Probing Evolution of Hot Gas and Galaxy Distributions in Galaxy Clusters

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Abstract

The purpose of this work is to answer the question of "how have spatial distributions of components in galaxy clusters evolved over the history of the universe?". It is well known that galaxy clusters consist of dark matter, intergalactic hot gas, and galaxies, and that hot gas has an extended distribution and galaxy components show a morphology–density relation and the Butcher–Oemler effect. However, the origin of these cluster component distributions is still unknown. One simple interpretation is that galaxies have gradually fallen to the cluster centers, with evolution of their color and morphology. If this simple scenario is correct, the relative distributions of galaxies to hot gas should become centrally-concentrated toward lower redshifts. Our exploratory study suggests that galaxies are falling to the cluster center while hot gas is expanding with decreasing redshifts.

Key words: galaxies: clusters: general—X-rays: galaxies: clusters

1. Background and Motivation

It is well known that galaxy clusters consist of dark matter, intergalactic hot gas, and galaxies. The distributions of each component are also well studied; for example, cluster hot gas distributions are known to be more extended than those of dark matter (or galaxies). That is, beta in the beta model measured using X-ray data is usually less than unity for hot gas distributions (e.g., Jones & Forman 1999), and this means that the hot gas has higher specific energy than dark matter. On the other hand, the morphology–density relation and the Butcher–Oemler effect are known for galaxy (optical) components in clusters (e.g., Goto et al. 2003). However, the origin of such cluster component distributions is still unknown. One simple interpretation is that galaxies have gradually fallen to the center of gravitational potential with evolution of their color and morphology and merged into a single central galaxy, and that kinetic energy lost from galaxies (through interactions of interstellar media and intergalactic hot gas) has expanded the hot gas distribution. In fact, there are some works which suggest this scenario. Zabludoff & Mulchaey (1998) predict that members of a galaxy group are merged into a central bright galaxy in a few tenths of the Hubble time if the galaxy density is initially high enough, and they found a rich population of dwarf galaxies around an isolated X-ray bright galaxy, NGC 1132, suspected to be in the process of galaxy mergers. Kawaharada et al. (2009) reported more direct evidence; using the XMM-Newton and 2MASS data, they found that the galaxy luminosity distribution is more centrally-concentrated than the corresponding metal distribution which has been provided from galaxies to the hot gas.

In this work, we aim to directly detect the spatial evolution of the galaxy components. For this purpose, we use the galaxy distributions divided by corresponding hot gas distributions at different redshifts. The hot gas distribution, which traces the dark matter, is indispensable to compensate for the effect of various dark matter profiles among different clusters. Since the hot gas is expected to expand toward lower redshifts, taking the relative profile also has the advantage of exaggerating the predicted redshift evolution. If our scenario is correct, this relative distribution of galaxies to hot gas should become centrally-concentrated toward lower redshifts. This will be direct evidence for explaining the origin of the observed morphology–density relation and Butcher–Oemler effect, and/or extended hot gas distributions.

2. Preliminary Result using the SDSS and XMM-Newton

As a preliminary study, we derive relative distributions of galaxies to hot gas for four galaxy clusters (with similar X-ray temperatures) at $0.073 < z < 0.282$, using the optical data from the Sloan Digital Sky Survey (SDSS) and the X-ray data from XMM-Newton. Two of them

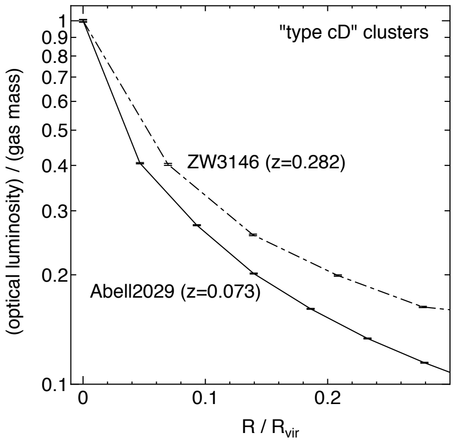

Fig. 1. The relative distributions of galaxy luminosity profiles to hot gas profiles of the two clusters, Abell 2029 at $z = 0.073$ (*solid line*) and ZW 3146 at $z = 0.282$ (*dot-dashed line*) derived from the combination of the SDSS and XMM-Neton archive data. The lower redshift cluster (Abell 2029) have steeper gradients; this suggests that galaxy members fall to the cluster center with decreasing redshift.

