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Observational Study of Environmental Effects on Gas Deficiency of Nearby Cluster Galaxies

(近傍の銀河団銀河のガスの欠乏と環境効果に関する観測的研究)

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Abstract

Galaxy is a fundamental component of the universe. They formed from small initial perturbation observed as the cosmic microwave background radiation and have evolved into various morphologies observed in the local universe through star formation. In other words, galaxy evolution can be considered as the evolution of star formation within galaxies. Previous works have revealed that global star formation is related to their environment. For example, red- and early-type galaxies are dominant in the higher density region such as a cluster of galaxies, while blue- and late-type galaxies are dominant in the lower density region outside a cluster. Therefore environmental effect has some crucial roles for galaxy evolution. One of the most important processes in environmental effect is ram pressure stripping of gas in galaxies. It is found that most galaxies located near the core of a cluster have lower atomic gas mass than that in isolated galaxies. As for molecular gas, some studies have revealed that molecular gas mass of cluster galaxies are also depleted compared to that of isolated galaxies through analysis of volume limited sample of galaxies, and considered that it is also due to ram pressure. If ram pressure stripping is also the dominant process for depletion of molecular gas, the deficiency of molecular gas should be related to the parameters that characterize objective clusters. Thus in order to reveal the mechanism that causes H_2 deficiency, we derive molecular gas mass of galaxies in some clusters that are in different evolutionary stages and investigate relationships between H_2 deficiency of cluster galaxies and the parameters that characterize each cluster.

In order to obtain molecular gas data of galaxies in clusters with different evolutionary stage with previously observed clusters, we observed $^{12}\text{CO}(J = 1 - 0)$ line in three galaxies (CGCG 108-121, IC 1173, CGCG 108-146) in the Hercules cluster using the 45-m radio telescope in the Nobeyama Radio Observatory. This cluster seems to be younger than the clusters whose galaxies have already observed in $^{12}\text{CO}(J = 1 - 0)$; the Virgo cluster, the Coma cluster, and Abell 1367. We could detect the emission in all three galaxies with signal-to-noise ratio of > 3.0 . The molecular gas masses are estimated as $\log M_{\text{H}_2} (M_{\odot}) = 9.2\text{--}9.4$. In order to compare the gas mass in the cluster galaxies with that in isolated galaxies, we derive H_2 deficiency from a relation between molecular gas mass and near infrared (H -band) luminosity, and HI deficiency from empirical relation between atomic gas mass and diameter of optical galactic disk for isolated galaxies. As a result, the observed three galaxies have possibility to be H_2 -deficient despite of having normal contents of atomic gas.

As well as the Hercules cluster galaxies, we derive HI deficiency and H_2 deficiency of cluster galaxies in the Virgo, the Coma, and Abell 1367 clusters using archival data. It is found that gas deficiencies have no clear correlation with both velocity dispersion and X-ray temperature

of the belonging cluster which represent dynamical state of belonging cluster. However, it seems that there is no H_2 -rich galaxy in the cluster with lower velocity dispersion, while no HI-deficient galaxy in such cluster. This might imply that global environment such as ram pressure removes atomic gas, while it has little effect on molecular gas.

Moreover, we investigate two alternative possibilities that cause the depletion of gas; galaxy–galaxy interaction and internal effect such as star formation activity and active galactic nucleus (AGN) feedback. Since the effect of galaxy–galaxy interaction is thought to be represented by local density of galaxies, we explore correlation between the local density and the gas deficiencies. However, there is no significant correlation between them. In addition, in order to explore the other possibility for exhaustion of molecular gas due to star formation, we examine relations between the gas deficiencies and star formation activities; star formation rate (SFR), stellar mass, and specific star formation rate ($\text{sSFR}=\text{SFR}/\text{stellar mass}$) for both isolated and cluster galaxies. The results show that the both deficiencies tend to be larger with star formation becoming passive, or with SFR and sSFR decreasing and with stellar mass increasing, independent of their environment. Furthermore we obtain positive correlations between the gas deficiencies and emission line ratio $[\text{NII}]/\text{H}\alpha$ as a tracer of nuclear activity for AGN–host galaxies especially in the case of H_2 deficiency. Therefore we can interpret that molecular gas is deficient due to star formation and/or AGN feedback.

Based on the above results, we discuss the consumption of gas on a plot of HI deficiency and H_2 deficiency. There is a weak positive correlation between them, which is consistent with a previous study. In order to reveal this correlation, we firstly examine principal component analysis for 41 cluster galaxies in which all of the above data are available. As a result, we obtain three composed variables which correlate with internal processes (star formation and nuclear activity), with local environment, and with global environment, respectively. We perform regression analysis and represent HI deficiency and H_2 deficiency by these three composed variables. It is found that the only variables which represent internal effect have a positive component of H_2 deficiency. This implies that the internal effect removes molecular gas. On the other hand, the direction that global environment becomes effective on the plot does not have a component of H_2 deficiency and corresponds to the direction that HI deficiency becomes large. Therefore, the global environment seems to have no relation to the depletion of molecular gas and to remove only atomic gas. In this way, it is revealed that cluster galaxies deplete their gas mainly due to internal mechanisms such as star formation and/or AGN feedback, and the global environment removes only atomic gas and hardly contribute to the depletion of molecular gas.

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1 Introduction

1.1 Cluster of Galaxies

1.1.1 General Properties

Galaxies are fundamental components of the universe. They formed from small initial perturbation observed as the cosmic microwave background radiation and have evolved into various morphologies observed in the local universe. Spatial distribution of galaxies is not uniform in the universe and a majority of nearby galaxies belong to a cluster of galaxies, which is the most massive gravitationally-bound object. Typical mass of a cluster of galaxies is $\sim 10^{14}M_{\odot}$ and typical diameter is ~ 5 Mpc. For example, over 2000 galaxies belong to the Virgo cluster that is the closest cluster from our Galaxy.



Figure 1 Image of and example of cluster of galaxies, Abell 2744 obtained with the Hubble Space Telescope (<http://hubblesite.org/gallery/>).

1.1.2 Dependence of Morphology and Color Environment

In higher local density region such as a cluster of galaxies, red- and early-type galaxies are dominant, and in contrast blue- and late-type galaxies are dominant in lower local density region. This is known as the morphology-density relation (Dressler 1980; Postman & Geller 1984), which is presented in figure 2. Here the local density represents how many galaxies there

are in their neighborhood. These studies have concluded that the local density is more tightly connected to morphology of galaxy, than the distance to the center of the nearest group. On the other hand, Whitmore & Gilmore (1991) and Whitmore, Gilmore, & Jones (1993) have claimed that the distance to the center of group have close connection to morphology than the local density. In addition, morphology–density relation has been found also at higher redshift $z \sim 0.5$ –1 (e.g., Dressler et al. 1997).

Moreover, it has been well known that there is a relationship between environment and color; the fraction of blue galaxies in cluster has decreased since $z \sim 0.5$ –1, which is called Bucher–Oemler effect (e.g., Butcher & Oemler 1984; Rakos & Schombert 1995). This has been confirmed using the sample of the Slone Digital Sky Survey (SDSS) even considered selection bias of the cluster and cluster members (Goto et al. 2003). Therefore it is predicted that blue late-type galaxies in a cluster of galaxies evolve rapidly and star formation in a cluster galaxy is quenched by environmental effects.

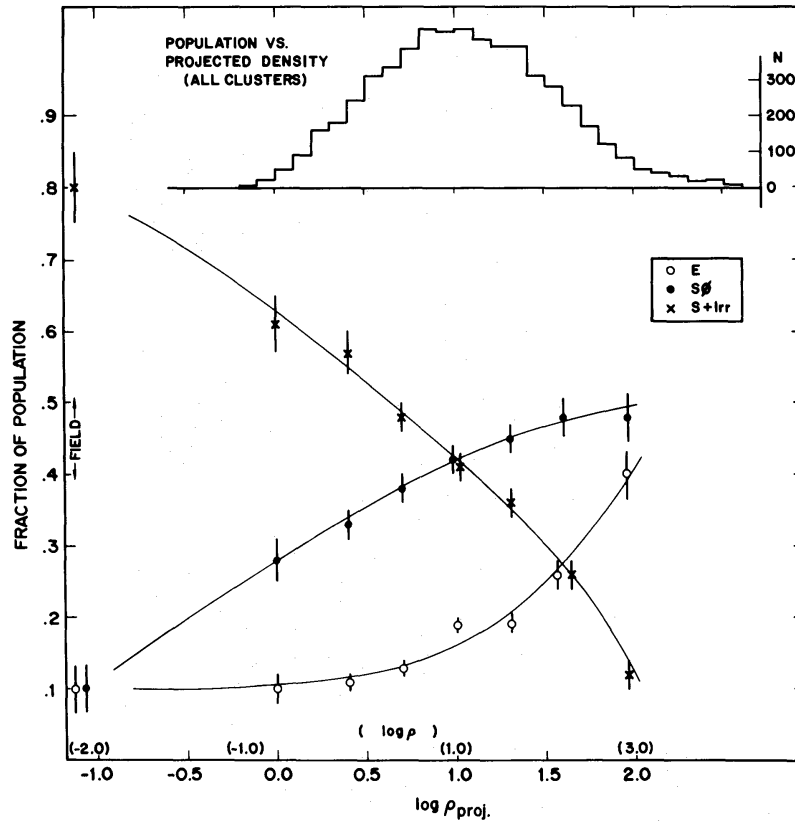


Figure 2 Morphology–density relation (Dressler 1980). Horizontal axis represents the local projected number density of galaxies and vertical axis represents the fraction of galaxy with each morphology. Empty circle, filled circle, and x-mark are elliptical, lenticular, and spiral and irregular, respectively. The histograms of the projected number density for all morphological type galaxies is also shown.

