Dwarf Galaxies: From the Deep Universe to the Present
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Dwarf Galaxies and Cluster Environments

Yasuhiro Hashimoto[1], J. Patrick Henry[2] and Hans Böhringer[3]

[1]Department of Earth Sciences National Taiwan Normal University, No.88, Sec. 4, Tingzhou Rd., Wenshan District, Taipei 11677 Taiwan,
email: hashimot@ntnu.edu.tw

[2]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA

[3]Max-Planck-Institut füextraterrestrische Physik, Giessenbachstrasse D-85748 Garching, Germany

Abstract. We report an investigation of the properties of dwarf galaxies (Mr < -15) inside 26 clusters at $z = 0.15 - 0.25$, using the X-ray data from the Chandra archive, and optical images taken with Subaru Suprime-Cam. Our results include: 1. Investigation of the dwarf galaxy density distribution is sensitive to the background galaxies and the choice of colour selection of galaxies. 2. Cluster-centric dwarf-to-giant ratio is highly sensitive to the level of subtracted background galaxies. 3. A certain fraction of faint galaxies always remain undetected by the detection algorithm near the center of clusters, even after carefully treating the halo or extra diffuse light created by bright galaxies. The number of 'undetected' faint galaxies varies significantly from cluster to cluster, and even from pointing to pointing. 4. Dwarf galaxies extend up to 2 Mpc from the center in most clusters. Meanwhile, the distribution of blue dwarf galaxies extends more to the outside. 5. For a given colour, the spatial distributions of dwarf galaxies and giant galaxies become similar. Namely, the most of the radial distribution comes from the colour, rather than the size, of galaxies. 6. Relative to the NFW profile, all of the galaxy populations are showing a deficit near the cluster core ($r < 0.3$ Mpc). 7. The dwarf-to-giant ratio shows no variation against cluster measures such as the richness and X-ray luminosity, as well as various cluster X-ray characteristics related to possible dynamical status of clusters.

Keywords. galaxies: dwarf,galaxies: clusters: general,X-rays: galaxies: clusters

1. Introduction

It has long been realized that morphology of bright cluster galaxies depends on the environments, such as local galaxy density, and the cluster-centric distance. At lower luminosity, the effect of environments on dwarf galaxies is less known. Early-type dwarf galaxies, such as dwarf Ellipticals (dEs), appear to be almost exclusively located in regions of high galaxy density. In fact, they can be regarded as the typical galaxy type in galaxy clusters, where they numerically dominate the total galaxy population. They seem to be almost absent in low density regions outside of clusters and groups of galaxies. However, an opposite trend that dwarf galaxies are more common (or dwarf-to-giant ratio is higher) in lower density environments are also reported. The effect of environments on dwarf galaxies is far from being well understood.

We are conducting a systematic and homogeneous multi-wavelength investigation of the relationship between the properties of ~ 70 clusters of galaxies and their member galaxies. The cluster properties are determined using the X-ray data from the Chandra ACIS archive, and optical images taken with 34' × 27' field-of-view Subaru Suprime-Cam. The large fov of Suprime-cam enables us to probe the effects of cluster environment across a wide range of cluster-centric distances, as well as help conducting more accurate

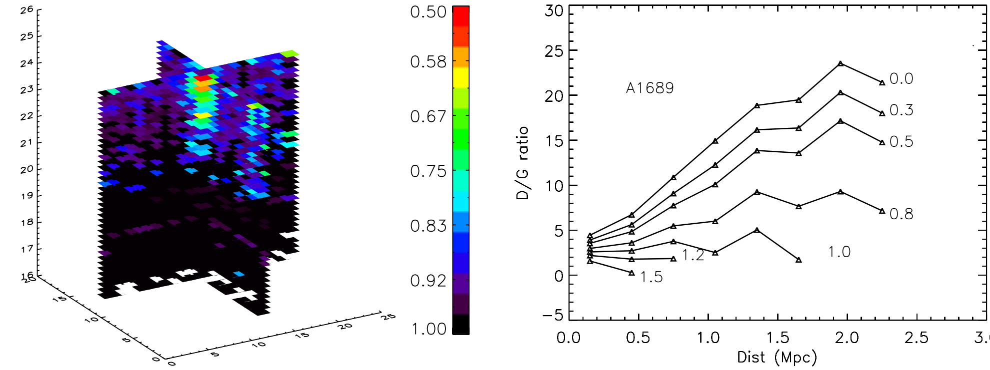

Figure 1. Left: 'Detection Correction' data cube that must be applied uniquely to the field toward cluster A1689. The vertical axis represents apparent I+ magnitude of galaxies, while the horizontal axises depict 36' x 29' fov around the cluster X-ray center. The colour in each pixel represents the inverse of the multiplicative correction one must apply to the number of galaxies. This correction is estimated by the ratio of detected galaxies to the input galaxies in the simulation using the real cluster image of Abell 1689. Right: Cluster centric dwarf-to-giant ratio profile is affected by various background subtraction levels. The number represents the factor applied to the background level estimated inside a bin centered at r $\sim$ 2.5 Mpc, e.g., 0.0 means no background subtraction is applied, and 1.0 means 100% of the background level is subtracted.