have the morphological R-S type (Rood & Sastry 1971) of "cD" and the other two have the R-S type of "C". To see galaxy distributions in optical, we make a luminosity profile of galaxies in each galaxy cluster as follows. First, we select all extended objects with i-band magnitudes of $i_{\rm BCG} < i < i_{\rm lim}$ (see below for the definitions), in a region with a physical radius of 2.5 Mpc at the cluster redshift (we use the current standard cosmological model throughout this paper) measured from the X-ray center. We define $i_{\rm BCG}$ as the i-band magnitude of the brightest cluster galaxy, and $i_{\rm lim}$ to detect galaxies with absolute magnitudes brighter than $M_* + 1$, including the combinations of evolution- and K-corrections. Second, we integrate fluxes of all extended objects in a circle centered on the X-ray center with an increasing radius in a step of 100 kpc, and then subtract the background flux derived from field galaxies around the cluster. Third, we normalize the luminosity profile to the flux in the central bin. To see gas mass profiles in X-ray, we first make a background-subtracted 0.5–10 keV MOS1 image (as a background, public blank sky image in the official XMM-Newton website is used), and divide it by its exposure map. X-ray surface brightnesses are square-rooted so that the profiles are nearly proportional to electron number (and hence gas mass) within each projected radius, and integrated in a circle with an increasing radius of 100 kpc. This gas mass profile is also normalized to values in the central bin.

To compare optical luminosity and gas mass distributions of different clusters, we normalize their physical distances from the X-ray centers by the virial radii ($R_{\rm vir}$) of each cluster. Then, we divide optical luminosity profiles by gas mass profiles, assuming that all galaxy members in a galaxy cluster have similar mass-luminosity ratios. While type C clusters do not show redshift evolution, type cD clusters evolve with redshift, just as we expected. The relative distribution of Abell 2029 at $z = 0.073$ is more concentrated than that of ZW 3146 at $z = 0.282$, as shown in Figure 1. Our exploratory study with small sample suggests that galaxies are falling to the cluster center while hot gas is expanding with decreasing redshifts.

3. Future Work

There are two problems to draw firm conclusion; one is too small size of the sample, and the other is that the magnitude limit in the SDSS data defined by the star-galaxy separation (Stoughton et al. 2003) is insufficient to derive galaxy distributions in detail. To solve these problems, we are now proposing deep imaging with larger telescopes for much more clusters which have XMM-Newton archival data. More importantly, we are also proposing deep (and multi-color) imaging observations for clusters at higher redshifts, in order to see the evolution of galaxy clusters backward in the history of the universe. We have a number of clusters at $0.3 < z < 0.8$ with good X-ray data quality, and are making a corresponding optical data set homogeneous for the overall redshift range of $0.1 < z < 0.8$. Then, we will be able to study the cluster evolution in a time interval of 5.5 Gyr, that is comparable to the dynamical time scale of a typical cluster, $\sqrt{R^3/GM} \sim 5$ Gyr.

References

Goto, T., et al. 2003 MNRAS, 346, 601
Jones, C., & Forman, W. 1999 ApJ, 511, 65
Kawaharada, M., et al. 2009 ApJ, 691, 971
Stoughton, C., et al. 2002 AJ, 123, 485
Rood, H.J., & Sastry, G.N. 1971 PASP, 83, 313
Zabludoff, A.I. & Mulchaey, J.S. 1998 ApJ, 496, 39