Recent observational results also have shown a bimodal distribution on color–magnitude diagram (e.g., Strateva et al. 2001; Bell et al. 2004). Red and luminous galaxies are called red sequence and blue and low-luminous galaxies are called blue cloud. The stellar mass density, which is representative of galaxy stellar mass, of the red sequence has increased a factor of 2 since $z \sim 1$. On the other hand, that of the blue cloud has not increased despite of forming stars (Bell et al. 2007; Faber et al. 2007; Brown et al. 2007). Therefore the quenching scenario that blue cloud ceases star formation and migrates to red sequence can explain the evolution of stellar mass densities.

The quenching of star formation has been thought to depend on stellar mass and environment (Peng et al. 2010). These are independent processes, which called mass–quenching and environment–quenching. However, the concrete mechanisms that involve each quenching are not clear. For mass–quenching, halo quenching (Rees & Ostriker 1977; Birnboim & Dekel 2003; Kereš et al. 2005) and active galactic nucleus (AGN) feedback (e.g., Fabian 1999; Granato et al. 2004; Hopkins et al. 2006) have been proposed as the physical process. In the halo–quenching scenario, cold accretion from halo to a galaxy contributes star formation in the galaxy with the lower mass halo ($< 10^{12} M_{\odot}$), on the other hand, the infalling gas toward a galaxy reaches the sound speed and the resultant shock prevents further accretion of gas in the case of the massive halo ($> 10^{12} M_{\odot}$). Thus the residual gas is used up by star formation with relatively longer timescale. On the other hand, the AGN heats or expels the surrounding gas, which might suppress star formation. Since the most AGN–host galaxies have been found in transition region between red sequence and blue cloud, there is a possibility that AGN feedback links to the quenching of star formation (Martin et al. 2007; Schawinski et al. 2007). The physical mechanisms of environment–quenching have been also proposed so far and is described in the next subsection.

1.2 Physical Process of Environmental Effects

Several physical processes involved to environment-quenching in a cluster of galaxy have been suggested so far. Following physical processes transmute distributions of gas and dust in a galaxy for the hydrodynamic interaction and those of also stars and dark matter for gravitational interaction.

1.2.1 Hydrodynamic Interaction

Since a cluster galaxy moves through hot ($\sim 10^7$ – 10^8 K) and dense ($\sim 10^{-3}$ – 10^{-4} atoms cm^{-3}) gas in cluster of galaxy at high speed (~ 1000 km s^{-1}), it is forced by ram pressure. The ram pressure, P , is given by

$$P \sim \rho_{\text{IGM}} V_{\text{gal}}^2, \quad (1)$$

where ρ_{IGM} is the density of intergalactic/intracluster medium (IGM) and V_{gal} is the velocity of galaxy relative to the IGM. When the force of the ram pressure exceeds the gravitational restoring force within a galaxy, or

$$P > 2\pi G \Sigma_{\text{star}} \Sigma_{\text{gas}}, \quad (2)$$

gas in the galactic disk is stripped (Gunn & Gott 1972). Σ_{star} and Σ_{gas} are surface density of star and gas, respectively. In Boselli & Gavazzi (2006), a comparison of an average ram pressure within the cluster with the gravitational pressure of cluster galaxies in nearby three clusters (Virgo, Coma, and Abell 1367) has been explored. The galaxy velocity was assumed to be $V_{\text{gal}} = (3\delta V_{\text{cluster}}^2)^{1/2}$, where $\delta V_{\text{cluster}}$ is the velocity dispersion of spiral galaxies in the cluster. The gas surface density was estimated by adding the atomic gas surface density and molecular gas surface density, and the molecular gas was assumed to be 15% of total gas for galaxies without H_2 data. The results have shown that the ram pressure is larger than the gravitational pressure in most galaxies (figure 18 in Boselli & Gavazzi 2006). Therefore it is expected that gas would be removed due to ram pressure in galaxies whose velocity is larger than the velocity dispersion within the cluster. This speculation that diffuse gas is stripped by ram pressure has been also followed by numerical simulation (e.g., Vollmer et al. 2001), and it is found that the timescale of ram pressure to perturb the gas disk is relatively short (e.g., < 300 Myr in Vollmer et al. 2004).

Two other processes are proposed as the hydrodynamic interaction of interstellar medium (ISM) with IGM; viscous stripping (Nulsen 1982) and thermal evaporation which is the effect of heating of the cold ISM in outer region of a galaxy by the hot IGM (Cowie & Songaila 1977). However the mass-loss rate due to ram pressure is dominant over the other two processes for

large galaxies, although the rate is different from one cluster to another (Boselli & Gavazzi 2006).

1.2.2 Gravitational Interaction

Tidal interaction among galaxies is proportional to M/R^3 , where M is the mass of the other galaxy and R is the separation between galaxies. It has been suggested that the tidal interaction removes matter from galactic halos and perturbed gas disks (e.g., Valluri & Jog 1990). However, duration time of the tidal interaction among galaxies in a cluster is shorter than in the field due to high relative velocity in the cluster. In addition, the frequency of galaxy–galaxy encounters is not high in the timescale of the universe (e.g., Byrd & Valtonen 1990). Therefore it seems that the effects of tidal interaction among galaxies is less severe in a cluster of galaxy. On the other hand, tidal interaction between a galaxy and cluster potential well has been proposed as an effective process in a cluster of galaxies in the case of its mass of $> 10^{14} M_{\odot}$ (Merritt 1984; Mamon 1987). It has been shown that the tidal interaction enhances nuclear activity and star formation activity and as a result, decreases gas content (Boselli & Gavazzi 2006).

Furthermore, a frequent high–speed and closer encounter (~ 50 kpc) is called galaxy harassment (Moore et al. 1996). This causes a heating of stellar component, decreasing angular momentum, and infall of gas toward the galaxy center. NGC 4254 in the Virgo cluster is a candidate of object that influenced by galaxy harassment because of an extreme long tail of HI gas with no stellar counterpart (Haynes, Giovanelli, & Kent 2007).

1.2.3 Relative Effects

A lack of infall of gas from galaxy halo suppresses further star formation within the disk, which is called starvation or strangulation (Larson, Tinsley, & Caldwell 1980). This is thought to be necessary for translation from a spiral galaxy to a lenticular galaxy. In addition, above these physical process are effective even in a group of galaxies which is falling into a rich cluster (e. g., Fujita 2004). This process is known as preprocessing. The relative effect of the above processes (hydrodynamical interaction with cluster IGM, tidal effect, harassment, starvation, and preprocessing) has been suggested to depend on the distance to the cluster core (e.g., Treu et al. 2003). The hydrodynamic interaction with cluster IGM and tidal interaction have been thought to be important in the cluster center, while the harassment, starvation, and preprocessing might be effective outside the cluster core.

1.3 Gas Deficiency

Stars are formed in molecular cloud that mainly consists of molecular hydrogen. The molecule is formed from atomic hydrogen on dust grain surface that works as catalysis. Thus contents of molecular gas and atomic gas are important to formation and also suppression of star formation.

1.3.1 Atomic Gas

It is found that atomic gas mass in isolated galaxies is closely correlated with their optical diameter. In order to compare atomic gas mass in cluster galaxies to that in the isolated galaxies, Haynes & Giovanelli (1984) proposed a parameter represents the degree of deficiency of atomic gas. This is defined as the logarithmic difference between the observed atomic gas mass and the expected mass, or

$$\text{HI deficiency} \equiv \log M_{\text{HI,expected}} - \log M_{\text{HI,observed}}, \quad (3)$$

where $M_{\text{HI,expected}}$ is the expected atomic gas mass and derived from empirical scaling relation between a size of optical disk and atomic gas mass. In Haynes & Giovanelli (1984), this scaling relation was determined for each Hubble type from 324 isolated galaxies. $M_{\text{HI,observed}}$ is the atomic gas mass obtained from the HI 21-cm observation. A galaxy with positive HI deficiency implies that atomic gas of their disk is depleted comparing with the averaged isolated galaxies.

