X-rays. From X-ray observations of clusters one can learn a variety of things out of which I can mention only a few here.

– Cluster detection is much easier in X-rays than in optical, because the X-ray emission is proportional to the square of the gas density, while in optical one sees only the galaxy density. Therefore, the detection is much less affected by projection effects, as one does not know a priori which of the galaxies observed in the direction of the cluster are really cluster galaxies. Moreover, the gas fills the potential well of the cluster throughout, so that one can see the structure of the cluster at first glance (see Fig. 1).

– ROSAT observations and also earlier missions revealed that clusters have very different morphologies: some have substructure (see Figs. 1, 2 and 4) while others show a spherically symmetric X-ray emission (see Fig. 3). These are indications for the different dynamical states; in the former case merging processes are taking place while the latter clusters are already in virial equilibrium. As different cosmological models predict a different percentage of virialized clusters, one can in principle
determine $\Omega_0$ with morphological studies (Richstone et al. 1992).

- From X-ray spectra, observed mainly with ASCA, one can determine the temperature of the cluster. The temperatures (2-10 keV) are generally in good agreement with the depth of the cluster potential well. Temperature variations over the cluster (see e.g. Markevitch et al. 1998) indicate the dynamical state of the cluster and can also be used to discriminate between different cosmological models. Another interesting parameter one can determine with X-ray spectra is the metallicity of the intra-cluster gas. Typical metallicities are between 0.2 and 0.5 in solar units (e.g. Mushotzky & Loewenstein 1997; Tsuru et al. 1997), indicating that at least part of the gas cannot be primordial but must have been processed in the cluster galaxies. The distribution of the metals within the cluster and the ratios between different elements give therefore important hints on the origin of the intra-cluster gas.

- In several clusters the Sunyaev-Zel’dovich effect was detected (Birkinshaw 1998), i.e. photons of the cosmic microwave background are inverse Compton scattered when they pass through the hot intracluster gas so that the apparent brightness of the cosmic microwave background in direction of the cluster is changed (Sunyaev & Zel’dovich 1972). A combination of this effect with an X-ray observation yields an estimate for the physical size of the cluster. Comparing it with the angular size one gets a direct estimate of the distance of the cluster, completely
independent from any other distance indicator.

- Assuming spherical symmetry one can determine from X-ray observations the amount of gas in a cluster. With the additional assumption of hydrostatic equilibrium one can estimate as well the total mass of the cluster, which is a very interesting quantity, because about 70-90% of the cluster mass is dark matter. The combination of both mass profiles yields the radial distribution of the dark matter. The ratio of gas mass and total mass gives $\Omega_{\text{baryon}}$, assuming that the matter is accumulated indiscriminately in the cluster potential wells. The values found for $\Omega_{\text{baryon}}$ are so high that for an $\Omega = 1$ universe they are in contradiction with primordial nucleosynthesis, a problem named “baryonic catastrophe” (see e.g. White et al. 1993).

- As clusters are the largest bound objects in the universe they trace the mass distribution of the universe very well and are thus excellent tracers for large-scale structure. Therefore statistical studies of the cluster distribution and cluster properties are very powerful to constrain cosmological parameters.

In the following I present as an example for a nearby cluster the Virgo cluster (Sect. 2.1) and two examples for distant clusters – RXJ1347.5-1145 and Cl0939+4713 (Sect. 2.2). In Sect. 3 X-ray properties of several clusters are compared and some (preliminary) cosmological conclusions are drawn.

2. CLUSTERS AT DIFFERENT REDSHIFTS

2.1 Morphology of the Virgo cluster: gas versus galaxies

As the Virgo cluster is the nearest cluster it is very well studied – both in X-rays and in optical. Therefore it is the ideal object for a detailed comparison of the two components – the gas and the galaxies. We use the X-ray emission from the ROSAT All-Sky Survey (Böhringer et al. 1994) and the optical information from the Virgo Cluster Catalog (Binggeli et al. 1985).

Fig. 2 shows a comparison of the X-ray emission of the gas and the galaxy distribution. It is obvious that the cluster is very irregular. There are several substructures, which are very similar in both components: the main X-ray maximum at M87 and a second maximum around M86 are connected by a region with the highest galaxy density. In the south, around M49, another maximum is visible – both in X-ray and in the galaxy density. South-west of M87 is a relatively steep slope visible in both components.

