Abstract

Some comments concerning the mass distribution and dynamical features of clusters of galaxies are presented. The double-core profile of the gravitational potential with core sizes of about 60 and 200 kpc seems to reflect an intrinsic property of the dark matter. The radial profile of the dark matter “temperature” studied by Ikebe raises interesting questions about the energy generation and its transportation between dark matter and baryons within clusters. Recent Chandra detection of both cold and shock fronts gives us a chance to observationally look into how the heat is transported in the cluster plasma. Finally, we will discuss possible new cluster sciences we can carry out from Astro-E2.

1 Introduction

Mass distribution and gas dynamics are the major sciences which have been attracting us to study clusters of galaxies mainly in X-rays. Following the first imaging spectroscopy carried out from ASCA, recent observations from Chandra and XMM-Newton show us detailed views of the hot intracluster medium (ICM) in the central regions of clusters.

As for the mass distribution, the hot ICM closely traces the profile of the gravitational potential when hydrostatic equilibrium and spherical symmetry can be assumed. Theoretical models such as the King model or the universal potential profile derived by Navarro, Frenk, & White (1997) are widely used, but significant deviations from these models are reported for a number of systems (e.g. Tamura et al. 2000). Clusters with isothermal ICM right into the center and no prominent cD galaxy are ideal objects in looking into the pure potential profile due to the dark matter. We will review past results and discuss new features revealed from Chandra observations. The “dark matter temperature” is a new concept introduced by Ikebe, Böhringer, & Kitayama (2003). We will look into some implications based on their results.

The cluster dynamics has been discussed from the Einstein days mainly based on the cluster morphology (e.g. Forman & Jones 1982). ASCA has brought us clear evidences that many clusters are undergoing mergers in the form of temperature distribution from a number of nearby clusters (e.g. Markevitch 1996; Furusho et al. 2001a). We will briefly discuss ASCA results and its connection to future studies. The next Japanese X-ray mission, Astro-E2, will start working early in 2005. We will examine some of the expected science on clusters.

2 Mass distribution

Mass distribution often exhibits a double profile. Ikebe et al. (1996) showed for the Fornax cluster that the potential profile takes a double structure even the hot gas temperature is constant. Later, Matsushita et al. (1998) showed that, based on the ASCA data, model independent estimation of the potential structure resulted a shoulder at a radius of 20 kpc as shown in Fig. 1.
In these cases, there were giant elliptical galaxies at the center and the detection of the double structure may not be recognized as a great surprise.

Recent Chandra data for A1060 show a different feature. The radial profile of the ICM in the 0.5–10 keV band excluding the 2 central galaxies, NGC 3311 and NGC 3309, was fitted with 3 models: single $\beta$, double $\beta$, and NFW models, respectively. Note that the cD galaxy, NGC 3311, in this cluster was shown to be X-ray faint and very compact (Yamasaki, Ohashi, & Furusho 2002), so it can be easily excluded from the X-ray image. As shown in Fig. 2, the profile is not described by the single $\beta$ model ($\chi^2$/d.o.f = 1.81) and the residuals indicate a dip feature at a radius around 3' or 40 kpc (Furusho, Yamasaki, & Ohashi 2002). The NFW profile also gave a poor fit. The fit becomes significantly better by applying the double $\beta$ model with the best-fit core radii of 40 kpc and 160 kpc. The ICM in A1060 is very isothermal to the center, and this double-core feature is only seen in the density profile of the ICM with no corresponding optical structure. Therefore, this double structure seems to reflect an intrinsic property of the dark matter potential. This feature may have some connection to so-called “dark clusters” in which a large potential well is implied from X-ray data, but accompanied with almost no optical galaxies.

The Chandra results on A1060 reminds us of the statistical study carried out by Ota & Mitsuda (2002), who showed that core radii for 79 clusters takes a double peak distribution with the peak values at 60 and 200 kpc as shown in Fig. 3. It is interesting that the double-core profile of the A1060 gas indicates just the same radii. Therefore, there seems to be a possibility that the dark matter tends to form some common structure with spatial scales of 60 and 200 kpc even without any optical galaxy.

The next topic I would like to discuss is the dark matter “temperature” studied by Ikebe, Böhringer, & Kitayama (2003), which is essentially a velocity dispersion of dark matter particles. Radial distributions of the dark matter “temperature” for the XMM data of A1795 by Ikebe, Böhringer, & Kitayama (2003) is shown in Fig. 4. They indicate a systematic drop to the center in parallel with the ICM temperature. The temperature values for the dark matter are lower than the ICM by about a factor of 2, which itself suggests that the ICM is probably heated also by a non-gravitational source such as supernova energy. On the other hand, it is not simply understood why dark matter has to be cooler even in the clusters center. In the cluster center, radiation from the gas is thought to be the most efficient cooling mechanism and we consider that the main reason for the presence of the central cool gas is the radiative cooling. In that
case, the ICM should be the cooler than the dark matter around the cluster center. Therefore, the feature that the ICM being hotter than the dark matter suggests that the thermal structure there may not be controlled by radiative cooling. This probably has connection with the recent XMM finding that the cool gas with $kT < 1 - 2$ keV is absent in many “cooling flow” clusters (Tamura et al. 2001; Peterson et al. 2001; Kaastra et al. 2001).

We also note that the dark matter temperature differs from the ICM value at almost all radii. Since A1795 is morphologically a relaxed system, so what is the mechanism that keeps the two temperatures so much different for a long time? We hope that further systematic studies of the dark matter temperature in connection with morphological or dynamical features of the cluster may give us new insight about the heating mechanism of the clusters gas. For example, we may find interesting features for clusters showing an elliptical shape such as AWM7 or for those indicating a large mass difference between the X-ray derived one and the one from gravitational lens effects.