Various studies used this parameter and derived that cluster galaxies have less atomic gas content compared to isolated galaxies that have the same Hubble type and the same size of optical disk (e.g., Haynes & Giovanelli 1984; Gavazzi et al. 2005). In Solanes et al. (2001), the atomic gas content for a total of 1900 spiral galaxies in 18 nearby clusters were examined. They concluded that two thirds of the clusters are HI-deficient inside the Abell radius which is defined as $1.7(\text{arcsec})/z$, where z is redshift.

In isolated spiral galaxies, atomic gas is distributed over ~ 1.8 times the optical disk (Cayatte et al. 1994). Thus atomic gas is thought to be weakly bounded by the galactic-gravitational potential well. Therefore it is speculated that atomic gas tends to be influenced by external environment. Since the cluster galaxies move fast through the hot and dense gas in the core of the cluster, they lose the atomic gas by ram pressure. This scenario is commonly accepted as the cause of the HI deficiency (Haynes, Giovanelli, & Chincarini 1984).

There are mainly two observational results that reinforce this scenario. First, a high-resolution HI mapping directly shows stripping event (e.g., Chung et al. 2009, see figure 3). The second one is that HI deficiency of cluster galaxies varies depending on the distance from the cluster core (Gavazzi et al. 2005; Gavazzi et al. 2006). The completed HI observation

of late-type CGCG galaxies in the Coma supercluster shows this relation (figure 4). Since ram pressure is proportional to density of IGM and square of velocity of galaxy (equation (1)), the stripping by ram pressure is thought to be enhanced in cluster core region.

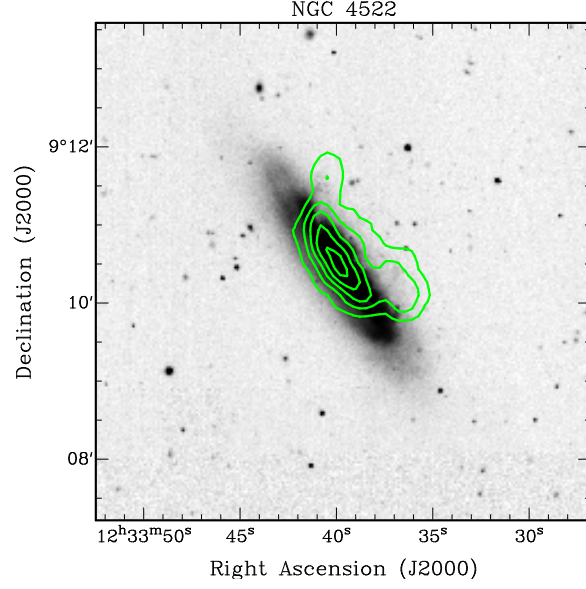


Figure 3 Contours of HI 21-cm emission (Chung et al. 2009) overlaid on SDSS image of NGC 4522.

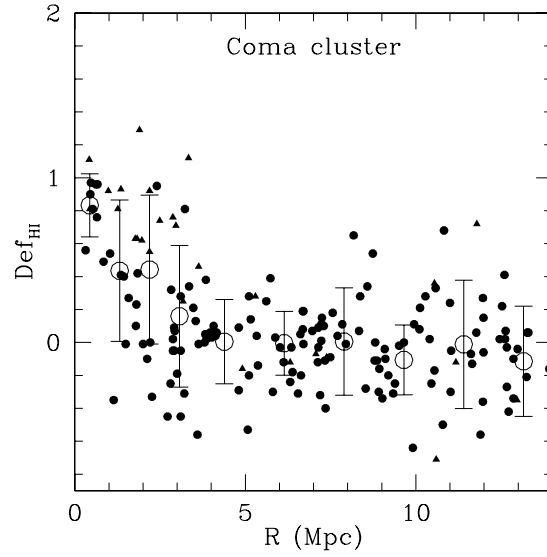


Figure 4 HI deficiency as a function of the distance from the Coma cluster core (Gavazzi et al. 2006).

1.3.2 Molecular Gas

Since molecular hydrogen does not have permanent electric dipole moment, it cannot radiate any emission at low temperature (10–20 K) in molecular clouds. Alternatively $^{12}\text{CO}(J = 1-0)$ emission line is used as a tracer of molecular hydrogen. Assuming CO-to- H_2 conversion factor, $X = N_{\text{H}_2}/I_{\text{CO}}$, where N_{H_2} is column density and I_{CO} is velocity integrated intensity of $^{12}\text{CO}(J = 1-0)$ emission line, we can estimate the column density of molecular hydrogen.

The first study of the contents of molecular gas in a cluster galaxy is Stark et al. (1986). Some previous works have shown that the cluster galaxies have similar amount of molecular gas to that of isolated galaxies, for the Virgo cluster (Kenney & Young 1989) and for the Coma cluster (Casoli et al 1996). This is thought to be because molecular gas is bounded more tightly inside the potential well than atomic gas.

On the other hand, Kenney & Young (1988) suggested that low-luminous cluster galaxies have poor molecular gas. However, these samples are biased toward molecular gas rich galaxies since they are selected based on far infrared luminosity. Boselli et al. (1997) observed optical-selected sample of spiral galaxies and suggested that cluster galaxies have similar amount of molecular hydrogen to the isolated galaxies. The authors have defined H_2 deficiency based on H -band luminosity and optical radius. The H_2 deficiency is given the logarithmic difference between the observed and expected molecular gas mass in the same way as HI deficiency in Haynes & Giovanelli (1984),

$$\text{H}_2 \text{ deficiency} \equiv \log M_{\text{H}_2, \text{expected}} - \log M_{\text{H}_2, \text{observed}}. \quad (4)$$

In addition, Boselli et al. (2002) have pointed out that using constant CO-to- H_2 conversion factor is not valid. The authors have shown that the conversion factor varies by a factor of 10 depending on the UV radiation field, metallicity, morphological type, and H -band luminosity. In fact, in the case of using H -band luminosity dependent conversion factor, it is found that the molecular gas mass of cluster galaxies is not different from that of isolated galaxies (Boselli et al. 2002).

Recent observations have shown cluster galaxies have lower molecular gas than isolated galaxies (Fumagalli et al. 2009; Scott et al. 2013). Fumagalli et al. (2009) have suggested that H_2 deficiency is caused by just depletion of atomic gas. Figure 5 (from figure 5 in Fumagalli et al. 2009) shows that the molecular gas is depleted from outside and that occurs only when total gas surface density becomes lower than $\sim 10 M_{\odot} \text{ pc}^{-2}$. This value is critical surface density to transform from atomic hydrogen to molecular hydrogen (Krumholz et al. 2009). Thus H_2 deficiency becomes large when HI deficiency is significantly large, or molecular gas is depleted in not only outer HI region but also the inner region (figure 5). On the other hand, although a statistical analysis have shown also the possibility of depletion of molecular gas in

galaxies in cluster, the authors have concluded that the depletion is attributed to ram pressure stripping through comparing timescale of star formation with that of the stripping (Boselli et al. 2014). To summarize, the amount of molecular gas in cluster galaxies is probably lower than that in isolated galaxies, but the cause of this depletion is not clear.

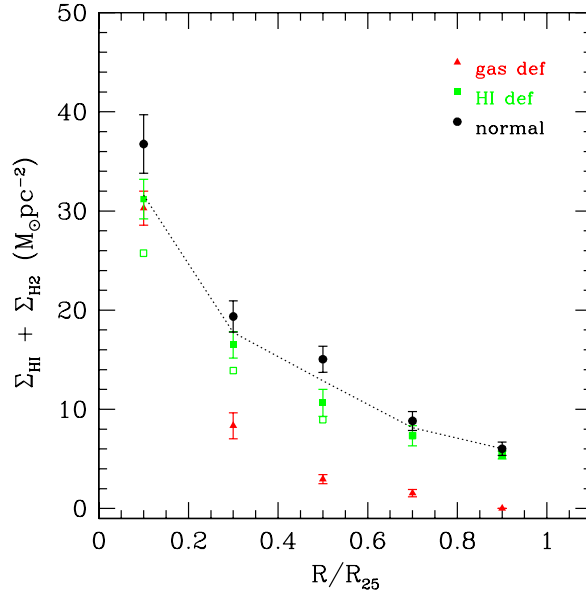


Figure 5 Total gas surface density as a function of radius of galactic disk (Fumagalli et al. 2009). Red triangle indicates the average of total gas surface density of both HI- and H₂- deficient galaxies. Green squares indicates HI deficient but H₂ normal galaxies. Black circle indicates normal galaxies. It is found that the molecular gas is lost from outside and that occurs only when total gas surface density becomes lower than $\sim 10 M_{\odot} \text{ pc}^{-2}$.