For a more quantitative analysis we decomposed the three different subclusters around M87, M49, and M86 and compared their three-dimensional density profiles individually. We found a large difference between the gas profile and the profile of the galaxy distribution in all subclusters. The gas profiles are much steeper in the centre (up to a radius of at least 80 arcminutes) and somewhat shallower in the outer regions than the galaxy profile.

Subdividing the galaxy sample into different morphological types confirms the
FIGURE 2. Comparison of the X-ray and the optical appearance of the Virgo cluster. The colour image shows the X-ray emission as observed in the ROSAT All-Sky Survey. The contours show the number density of the 1292 member galaxies of the Virgo Cluster Catalog (Binggeli et al. 1995). The galaxy distribution is smoothed with a Gaussian of $\sigma = 24'$. The size of the image is $12^\circ \times 12^\circ$. 
FIGURE 3. ROSAT/HRI contours of RXJ1347.5-1145 superposed on an optical image. The X-ray emission is strongly peaked. In the optical image one can see that the cluster acts as a gravitational lens. The positions of the gravitational arcs are marked with letters.

different distributions for early and late-type galaxies found by Binggeli et al. (1997). The spiral and irregular galaxies have a very flat profile, while the elliptical galaxies have a steep profile, indicating that they are more concentrated on the subcluster centres. But although their distribution is relatively steep compared to the rest of the galaxies, it is still much flatter than the X-ray profile in particular in the centre.

Comparing the profiles of the different subclusters one finds a systematic effect: the smaller the subcluster, the steeper the profile, both in X-rays and optical. This effect together with the very similar appearance of the two components shows that some kind of equilibrium state must have established within the potential wells of the subclusters although the cluster has such a irregular structure. For details see Schindler et al. (1998b).
FIGURE 4. ROSAT/HRI image of the Cl0939+4713. The cluster consists of two subclusters (marked M1 and M2) which have even some internal structure. The source marked with a cross is a background quasar at a redshift of 2.

2.2 Properties of distant clusters

Exemplarily, I will present two clusters at about the same redshift, but with very different properties.

RXJ1347.5-1145 at z=0.45 is an exceptional cluster in many respects (Schindler et al. 1997). With a luminosity of $L_{X,bol} = 2.1 \times 10^{46} \text{erg/s}$ it is the most luminous X-ray cluster found so far. The X-ray image (Fig. 3) is strongly peaked which suggests that there is a cooling flow in the centre of the cluster. In a standard cooling flow analysis one finds a mass accretion rate of more than 3000 $M_\odot$ per year, which is also an extreme value.

The optical image (Fig. 3) taken with the NTT reveals several arcs, indicating that the cluster is acting as a gravitational lens. The large distance of the arcs from the cluster centre of 240 kpc shows that the cluster is very massive. From ASCA observations we found a relatively high gas temperature of 9.3 keV and a metallicity of 0.33 in solar units.

All these properties suggest that this cluster is dynamically old: well virialized structure, indications for high mass, early metal enrichment, no merger in the recent past.
The cluster Cl0939+4713 – also known as the most distant Abell cluster A851 – is at about the same redshift (z=0.41) and shows also the gravitational lens effect, i.e. is also a massive cluster. But already the ROSAT/HRI image (Fig. 4) shows that the cluster is very different (Schindler et al. 1998a). It consists of two subclusters which have even some internal structure. Obviously, this cluster is in a merging process. The X-ray luminosity is more than an order of magnitude lower than the one of RXJ1347.5-1145 and the metallicity is even compatible with 0 (determined with an ASCA observation). This is all the more surprising as the cluster has so many galaxies. While it is claimed to be the optically richest cluster, RXJ1347.5-1145 is relatively poor in terms of galaxies.

From all its X-ray properties one would conclude that Cl0939+4713 is a dynamically young cluster.

