論文の内容の要旨

The nature of star forming galaxies and environmental influence during cluster formation
(銀河団形成期における星形成銀河の性質および環境依存性に関する研究)

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Galaxies are formed in various environments of the Universe, such as clusters, groups, fields and voids. During the last decade, we have seen a great improvement in understanding galaxy formation and evolution in field population at high redshift. Several dedicated observations on gas content and kinematics have been conducted toward star forming galaxies in general fields; at least up to z ~ 3, both a large gas content and efficient star formation explain the high cosmic star forming activity at high redshift galaxies, and turbulence in gas has been also found to increase. In contrast, such observations are lack in overdense regions at high redshift. Overdense regions in the early Universe are expected to be a progenitor of the present-day clusters of galaxies, so that we refer as protoclusters.

Probing star-forming galaxies in protoclusters is essential for understanding the formation mechanism of disks and early-type galaxies, and environmental effects at the very early epoch of cluster and galaxy formation. A few observations in overdense regions have focussed only on extremely bright populations of star-forming galaxies and AGNs, which are easy to probe in more details. Observational studies of less extreme, typical star-forming galaxies have been desired but not executed yet, because they need large survey volumes, spectroscopic confirmation of member galaxies and a proper sample selection of protoclusters. Recently, well-defined overdense regions as targets

for the studies have been increasing by large surveys, and allowed us to perform systematic surveys of star forming galaxies in overdense regions.

In this Dissertation, we report on a systemic study on the cold gas properties for the first time toward typical star forming galaxies in a z = 2.49 protocluster, which is one of the overdense regions of Hα emitters (HAEs), the star forming galaxies. We observed the HAEs in dust continuum emission at 1.1 mm and in CO rotational transitional lines (CO (3–2) and CO (4–3)) with Atacama Large Millimeter/submillimeter Array (ALMA); our sample for the study consists of 25 HAEs found by the Subaru telescope.

We probe the global gas content of the star forming galaxies associated to the protocluster by using the 1.1 mm dust continuum and CO (3–2) emissions observed at spatial resolutions of 0″.7 – 0″.9. We detect the CO (3–2) emission from seven HAEs and the 1.1 mm dust continuum from four HAEs, among 22 and 19 HAEs targeted, respectively. Two independent gas-mass estimates from the CO (3–2) and 1.1 mm are consistent with each other for simultaneous detections. From the gas measurements, we find that the average gas fraction of the star forming galaxies is comparable to that of field galaxies, with fgas(= Mgas/(Mgas + Mstar)) of 0.53±0.07. We find a correlation between the gas fraction and mass, and between the gas fraction and the local density, though the latter case is very marginal. Furthermore, we find that the average depletion-time scales of HAEs are similar to those obtained in fields. A positive correlation between the global star forming efficiency and the stellar mass is tentatively found in the mass range of log $M_\star$ = [10.64, 11.30]. Further studies are necessary for the confirmation of the correlation by observing a larger number of galaxies in a wider mass range.

We also analyze CO (4–3) data observed toward 16 HAEs, a subset of 22 HAEs observed in CO (3–2). We detect a total of ten HAEs in CO (4–3); five galaxies are previously detected in CO (3–2) line, and other five HAEs are newly detected in CO (4–3). The redshifts are roughly consistent between CO (3–2) and CO (4–3) for the five HAEs, which provides more robust detection of the CO emissions. From the CO redshifts, we calculate the halo mass of the protocluster and the estimate suggests the protocluster to be a possible candidate for local Virgo-like clusters. The spatial resolution in CO (4–3) is 0″.3 × 0″.5, which is improved by a factor of two than our previous CO (3–2) observations. Two galaxies, HAE8 and HAE16, are detected in relatively high S/N > 8, and show indications of disk-like galaxies with smooth velocity gradients in the data cubes. It allows us to make a detailed kinematic model for these galaxies. From the best-fit model, we estimate a ratio between rotational velocity (V_{rot}) and intrinsic velocity dispersion (σ_0), which evaluates how rotation dominates the gas kinematics. HAE16 shows a clear velocity gradient and $V_{rot}/\sigma_0 \simeq 2$, and HAE8 has a less clear velocity gradient with a narrower line width and $V_{rot}/\sigma_0 \simeq 10$. Provided the average value that found in fields, which is $V_{rot}/\sigma_0 \sim 4$, the ratios found for protocluster galaxies seem to be consistent with that obtained in general fields, if we consider a large scatter of the observed V_{rot}/σ_0 in field disk-like galaxies and a large uncertainty in the estimate from the modeling. We also find that these two galaxies are consistent with local spiral galaxies in terms of the specific angular momentum; they need to lose the angular momentum to evolve into elliptical galaxies. Also, they are located within the expected

range of Tully-Fisher relation at high redshift ($z \sim 2$). In addition to these disk-like population, we also find three candidates of mergers or interacting galaxies by investigating CO line widths and images in CO velocity channels together with a help of multi-band Opt/IR data sets, e.g., high spatial resolution Ks-band images. Such merger candidates need to be investigated by future deeper, higher angular resolution observations for the confirmation.

Our findings on cold gas properties suggest that the nature of protocluster galaxies is, on average, similar to those in general fields. We find no clear environmental dependence, although some tentative hints are found; (1) a larger (by 13%) scatter in gas fraction, (2) a negative correlation between depletion time scale and stellar mass (at almost fixed sSFR and redshift), and (3) a high value of $V_{rot}/\sigma_0 \simeq 10$ for one of two disk galaxies. We need to investigate such trends with a large sample of galaxies as well as with higher angular resolution imaging.