1.4 Strategy

1.4.1 Aim of This Thesis

It is established that galaxies in a cluster evolve faster than isolated galaxies. In other words, the transition from blue cloud to red sequence is effective in cluster galaxies due to the environmental effects such as ram pressure. In fact, recent observational studies have shown depletion of molecular gas in cluster galaxies. However, the cause for depletion of molecular gas is not clear. If ram pressure stripping is dominant process for this, the deficiency of molecular gas should be related to the parameters that characterize objective clusters. In order to reveal the mechanism that causes H_2 deficiency of cluster galaxies, we derive molecular gas mass of galaxies in some clusters.

1.4.2 Target Cluster

In order to obtain molecular gas data of galaxies in a cluster in different evolutionary stage with previously observed clusters, we selected the Hercules cluster (figure 6). Since the fraction of spiral galaxies in the Hercules cluster is much higher than that in other nearby clusters in the Dressler's catalogue (Dressler 1980), this cluster is thought to be younger than other clusters such as the Virgo cluster and the Coma cluster. In addition, the flat morphology of the Hercules cluster and the presence of at least three distinct regions with different dwarf-to-giant galaxy ratio (Sanchez-Janssen et al. 2005) show that this cluster does not appear to be in relaxed state. Therefore, the Hercules cluster has been thought to be still in the process of evolution as cluster of galaxies.



Figure 6 DSS B -band image of the Hercules cluster region ($0.4^\circ \times 0.4^\circ$).

2 Observation with the Nobeya 45-m Radio Telescope

2.1 Target Selection

We selected targets from galaxies in the Hercules cluster. First of all, we determined candidates of the member galaxies from following seven catalogues with systemic velocity of $8000 \leq v_{\text{LSR}} \leq 15000 \text{ km s}^{-1}$; Dressler (1980); Maccagni et al. (1995); Butcher & Oemler (1985); Fasano et al. (2002); Zhao et al. (1989); Cedres et al. (2009); Dickey (1997). From 107 spiral galaxies in this parent sample, we further selected 54 spiral galaxies that included in the Two Micron All Sky Survey (2MASS) extended source catalog (Jarrett et al. 2000) in order to estimate the H_2 -deficiency parameter. As described in section 1, H_2 deficiency expresses how much deficient in molecular gas mass in a galaxy compared with that in galaxy having similar H -band luminosity. Furthermore, in order to examine the relation to atomic gas contents, we selected 10 spiral galaxies that had already observed in HI 21-cm line and are included in data set of Giovanelli & Haynes (1985). We selected CGCG 108-121 and IC 1173 since they did not show interaction with other galaxies and their SFRs had been already estimated by Petropoulou et al. (2011). Since HI deficiencies estimated by Giovanelli & Haynes (1985) in CGCG 108-121 and IC 1173 are negative, we selected CGCG 108-146 whose HI deficiency is positive value ^{*1}. We finally observed three spiral galaxies; CGCG 108-121, IC 1173, and CGCG 108-146. We show images from the Slone Digital Sky Survey (*SDSS*) and a table about properties of observed galaxies below (figure 7 and table 1).

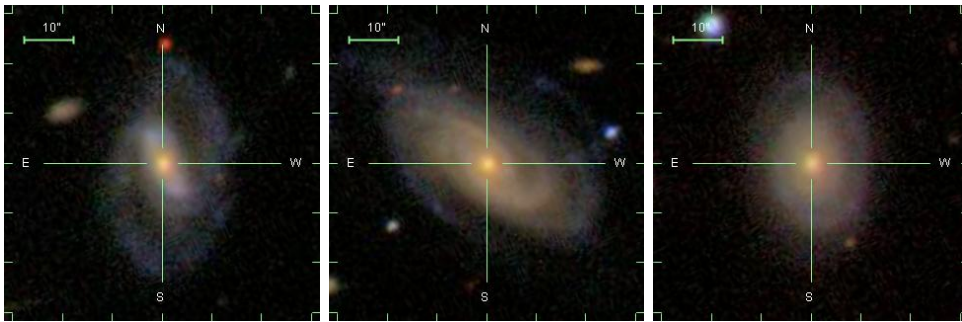


Figure 7 *SDSS* images of CGCG 108-121, IC 1173, and CGCG 108-146 respectively from left to right. The horizontal bar drawn in each image represents angular size of $10''$.

^{*1} However, the HI deficiencies that re-defined by us are slightly different from those in Giovanelli & Haynes (1985).

Table 1 The basic properties of observed galaxies

(1)	(2)	(3)	(4)	(5)
Galaxy	RA	DEC	V_{LSR} (km s $^{-1}$)	D_{25} (arcsec)
CGCG 108–121	16 ^h 05 ^m 30.63 ^s	+17°46′07.17″	10803	42
IC 1173	16 ^h 05 ^m 12.56 ^s	+17°25′22.33″	10096	57
CGCG 108–146	16 ^h 06 ^m 14.26 ^s	+18°24′52.05″	10777	38

References of (2), (3) *SDSS* data release 6 (<http://cas.sdss.org/dr6/en/tools/explore/>), (4) (CGCG 108–121, IC 1173) Third Reference Catalog of Bright Galaxies (RC3), (CGCG 108–146) Daniel (1999), (5) RC3.

2.2 Observation

We observed $^{12}\text{CO}(J = 1 - 0)$ line in the three galaxies in the Hercules cluster using the 45-m radio telescope in the Nobeyama Radio Observatory (NRO, Figure 8) on March and April 2014. The half-power beam width (HPBW) of the telescope was $\sim 16''$ at 115 GHz, corresponding to ~ 12 kpc at the distance of 150 Mpc, which we adopted for the distance of the Hercules cluster. The observed line frequency shifted from the rest-frequency of 115.271 GHz to 111.117–111.389 GHz due to the redshift of the objects. We performed pointing observations of one position per each galaxy with the two-beam (beam1, 2) dual-polarization (H, V) sideband-separating SIS receiver, TZ (Nakajima et al. 2013). The two beams of this receiver provided us to observe continuously on-source by turning toward on-source and off-source in the each receiver alternatively. Hence this on-on observation reduced the observational time. We used digital FX-type spectrometer SAM45 (Kamazaki 2012). The frequency resolution and band width were 244 kHz and 1 GHz, respectively. The corresponding velocities are 0.658 km s $^{-1}$ and ~ 2700 km s $^{-1}$ at observed frequency of 111.2 GHz.



Figure 8 The 45-m radio telescope in the Nobeyama Radio Observatory.

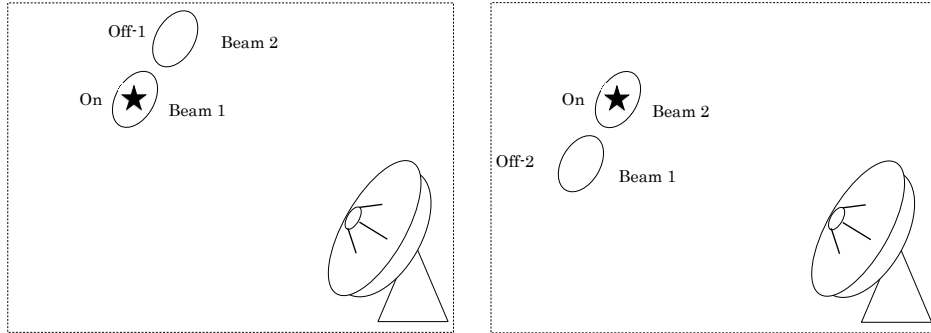


Figure 9 On-on observation. We observed on-source like left panel and right panel alternatively.

We measured an image rejection ratio (IRR) at the center of the IF before each observation, which was 10.2–19.3 dB. The system-noise temperature during our observation was typically 150–400 K. We checked the accuracy of the telescope pointing by observing SiO masers U-Her in 43 GHz line every one hour using H40 receiver, which ensured the pointing accuracy better than $\sim 7''$. When U-Her was at lower elevation than 20° , S-Crb was observed alternatively.

2.3 Data Reduction

The spectral data were reduced with NEWSTAR software package, which was developed by NRO based on the Astronomical Image Processing System (AIPS). We excluded the bad data which were obtained in the condition of wind speed $\geq 5 \text{ m s}^{-1}$. We subtracted the baseline which were determined by fitting the original spectral data in a velocity range where no galactic emission was expected with a linear function. If the residual baseline was not flat after subtraction, we did not use the spectrum. In order to determine the spectrum with bad baseline, spectra were smoothed with wide range ($\sim 170 \text{ km s}^{-1}$) compared to the final velocity resolution of 50 km s^{-1} . In the case of random noise, the rms noise temperature after smoothing is expected to be small by a factor of the reciprocal of square root of the number of binding. Therefore we recognized the spectrum whose rms noise temperature after smoothing is larger than the expected one as the bad data.