In Table 1 a few properties are summarized. The table is complemented by a few other clusters which cannot be discussed explicitly because of lack of space. But I would like to draw your attention on the puzzling cluster AXJ2019 (Hattori et al. 1997) – a distant cluster at a redshift of 1.0 which shows an Fe line corresponding to a supersolar abundance.

|                      | nearby | AC118 | Cl0500 | Cl0939 | RXJ1347 | Cl0016 | AXJ2019 |
|----------------------|--------|-------|--------|--------|---------|--------|---------|
| redshift             | 0.31   | 0.32  | 0.41   | 0.45   | 0.55    | 1.0    |
| $L_{X,bol}$          | 0.05-5 | 6.8   | 0.6    | 1.6    | 21      | 5.0$^b$| 1.9     |
| metallicity          | 0.2-0.5| 0.23$^c$| 0.0-1.5$^d$| 0.22  | 0.33    | 0.11$^e$| $\approx$1.7 |
| temperature          | 2-10   | 9.3$^e$| 7.2$^d$| 7.6    | 9.3     | 8.0$^e$| 8.6     |
| substructure         | in 25%$^f$ | yes | yes | yes | no | yes | ? |

TABLE 1. Comparison of some properties of nearby and distant clusters. The clusters are ordered according to their redshift. The properties in the second column are average values for nearby clusters. The X-ray luminosity is in units of $10^{45}$ erg/s and the temperature is in keV. $^a$ from Hattori et al. (1997), $^b$ from Neumann & Böhringer (1997), $^c$ from Mushotzky & Loewenstein (1997), $^d$ from Ota et al. (1998), $^e$ from Furuzawa et al. (1998), $^f$ from Neumann (1997)

3. CONCLUSIONS

A comparison of several properties at different redshifts (Table 1) shows in none of the properties a clear trend with time. Similar results were found e.g. by Mushotzky & Loewenstein (1997) and Tsuru et al. (1997). These findings sug-
gest an early evolution of galaxy clusters, which is almost completed at a redshift of 0.5-1.0. This results points a low $\Omega$ universe, because in a high $\Omega$ universe one would expect a strong evolution in this period. Of course this result is very preliminary given the small sample of high-redshift clusters.

Another obvious feature in Table 1 is the strong variation in the properties, e.g. in the X-ray luminosity which varies over more than an order of magnitude. The optical richness does not seem to have any correlation with the metallicity or the X-ray luminosity. In some properties like in the metallicity the large scatter might be caused by the large uncertainties in the metallicity determination, but in other parameters like the X-ray luminosity the scatter is certainly real. Obviously, cluster evolution is quite complex, i.e. not every cluster is evolving in the same way with the same initial ingredients. For understanding the cluster evolution we need clearly larger samples of more distant clusters and properties like the metallicity determined to a higher accuracy. We hope that all these goals will be achieved by the next X-ray missions XMM, AXAF and ASTRO-E.

REFERENCES

Birkinshaw M., Physics Reports, in press [astro-ph/9808056]
Binggeli B., Sandage A., Tammann G.A., 1985, AJ 90, 1681
Binggeli B., Tammann G.A., Sandage A., 1987, AJ 94, 251
Böhringer H., Briel U.G., Schwarz R.A., Voges W., Hartner G., Trümper J., 1994, Nature 368, 828
Furuzawa A., Tawara, Y., Kunieda, H., Yamashita, K., Sonobe T., Tanaka, Y., Mushotzky R., 1998, ApJ 504, 35
Hattori, M., Ikebe, Y., Asaoka, I., Takeshima, T., Böhringer, H., Mihara, T., Neumann, D.M., Schindler, S., Tsuru, T., Tamura, T., 1997, Nature 388, 146
Markevitch M., Forman W.R., Sarazin C.L., Vikhlinin A., 1998, ApJ 503, 77
Mushotzky R.F., Loewenstein M., 1997, ApJ 481, L63
Neumann, D.M., Böhringer, H. 1997, MNRAS, 289, 123
Neumann, D.M. 1997, Ph.D. Thesis, Ludwigs-Maximilians-Universität, München
Ota N., Mitsuda K., Fukazawa Y., 1998, ApJ 495, 170
Richstone D., Loeb A., Turner E.L., 1992, ApJ 393, 477
Schindler S., 1996, MNRAS 280, 309
Schindler S., Hattori M., Neumann D.M., Böhringer H., 1997, A&A, 317, 646
Schindler S., Belloni P., Ikebe Y., Hattori M., Wambsganss J., Tanaka Y., 1998a, A&A, 338, 843
Schindler S., Binggeli B., Böhringer H., 1998b, A&A, submitted
Sunyaev R.A., Zel’dovich Y.B., 1972, Comments Astrophys. Space Sci. 4, 173
Tsuru T.G., Matsumoto H., Koyama K., Tomida H., Fukazawa Y., Hattori M., Hughes J.P., 1997, [astro-ph/9711353]
White S.D.M., Navarro J.F., Evrard A.E., Frenk C.S., 1993, Nature 366, 429