statistical background correction which is crucial for the investigation of dwarf galaxies. In this study, we report an investigation of the properties of dwarf galaxies brighter than Mr ~ -15 inside 26 clusters at $z = 0.15 - 0.25$. Our goal is to help understand the relationship between the dwarf and giant galaxies, and between the dwarfs and their host clusters, in particular, the abundance and the distribution of dwarf galaxies and variation of them under various environments. inside a cluster and outside, to eventually address the question of the formation and evolution of dwarfs and clusters of galaxies.

2. Datasets and Methods

Our sample consists of 26 clusters of galaxies around redshifts of $z = 0.15 - 0.25$ taken from Hashimoto *et al.* (2014). Our sample is designed so that all of our clusters are observed in a relatively homogeneous manner with identical filters (V and I). This particular redshift range is chosen so that we can obtain deep photometry of dwarf galaxies up to M* + 7 with a large physical fov ($\sim$ 4 Mpc) to enable a comprehensive statistical study of cluster galaxies. Our sample covers a range of X-ray bolometric luminosity (Lx $\sim 3 - 41 \times 10^{44}$ erg s^{-1}). The X-ray morphology of an individual cluster was characterized by ellipticity, asymmetry, and concentration. The optical broad band images, taken with Suprime-Cam on the Subaru telescope, were retrieved from Subaru-Mitaka-Okayama-Kiso Archive (SMOKA). We also measured the concentration index and the asymmetry of each galaxy, that were mainly used, in this study, to determine the systematics and contamination.

3. Results & Discussion

We have investigated various systematics and contamination sources related to accurately recovering the dwarf galaxies from the image. The systematics and contamination include the effect from, such as, the signal-to-noise ratio variations, the apparent angular size of galaxies, the superposed bright galaxies, and the fore-/background galaxies (Figure 1).

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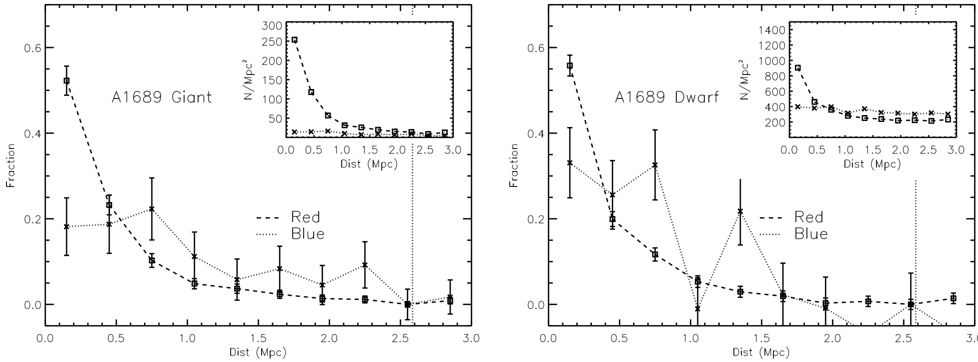

Figure 2. Left: Distribution of 'giant' ($-22.75 < I < -18.75$) galaxies over various cluster-centric distances in A1689. The number of galaxies in each bin is corrected on the basis of the detection simulation, that also includes area correction of various distance annuli. After further subtracting the background, the number fraction, the ratio of the number of galaxies in each radial bin to the total number of galaxies is then plotted in the y axis, while in the inset, the raw number density without background subtraction, but with detection correction, is plotted for comparison. Right: Distribution of dwarf galaxies ($-18.75 < I < -14.75$) over various cluster-centric distances.