The observed intensities were converted from T_{A}^* scale to $T_{\text{mb}} (= T_{\text{A}}^* / \eta_{\text{mb}})$ scale, here η_{mb} is the main beam efficiency of the antenna. We adopted either 0.29 in beam1-H, 0.31 in beam1-V, 0.38 in beam2-H, or 0.34 in beam2-V for η_{mb} . Since one day the observation was performed with a little snow resided on the antenna surface, we further calibrated through comparing the antenna temperature of a standard source, IRC 10216, with the one in other days. Moreover, the intensity were corrected by a following factor,

$$f = 1 + \frac{1}{10^{\text{IRR}/10}}. \quad (5)$$

The final rms became 3.6–5.0 mK in T_{mb} scale at 50 km s^{-1} resolution. The total on-source time was 1.7–2.8 hours in each galaxy.

3 Data Analysis of Archival Data

In order to understand the environmental effects on quenching of star formation in nearby clusters of galaxies, we considered the contents of gas and the properties of star formation using archival data in addition to our own observational data. In this section, we describe samples, methods of deriving physical quantities, and finally effects of a selection bias of isolated galaxies and cluster galaxies.

3.1 Samples

3.1.1 Samples of Isolated Galaxies

In order to collect a number of samples and define the deficiencies of HI and H₂ individually, we prepared two sets of isolated galaxies. One contained isolated galaxies for deriving HI scaling relation between atomic gas and typical sizes of galactic disks, D_{25} and the other was for H₂ scaling relation between molecular gas mass and a H -band luminosity. First of all, both isolated samples were selected from the Two-Micron All-Sky Survey (2MASS) Isolated Galaxies Catalog (2MIG; Karachentseva et al. 2010). We selected 2617 galaxies satisfying that the Hubble type was later than Sa. Moreover we selected 2072 galaxies that have recession velocities $\leq 12000 \text{ km s}^{-1}$ were selected in order to cover the same distance as the Hercules clusters of galaxies. We fixed these samples as parent samples in the isolated and, individually extracted the objective samples for HI and H₂ scaling relation.

We cross-matched the galaxies in the parent sample with HI-detected galaxies included in the $\alpha.40$ catalog (Haynes et al. 2011) to determine the HI scaling relation for the samples. This catalog covers 40% of the final survey area of Arecibo Legacy Fast Arecibo H -band Feed Array survey (ALFALFA; Giovanelli et al. 2005), which is the blind extragalactic HI survey with the Arecibo radio telescope. We also cross-matched with the Third Reference Catalogue of Bright Galaxies (RC3; de Vaucouleurs et al. 1991) to bring D_{25} for scaling relation. Finally, we equipped 66 galaxies as the samples to derive HI scaling relation.

For H₂ scaling relation, we cross-matched the parent samples with the catalog of following four survey projects observing $^{12}\text{CO}(J = 1 - 0)$ emission line.

1. $^{12}\text{CO}(J = 1 - 0)$ observations in Analysis of the Interstellar Matter of Isolated Galaxies (AMIGA; Lisenfeld et al. 2011)

The AMIGA sample has been chosen from the Catalog of Isolated Galaxies (CIG; Karachentseva 1973) and satisfied $m_{\text{B,corr}} \leq 15.0 \text{ mag}$ and $\delta > -3^\circ$ (Verdes-Montenegro et al. 2005). The CIG catalog contains only isolated galaxies, which have no similar sized galaxies with diameter, d in neighborhood of $20 \times d$. In Lisenfeld et al. (2011), the

molecular gas mass estimated from the emission of $^{12}\text{CO}(J = 1 - 0)$ are collected for 173 galaxies in the velocity range between 1500 and 5000 km s^{-1} . Galaxies that have been observed in $^{12}\text{CO}(J = 1 - 0)$ emission but are located outside this velocity range is added, and eventually the $^{12}\text{CO}(J = 1 - 0)$ data for 273 galaxies are presented.

2. The CO Legacy Data base for the *GALEX* Arecibo SDSS Survey (COLD GASS; Saintonge et al. 2011)

The 366 target galaxies were observed in $^{12}\text{CO}(J = 1 - 0)$ emission line in the third COLD GASS (Saintonge et al. 2012). These were selected at random from the GASS survey, which was designed to measure the HI content for a large-unbiased sample of ~ 1000 massive galaxies (Catinella et al. 2010). The target of GASS survey were also selected at random from the parent samples of galaxies that satisfy the following criteria: (1) located within the area of overlap of the SDSS spectroscopic survey, the ALFALFA survey and the *GALEX* Medium Imaging Survey (MIS), (2) the redshift range of $0.025 < z < 0.05$, (3) a stellar mass range of $10^{10} M_{\odot} < M_{\text{stellar}} < 10^{11.5} M_{\odot}$. Thus, the COLD GASS sample of galaxies were unbiased for color, morphology, or any other parameters but distance and stellar mass.

3. $^{12}\text{CO}(J = 1 - 0)$ observations in *Herschel* Reference Survey (HRS; Boselli, Cortese, and Boquien 2014)

The HRS is an *Herschel*/SPIRE guaranteed time key project aimed at observing a complete, K -band selected ($K \leq 8.7$ mag for early-type galaxies, $K \leq 12$ mag for morphological type $\geq \text{Sa}$), volume-limited ($15 \lesssim D \lesssim 25$ Mpc) sample of galaxies (Boselli et al. 2010). The 322 target galaxies were observed in this survey. In Boselli et al. (2014), K -band selected ($K < 10$ mag) late-type galaxies were observed in $^{12}\text{CO}(J = 1 - 0)$ emission line. The CO observational data for 255 galaxies including previous studies from literatures were presented.

4. Nobeyama CO Atlas of Nearby Spiral Galaxies (Kuno et al. 2007)

This survey performed mapping observations of $^{12}\text{CO}(J = 1 - 0)$ in 40 nearby spiral galaxies with the Nobeyama 45-m telescope. These samples were selected based on the following criteria: (1) Morphological type ranging from Sa to Scd, (2) distance of less than 25 Mpc, (3) an inclination angle less than $< 79^\circ$, (4) flux density at 100 μm in the IRAS Point Source Catalogue higher than ~ 10 Jy, and (5) spiral structure not destroyed by interactions with other galaxies.

We selected CO-detected galaxies from these four survey and cross-matched with the parent samples. Finally, 86 spiral galaxies to derive H_2 scaling relation are prepared. Summarizing the above, we determined 66 isolated galaxies for HI scaling relation and 86 isolated galaxies for H_2 scaling relation. For the comparison of cluster galaxies in the following sections, we

selected 36 isolated galaxies of which the data are assembled to derive HI deficiency, H₂ deficiency, star formation rate, and stellar mass.

3.1.2 Sample of Galaxies in Clusters

A number of galaxies in some clusters have already observed in $^{12}\text{CO}(J = 1 - 0)$ line in previous studies. Most of them are in the Virgo cluster or the Coma cluster as described in section 1. Therefore in order to compare environmental effects in the Hercules cluster with other clusters, we chose three clusters; the Virgo cluster, the Coma cluster, and Abell 1367. Since the number of galaxies observed in $^{12}\text{CO}(J = 1 - 0)$ was much smaller than the data obtained in other wavelengths, we determined the sample of galaxies in the cluster from those have been observed in $^{12}\text{CO}(J = 1 - 0)$ emission line.

- The Virgo cluster

We searched galaxies that had been mapped in $^{12}\text{CO}(J = 1 - 0)$ from the Virgo Cluster Catalog (VCC; Binggeli, Sandage & Tammann 1985), in which 2096 galaxies located within an area of $\sim 140 \text{ deg}^2$ roughly centered on M 87 were presented. A single pointing observation toward the center of the Virgo spiral galaxy cannot be usually covered its entire gas disk due to its proximity. In addition, the aperture correction cannot be applied in the same way as the isolated galaxies since cluster of galaxies have possibility to be disturbed due to interaction with neighbor galaxies or ram-pressure stripping. Thus, we confined to the archival data that performed by not single pointing observations but mapping observations. After that we selected the galaxies whose morphological type in RC3 is later than Sa. We finally selected 15 spiral galaxies from Kuno et al. (2007), four spirals from Chung et al. (2009), and three spirals from Pappalardo et al. (2012).

- The Coma cluster and Abell 1367

Both clusters were the member of the Coma/Abell 1367 supercluster. Segregation between the Coma cluster and Abell 1367 and the distance to objects followed by Gavezzi & Boselli (1996). The galaxies that classified as isolated ones in this paper were added in our isolated sample of galaxies. Thus, we divided the Coma/Abell 1367 samples into Coma cluster, Abell 1367, and isolated as shown in table 2.