3 Dynamics in clusters

Chandra images of clusters have revealed new dynamical features based mainly on the work by Maxim Markevitch. One is the so-called cold fronts, which have been detected from A2142 (Markevitch et al. 2000), A3667 (Vikhlinin, Markevitch, & Murray 2001) and many other clusters. This is characterized by sharp edges, across which the density and temperature show a sharp jump by a factor of about 2. The high density side of the edge shows a lower temperature, keeping the pressure ($\propto nT$) almost constant across the edge. Therefore, these edges are not shock fronts. It is discussed that the edge is probably the core of a cool subcluster which has collided into the main cluster (Markevitch et al. 2000). The other feature is the bow shock detected in the cluster 1E 0657-56 (Markevitch et al. 2002), in which a significant jump in the pressure is found across the edge in contrast to the case of cold edge.

One of the major findings from ASCA is the prevalence of temperature structures in many
clusters of galaxies even when there are no morphological substructures. Because of the complicated angular response of ASCA’s telescope, mapping observations of nearby clusters give us the most reliable results. Significant temperature structures by a factor of about 2 were obtained from the Virgo (Shibata et al. 2001), Coma (Watanabe et al. 1999), Ophiucus (?), Perseus (Furusho et al. 2001b), Centaurus (Furusho et al. 2001a) clusters. The results for the Perseus and the Centaurus clusters are shown in Figs 7 and 8. These are among the brightest clusters in the sky and have been known as the typical systems with relaxed smooth morphology. For the Coma cluster, the hot temperature is recognized rather outside of the cluster in the north-west region. Note that this cluster shows a prominent radio halo which indicates presence of relativistic electrons (Feretti, Dallacasa, Giovannini, & Tagliani 1995), therefore both X-ray and radio data indicates that an energetic non-thermal process may be going on in the outskirts of this cluster.

Perseus cluster is also morphologically smooth and the central region is characterized by a strong cool component (Furusho et al. 2001b). ASCA’s mapping observation showed unusual temperature structure in this system. It is characterized by an extended cool region in the east of the center. This cool region seems to be encircled by a hot region, and the eastern edge of the cluster shows a hot ridge running in the north-south direction. These features strongly suggests that the Perseus cluster has experienced a major merger and probably a large-scale gas motion is still going on. We hope detailed studies from XMM-Newton and Astro-E2 will be able to give us closer features about the gas motion.

Numerical simulations for the formation of clusters indicate that the growth of clusters takes the form of subcluster mergers (Navarro, Frenk, & White 1995). The cluster mass jumps up in a short time scale during a major merger, and in later cosmic times the mass scale of subcluster mergers become larger because each merging body becomes more massive. This situation seems to enhance our chance of observing major mergers in nearby clusters.

Figure 5: Profiles of X-ray intensity and estimated pressure across the sharp edge in A2142 by Markevitch et al. (2000).

Figure 6: Profiles of gas density and pressure across the 2 sharp edges in 1E 0657-56 by Markevitch et al. (2002). The pressure jump is seen at the shock front.
Figure 7: Color-coded X-ray temperature map obtained with ASCA by Furusho et al. (2001a). Contours represent X-ray intensity.

Figure 8: ASCA temperature map of the Perseus cluster by Furusho et al. (2001b). Contours show residual flux over a $\beta$ model.

4 Science from Astro-E2

The next Japanese X-ray astronomy satellite Astro-E2 will be launched in early 2005. The spacecraft carries microcalorimeters (XRS) for the first time (e.g. Kelley et al. 1999). The energy resolution is about 6 eV which is a factor of about 20 better than the CCD instruments. Also, XRS can observe 0.5–10 keV spectra of extended objects with a field of view of about $3' \times 3'$. With the help of a mechanical cooler, the life of XRS in the orbit is now expected to be 2.5–3 yrs.

Figure 9: Simulated spectra of A2199 observed with XIS (CCD instrument; dark) and XRS (red), performed by T. Dotani. The XRS data clearly resolve the Fe-K line complex.

These features are in a marked contrast to the grating spectrometers which observe point sources only in the energy range below 2 keV. Clearly, the science concerning the hot gas in galaxies and clusters will be the most important area to be explored with Astro-E2. In particular, with this energy resolution covering the energy of Fe-K line, we can carry out Doppler spectroscopy.
of the cluster hot gas and a model independent study of metal abundances for the first time. Let me briefly show some examples and discuss what kind of science we can expect for clusters of galaxies.

A simulated spectrum for A2199 is shown in Fig. 9. The Fe-K line can be resolved into resonance, inter-combination, forbidden, and dielectronic recombination lines. The ratio of these lines will directly tell us the gas temperature and density in some cases. Significance of the resonance scattering in the cluster center can be studied in a clear way. The new science we can carry out with the XRS is the Doppler spectroscopy of cluster gas. So far, evidence of mergers are given in the form of temperature distribution and sharp-edge features. No direct information on the gas motion has been obtained yet. With the energy resolution of XRS, we can resolve the motion with a velocity of a few hundred km s$^{-1}$. Since subcluster mergers involve more than 1000 km s$^{-1}$, we can resolve most of the gas motion present in clusters. The capability of XRS in resolving the Doppler shifted Fe-K line will show us the gas dynamics directly. We hope that in about 2 years time the new data from Astro-E2 will give us various exciting features about the clusters of galaxies.

References

Ikebe, Y., Böhringer, H., & Kitayama, T. 2003, this volume