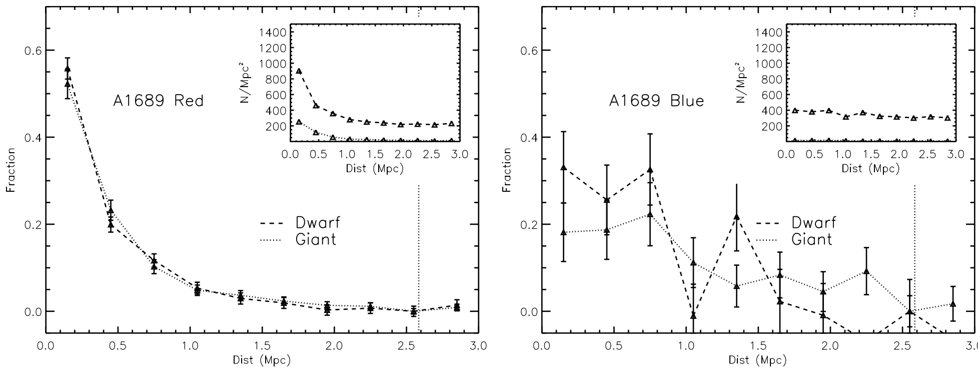

Figure 3. Left: Distributions of giant and dwarf galaxies in A1689, for red galaxies. The number of galaxies in each bin is corrected on the basis of the detection simulation, then the number fraction after subtracting the background is plotted in the y axis, while the raw number density without background subtraction is plotted for comparison in the inset. Right: Distributions of giant and dwarf galaxies in A1689 for blue galaxies. Left and right figures illustrate that the major contribution to the difference in the radial distribution comes from the colour, rather than the size, of galaxies.

Our investigation of the spatial distribution illustrates that the dwarf galaxies, for a given colour, are distributed in a similar manner with the giant galaxies inside a cluster (Figure 2, 3). This result agrees with some previous studies, such as Sanchez-Jansen *et al.* (2008), that reported the red dwarfs and red giants are showing a similar radial distribution inside a cluster. Part of the heterogeneous results in other previous studies can be mostly attributed to the heterogeneous colours of their dwarf samples (and giant samples for comparison) among various studies, as well as various levels of unwanted residual background contamination. The lack of image-by-image based 'detection correction' can also partially have contributed to the contradicting previous results near the center of clusters.

The apparent correlation of dwarf-to-giant ratio to the richness of clusters, that is qualitatively in agreement with some previous studies reporting a trend that dwarf galaxies

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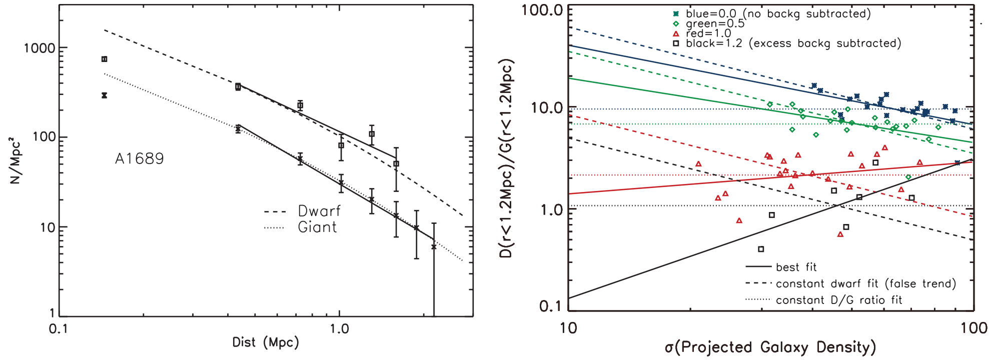

Figure 4. Left: Radial profiles of galaxy distributions inside A1689. The fitted NFW profiles are shown for dwarf (dashed line) and giant (dotted line) galaxies. The solid line represents the (logarithmic) linear fit for comparison. Both NFW and linear fits are performed by ignoring the central $r < 0.3$ Mpc. The fitted NFW are extended to the center to illustrate the lack of galaxies near the center. Right: Effect of residual background galaxies on dwarf-to-giant (DG) ratio trend. DG ratio in each cluster are plotted against the projected density of giant cluster galaxies, with various subtracted background levels. Various symbols and colours represent the various factors applied to the background levels before subtracting them from cluster samples. The solid and dashed lines correspond to the best fitted linear lines and the fits assuming constant dwarf counts (i.e. the trivial relation), respectively. The dotted lines are fitted 'horizontal' lines ('no DG trend'). The figure illustrates that often reported apparent correlation of DG ratio to the richness of cluster, typically measured by the density of giant galaxies, is suspected to be contaminated by the effect of the residual background dwarf galaxies.

are more common in low density environments, is suspected to be contaminated by the effect of the residual background dwarf galaxies, and by the fact that the giant counts (i.e. the denominator of the dwarf-to-giant ratio) and projected galaxy density are highly correlated by trivial reason (Figure 4). This interpretation is consistent with the fact that dwarf-to-giant ratio shows no correlation to galaxy density or X-ray luminosity of clusters, once the proper background subtraction is applied. This also agrees with some previous results (e.g. Driver *et al.* 1998) reporting that the dwarf-to-giant ratio in the central part of cluster shows no systematic variation with respect to the galaxy density among various clusters, because the central part of cluster is likely to be less affected by the background.

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