Galaxies in the Coma cluster that obtained CO data with a single pointing observation are included in our sample. At the typical distance to the Coma cluster, 90 Mpc, apparent D_{25} of $\sim 20 \text{ kpc}$ corresponds to $\sim 46''$. Thus, when observation has been performed using the National Radio Astronomy Observatory (NRAO) Kitt Peak 12-m

Table 2 The segregation of affiliation in the Coma/Abell 1367 supercluster

Aggregation in this paper	Aggregation in in Gavezzi & Boselli (1996)	Distance
Coma cluster	Coma cluster core, Coma cluster	92 (Mpc)
Coma cluster	Possible Coma cluster	from individual recession velocity
Abell 1367	Abell 1367 core, Abell 1367	87 (Mpc)
Field	Isolated	from individual recession velocity

telescope of which HPBW is $55''$ at $^{12}\text{CO}(J = 1 - 0)$, the telescope beam is expected to be sufficiently covered galactic gas disk. Since most of observations of the Coma cluster were used the NRAO 12-m telescope, there is no huge issue that the single beam may not cover whole gas disk. However we need attention in the case of Institut de Radio Astronomie Millimetrique (IRAM) 30-m telescope since HPBW at $^{12}\text{CO}(J = 1 - 0)$ of the telescope is $22''$. As a result, 166 candidates of galaxies were found from previous studies (Casoli et al. 1991, 1996; Dickey & Kazes 1992; Boselli et al. 1994, 1995, 1997; Lavezzi et al. 1999; Scott et al. 2013). We selected 99 galaxies that are included in Gavezzi & Boselli (1996) and have morphology of later than Sa. Finally, we determined 35 sample of galaxies in cluster whose HI deficiency, H_2 deficiency, star formation rate, and stellar mass can be estimated in the next section.

3.2 Physical Quantities

We finally determined the sample of galaxies belonging to the isolated and cluster that could be collected for all parameters about gas and star formation. In this section, we show the methods to derive the molecular gas mass, atomic gas mass, star formation rate (SFR), and stellar mass using archival data in various wavelengths. We summarize the final sample of galaxies and their parameters in table 3 and 8.

3.2.1 Molecular Gas Mass

We estimated the molecular gas mass from the CO integrated intensity (I_{CO}) measured in the literature using the Galactic conversion factor to column density (X_{CO}). We adopted the constant value of $2.0 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (Dickman, Snell, & Schloerb 1986),

$$M_{\text{H}_2} = I_{\text{CO}} (\text{K km s}^{-1}) \times X_{\text{CO}} (\text{cm}^{-2} (\text{K km s}^{-1})^{-1}) \times S (\text{cm}^2) \quad (6)$$

$$= 75 \times I_{\text{CO}} (\text{K km s}^{-1}) \times D^2 (\text{Mpc}) \times \Omega (\text{arcsec}^2). \quad (7)$$

where S is the area covered by the telescope beam, D is the distance to the galaxy, and Ω is the solid angle of the beam. We adopted $\Omega = \frac{\pi}{4 \ln 2} \theta_{\text{beam}}^2$ for a single pointing observation where θ_{beam} was HPBW. We took into account the mass of heavy elements, mostly Helium, for the molecular gas mass by multiplying 1.36. The error of the CO flux was obeyed (Sage 1993),

$$\Delta I_{\text{CO}} (\text{K km s}^{-1}) = T_{\text{rms}} (\text{K}) \times \sqrt{\Delta V_{\text{CO}} (\text{km s}^{-1}) \times \delta V_{\text{CO}} (\text{km s}^{-1})}, \quad (8)$$

where T_{rms} is rms noise temperature, ΔV_{CO} is the total line width, and δV_{CO} is a velocity resolution. The 2σ -upper limit was used for galaxies whose CO emission could not be detected.

Since a galactic disk in the isolated is not disturbed, the assumption of exponentially declining gas disk is thought to be valid. If the flux emitted only from the central region is obtained, we can predict the flux emitted from whole gas disk assuming the exponential gas disk. Thus we include galaxies that were carried out by a single pointing observations in our isolated sample and convert the observed flux to expected flux from whole gas disk. The molecular gas distribution was assumed to obey the exponentially declining disk with optical scale length in AMIGA survey. As to galaxies in HRS survey, it was assumed the 3-D exponential disk with optical scale length. Using these models, the ratio of the flux measured by central pointing observations to the total flux were defined as a correction factor. In the COLD GASS survey, the correction factor was speculated from the empirical relation between optical disk size, D_{25} and the ratio measured by the central pointing observations to the total flux using the

mapping data of nearby spiral galaxies (Kuno et al. 2007). As to the cluster samples, we did not correct for source coverage since it is sufficient to cover whole disks of their distances. However the attention to the coverage of disks with the telescope beam are required depending on the size ratio of the beam size to a galactic disk.

3.2.2 Atomic Gas Mass

We derived atomic gas mass from the flux density obtained from 21-cm observations in the literature. Almost all galaxies were observed with the 305-m Arecibo telescope in the National Astronomy and Ionosphere Center toward the center of each galaxy. The HI observations at the Arecibo were used three types of H -band feed systems; dual circular polarization feeds with HPBW of $3'.3$, low sidelobe linear polarization feed with HPBW of $3'.9$, and updated and low-noise, broadband secondary and tertiary reflector Gregorian optical system with HPBW of $3'.5$. For objects with larger disk, the total flux cannot be covered with the beam. Thus we corrected the aperture effects based on the method mentioned by Sullivan et al. (1981) for objects with a larger disk ($> 1'.8$). First of all, they have converted the major and minor axes in blue band in the Uppsala General Catalogue of Galaxies (UGC; Nilson 1973), a and b in the unit of arcmin respectively, to that on the Holmberg (1958) system that were measured at $26.5 \text{ mag arcsec}^{-2}$ isophote,

$$\log a_H = 0.81 \log a + 0.26, \quad (9)$$

$$\log r_H = 0.73 \log r + 0.03, \quad (10)$$

$$(11)$$

where r is the ratio of the major axis to minor axis ($r = a/b$). Next, we converted the major axis, a_H , to the one measured from face-on angle, $a_H(0)$, in order to correct the effects of projection and obscuration,

$$\log a_H(0) = \log a_H - 0.3 \log r_H. \quad (12)$$

$$(13)$$

We yielded the correction factor assuming an elliptical Gaussian distribution with full width at half-maximum (FWHM) of $0.7a_H(0)$ and $0.7b_H$,

$$f = \sqrt{1 + \left(\frac{0.7a_H(0)}{beam}\right)^2} \sqrt{1 + \left(\frac{0.7b_H}{beam}\right)^2}, \quad (14)$$

where $beam$ is a observed beam size in the unit of arcmin. The assumption of the factor of 0.7 and of the Gaussian distribution has large uncertainty, but it has been confirmed at least

in late-type galaxies (e.g., Shostak 1978). We did not correct for the HI self-absorption since it was difficult for determining the scaling factor due to large error.

Finally, we estimated the HI gas mass from the HI flux, or aperture corrected HI flux for necessary using the following formula,

$$M_{\text{HI}}(M_{\odot}) = 2.36 \times 10^2 \times D^5(\text{Mpc}) \times S_{\text{HI}}(\text{Jy km s}^{-1}), \quad (15)$$

where D is the distance of each galaxy and S_{HI} is the velocity integrated flux density of HI. The velocity width ($W_{20,50}$) were adopted averaging the width at 50% of the mean signal intensity (W_{50}) and the width at 20% of the peak signal intensity (W_{20}). When we obtained only either W_{50} or W_{20} , we alternatively adopted this value. The error of the mass of HI gas were estimated 15% for the aperture corrected objects, and $\Delta S_{\text{HI}}(\text{Jy km s}^{-1}) = \Delta v(\text{km s}^{-1})^{1/2} \times W_{20,50}(\text{km s}^{-1})^{1/2} \times T_{\text{rms}}(\text{Jy})$ for the other objects, where Δv is the velocity resolution and T_{rms} is the rms noise temperature. The upper limit for galaxies which had not detected was estimated by $2 \times \Delta S_{\text{HI}}$. In this case, we adopted velocity width of 300 km s^{-1} for the morphological type in RC3 Sa–Sbc and classified in probably spirals, S?, and 190 km s^{-1} for Sc–Scd.

We presented the reference for the HI observations in the table. As described in section 3.1, we collected the data from ALFALFA for the isolated samples to derive the HI scaling relation. As to the isolated samples for H_2 scaling relation, we collected from mainly ALFALFA, but when not be included, we collected from the catalog by Spingob et al. (2005). For the Virgo cluster, we collected from the ALFALFA and the VLA Imaging of Virgo galaxies in Atomic gas (VIVA; Chung et al. 2009). As to the other clusters, the Hercules cluster, the Coma cluster, and Abell 1367 cluster, we individually searched the archival HI data (Haynes et al. 1997; Eder, Giovanelli & Haynes 1991; Gavazzi 1989; Chincarini, Giovanelli & Haynes 1983; Beijersbergen 2003; Bravo-Alfaro et al. 2000; Giovanelli & Haynes 1985; Gavazzi et al. 2006; Gavazzi 1987; Fontanelli 1984; Scoddeggio & Gavazzi 1993; Schommer, Sullivan, & Bothun 1981).

3.2.3 Star Formation Rate

The SFR is defined as the sum of stellar mass formed every one year. The SFRs of almost all galaxies except the Virgo galaxies and some galaxies in the isolated were adopted from Max Plank Institut for Astrophysics–Johns Hopkins University (MPA–JHU) data base ^{*2}. This is based on Brinchmann et al. (2004) and derived the SFRs from the SDSS spectra data, mainly $\text{H}\alpha$ emission line luminosity for star-forming galaxies. A classification into star-forming, AGN,

^{*2} <http://www.mpa-garching.mpg.de/SDSS/DR7/>

and composite have been based on the BPT diagram (Baldwin et al. 1981) which is the plot of the flux ratio of $[\text{OIII}]\lambda 5007 \text{ \AA}$ and $\text{H}\beta$ lines against the flux ratio of $[\text{NII}]\lambda 6584 \text{ \AA}$ and $\text{H}\alpha$ line. For the AGN and composite classes, it is impossible to estimate SFRs from the emission line since it originates from not only star formation but also AGN. However, it is well known that there is a relationship between the $4000\text{-}\text{\AA}$ break (D4000) and specific SFR (SFR/stellar mass; sSFR). Therefore, they used D4000 to estimate the sSFRs and then SFRs. Since SDSS spectroscopic data were obtained through $3''$ diameter fiber, whole region in a galactic disk cannot be covered by this fiber in the range of redshift ($z \lesssim 0.04$). Hence the SFRs derived in this way have been corrected for aperture effects using spatially-resolved color images that were obtained up to outer region of the disk. In addition, since the SFRs were computed assuming a Kroupa (2001) initial mass function (IMF), we multiplies by 1.5 to convert Salpeter (1955) IMF.

For galaxies in the Virgo cluster, we calculated the SFR using the following relation by Kennicutt (1998a) based on the $\text{H}\alpha$ observational data (Koopmann, Kenney, & Young 2001; Kennicutt et al. 2009),

$$SFR (M_{\odot} \text{ yr}^{-1}) = 7.9 \times 10^{-42} L_{\text{H}\alpha} (\text{erg s}^{-1}), \quad (16)$$

where $L_{\text{H}\alpha}$ is the luminosity of $\text{H}\alpha$ emission line. In Koopman, Kenney, & Young 2001, narrowband $\text{H}\alpha$ and broadband R images have been presented for 63 bright spiral galaxies located in the Virgo cluster. We adopt the total $\text{H}\alpha$ fluxes that have been measured through a polygonal aperture using the POLYPHOT task in Image Reduction and Analysis Facility, IRAF. Correct for dust attenuation is applied $A_V = 1.0$ (mag), which corresponding to $A_{\text{H}\alpha} = 0.78$ by following Charlot et al. (2002) and Sullivan et al. (2000). The SFRs estimated from the corrected $\text{H}\alpha$ fluxes were confirmed higher consistency with those in the MPA-JHU catalog than those not corrected the attenuation (figure 8 in Brinchmann et al. 2004).

3.2.4 Stellar Mass

Stellar mass can be estimated using the relation between stellar mass-to-light ratio and optical color. As presented in Bell et al. (2003), we adopted the following relation

$$\log \frac{M_{\text{stellar}}(M_{\odot})}{L_i(L_{\odot})} = -0.152 + 0.518(g - i). \quad (17)$$

This relation were estimated assuming under the assumption of a diet Salpeter (1955) IMF that has the same colors and luminosity as a normal Salpeter IMF, but has only 70% of the mass due to a lower number of faint low-mass stars. Thus we converted normal Salpeter IMF by multiplying by $1/0.7$.

For all sample of galaxies in the isolated and cluster except the Virgo cluster, Petrosian magnitudes in g -band and i -band images in the SDSS photometric data catalog, release 7 (Adelman-McCarthy et al. 2009) were applied. The SDSS Petrosian magnitude is defined to the magnitude within the Petrosian radius at which the local surface brightness in an annulus is one-fifth of the mean surface brightness inner region (Strauss et al. 2002). These magnitudes are corrected for the Galactic foreground extinction given by Schlafly & Finkbeiner (2011) and Schlegel, Finkbeiner, & Davis (1998) as reported by NASA/IPAC Extragalactic Database.

There is no reliable data of such nearby galaxies with large apparent diameter of disks as the Virgo cluster in the SDSS photometric data catalog. Therefore, we applied the photometric magnitude measured by Kim et al. (2014) based on the SDSS images. This is the total magnitude of a galaxy calculated within 2.5 times the Kron radius. A comparison between the total magnitude and the Petrosian magnitude from the SDSS photometric pipeline has been performed by Kim et al. (2014), which have shown that the later systematically underestimated the fluxes of larger galaxies due to shredding and larger sky subtraction.

Table 3: Physical Properties in the isolated galaxies

Galaxy	Classification ^a	D (Mpc)	$\log M_{\text{HI}}$ ($M_{\odot}$)	Reference ^b	$\log M_{\text{H}_2}$ ($M_{\odot}$)	Reference ^c	SFR ($M_{\odot} \text{ yr}^{-1}$)	$\log M_{\text{stellar}}$ ($M_{\odot}$)
UGC 03944	isolated	53.9	9.7	1	9.4	1	0.611	10.1
UGC 04107	isolated	48.4	9.2	1	9.2	1	0.314	10.2
IC 0509	isolated	76.4	9.9	2	9.2	1	6.64	9.80
UGC 04733	isolated	112	9.9	2	9.1	2	0.192	10.1
UGC 05055	isolated	103	10.3	1	9.77	1	6.01	10.8
NGC 3049	isolated	24.4	9.3	2	8.1	1	0.729	9.78
IC 0619	isolated	101	10.2	2	9.4	2	0.796	9.78
NGC 3359	isolated	15.2	10	1	8.6	1	0.0107	9.82
UGC 06879	isolated	43.6	9.6	1	8.6	1	0.164	9.95
NGC 4348	isolated	31.4	9.5	1	9.2	1	0.409	10.6
NGC 4713	isolated	15.9	9.5	1	8.7	3	0.338	9.70
NGC 5584	isolated	25.2	9.7	1	8.4	1	0.342	9.70
NGC 5913	isolated	39.0	9.1	1	8.9	1	0.379	10.5
UGC 11816	isolated	58.7	9.9	1	8.8	1	0.133	10.2
CGCG 127-018	isolated (C)	92.6	9.63	3	9.49	4	0.934	10.5
CGCG 127-038	isolated (C)	92.1	10.5	4	9.94	5	1.17	10.9
CGCG 157-035	isolated (C)	83.6	10.2	5	9.80	6	5.16	11.1
CGCG 098-116	isolated (C)	83.1	9.93	5	9.25	4	0.0250	10.2
CGCG 158-054	isolated (C)	103	9.79	4	9.16	4	2.76	10.0
CGCG 128-073	isolated (C)	92.6	9.91	6	9.51	4	0.375	10.6
CGCG 128-080	isolated (C)	98.0	9.41	5	9.52	4	2.29	10.5
CGCG 158-105	isolated (C)	90.1	10.0	5	9.18	4	0.479	10.5
CGCG 128-089	isolated (C)	90.7	9.24	7	9.21	4	0.0608	11.0
CGCG 159-008	isolated (C)	98.0	9.95	6	9.62	4	0.601	10.7
CGCG 159-059	isolated (C)	100	9.79	4	9.63	4	3.06	10.3
CGCG 160-182	isolated (C)	93.4	9.62	8	9.59	4	1.16	10.7
CGCG 160-192	isolated (C)	88.9	10.3	6	9.74	4	0.0325	10.9

Table 3: Physical Properties in the isolated galaxies (continued)

Galaxy	Classification ^a	D (Mpc)	$\log M_{\text{HI}}$ ($M_{\odot}$)	Reference ^b	$\log M_{\text{H}_2}$ ($M_{\odot}$)	Reference ^c	SFR ($M_{\odot} \text{ yr}^{-1}$)	$\log M_{\text{stellar}}$ ($M_{\odot}$)
CGCG 101-054	isolated (C)	87.9	9.94	5	9.21	4	0.755	10.9
CGCG 159-033	isolated (C)	102	9.31	6	9.10	4	0.0740	11.0
CGCG 159-061	isolated (C)	93.9	9.52	4	8.92	4	0.0572	10.8
CGCG 100-005	isolated (C)	88.0	9.39	5	9.24	7	0.342	10.8
CGCG 129-021	isolated (C)	89.3	9.87	5	9.26	4	3.76	10.5
CGCG 159-095	isolated (C)	90.8	9.65	4	8.75	4	0.0442	10.7
CGCG 159-096	isolated (C)	83.0	9.97	6	8.88	4	0.201	10.1
CGCG 130-006	isolated (C)	87.0	9.36	5	9.21	5	1.58	10.3
CGCG 130-008	isolated (C)	96.9	9.76	4	9.63	5	3.05	10.4
CGCG 101-043	isolated (C)	89.0	8.28	9	8.89	4	0.0292	10.9

(a) Isolated: isolated galaxies defined from 2MIG catalog; isolated (C): isolated galaxies in the Coma supercluster

(b) 1: Springob et al. (2005); 2: ALFALFA; Haynes et al. (2011); 3: Gavazzi et al. (2006);

4: Chincarini, Giovanelli & Haynes (1983); 5: Gavazzi (1987); 6: Haynes et al. (1997); 7: Gavazzi (1989);

8: Fontanelli (1984); 9: Scodreggio & Gavazzi (1993).

(c) 1: Lisenfeld et al. (2011); 2: Saintonge et al. (2011); 3: Boselli, Cortese, & Boquien (2014); 4: Boselli et al. (1997);

5: Casoli et al. (1996); 6: Dickey & Kazes (1992); 7: Lavezzi et al. (1999).

Table 4: Physical Properties in the cluster galaxies

Galaxy	Classification ^a	D (Mpc)	log M_{HI} ($M_{\odot}$)	Reference ^b	log M_{H_2} ($M_{\odot}$)	Reference ^c	SFR ($M_{\odot} \text{ yr}^{-1}$)	log M_{stellar} ($M_{\odot}$)
CGCG 108–121	Hercules	150	9.89	1	9.18	1	0.0607	10.6
IC 1173	Hercules	150	9.92	1	9.06	1	0.557	10.9
CGCG 108–146	Hercules	150	9.64	2	9.22	1	0.663	10.7
NGC 4189	Virgo	16.1	8.87	3	8.78	3	0.604	9.98
NGC 4192	Virgo	16.1	9.66	3	9.13	2	1.59	10.9
NGC 4208	Virgo	16.1	8.93	3	9.13	2	0.853	10.3
NGC 4254	Virgo	16.1	9.67	3	10.0	2	5.64	10.7
NGC 4298	Virgo	16.1	8.70	4	9.05	4	0.564	10.3
NGC 4303	Virgo	16.1	9.71	3	9.97	2	8.73	10.8
NGC 4321	Virgo	16.1	9.47	3	9.94	2	3.72	11.0
NGC 4419	Virgo	16.1	7.94	3	9.13	2	0.100	10.5
NGC 4501	Virgo	16.1	9.25	3	9.91	2	3.10	11.1
NGC 4535	Virgo	16.1	9.64	3	9.58	2	3.10	10.7
NGC 4536	Virgo	16.1	9.68	4	9.48	2	1.91	10.6
NGC 4548	Virgo	16.1	8.79	3	8.91	2	0.551	10.9
NGC 4567	Virgo	16.1	9.16	3	9.62	4	0.618	10.3
NGC 4569	Virgo	16.1	8.83	3	9.71	2	0.743	10.9
NGC 4579	Virgo	16.1	8.77	3	9.39	2	1.45	11.1
NGC 4647	Virgo	16.1	8.68	3	9.23	4	0.957	10.7
NGC 4654	Virgo	16.1	9.49	3	9.64	2	1.26	10.5
NGC 4689	Virgo	16.1	8.71	3	9.34	2	0.604	10.4
CGCG159–102	Coma	92	9.92	5	10.0	5	2.60	10.9
CGCG160–025	Coma	92	8.29	6	8.98	6	0.128	11.1
CGCG160–026	Coma	92	9.27	7	9.09	6	0.758	10.1
CGCG160–032	Coma	92	8.33	8	9.06	6	1.65	10.6
CGCG160–058	Coma	92	9.43	5	9.55	7	0.950	10.4
CGCG160–067	Coma	92	9.30	9	9.35	7	1.45	9.89

Table 4: Physical Properties in the cluster galaxies (continued)

Galaxy	Classification ^a	D (Mpc)	$\log M_{\text{HI}}$ ($M_{\odot}$)	Reference ^b	$\log M_{\text{H}_2}$ ($M_{\odot}$)	Reference ^c	SFR ($M_{\odot} \text{ yr}^{-1}$)	$\log M_{\text{stellar}}$ ($M_{\odot}$)
CGCG160-073	Coma	92	8.53	10	9.23	7	2.60	10.2
CGCG160-081	Coma	92	8.36	2	8.90	7	0.745	10.9
CGCG160-086	Coma	92	8.68	5	8.34	7	1.16	9.80
CGCG160-088	Coma	92	9.34	7	9.58	7	0.327	10.7
CGCG160-257	Coma	92	8.62	10	9.34	7	0.0573	10.9
CGCG160-260	Coma	92	9.10	5	9.92	5	0.428	11.1
CGCG160-098	Coma	92	9.03	2	9.36	7	1.78	10.3
CGCG160-095	Coma	92	9.33	5	9.77	7	0.0616	11.1
CGCG160-102	Coma	92	9.88	5	9.28	7	0.0769	10.8
CGCG160-106	Coma	92	9.02	10	9.46	5	2.59	10.4
CGCG160-128	Coma	92	9.69	11	9.08	7	2.06	9.74
CGCG160-127	Coma	92	9.66	5	8.86	7	0.631	9.67
CGCG097-068	A1367	87	9.92	5	9.67	5	3.40	10.6
CGCG097-072	A1367	87	9.08	5	9.52	7	1.32	10.6
CGCG097-091	A1367	87	9.70	5	9.24	8	2.90	10.6
CGCG097-129W	A1367	87	10.1	12	9.52	7	0.0417	11.0
CGCG127-052	A1367	87	9.71	5	9.46	7	0.0449	11.3

(a) Segregation between the Coma cluster and Abell 1367 are based on Gavezzi & Boselli (1996).

(b) 1: Schommer, Sullivan, & Bothun 1981; 2: Giovanelli & Haynes 1985; 3: ALFALFA; Haynes et al. (2011);

4: Chung et al. (2009); 5: Haynes et al. (1997); 6: Eder, Giovanelli & Haynes (1991);

7: Gavazzi (1989); 8: Chincarini, Giovanelli & Haynes (1983); 9: Beijsbergen (2003);

10: Bravo-Alfano et al. (2000); 11: Gavazzi et al. (2006); 12: Gavazzi (1987).

(c) 1: this observation; 2: Kuno et al. (2007); 3: Pappalardo et al. (2012) 4: Chung et al. (2009); 5: Casoli et al. (1996);

6: Casoli et al. (1991); 7: Boselli et al. (1997); 8: Lavezzi et al. (1999).

3.3 Effects of Sample Selection

3.3.1 Selection Bias in a Samples of Isolated Galaxies

We select the isolated galaxies that were detected in both HI and $^{12}\text{CO}(J = 1 - 0)$ emission lines, while some objects which does not been detected in HI and/or $^{12}\text{CO}(J = 1 - 0)$ are included in the sample of cluster galaxies. Thus atomic gas and molecular gas mass in cluster galaxies have possibility to be overestimated. In order to examine a selection bias due to including upper-limit mass in only sample of cluster galaxies, we compare the sample of isolated galaxies in our study and a non-bias sample of isolated galaxies.

Since gas-rich galaxies are expected to be bluer and lower luminous, we compare the color-magnitude distribution between a non-biased sample of isolated galaxies and the sample of isolated galaxies that have all parameters necessary for deriving HI deficiency, H_2 deficiency, SFR, and stellar mass. The non-biased sample is selected from the parent isolated sample in section 3.1.1, which is included in 2MIG and later than Sa, and velocity of $\leq 12000 \text{ km s}^{-1}$. We can prepare 117 isolated galaxies for the non-biased isolated sample through performing cross-match with SDSS photometric data.

Color-magnitude distribution is shown in figure 10. There is no significant difference between the distribution of isolated galaxies detected in both HI and $^{12}\text{CO}(J = 1 - 0)$ emission line and that of non-biased galaxies, but little bluer in both HI- and CO-detected galaxies. In order to verify the difference between these two types of isolated samples in $g - r$ color distribution and in r -band magnitude distribution, we show their histograms and performe Kolmogorov-Smirnov (K-S) test in each distribution. According to this test, the hypothesis that the distributions of r -band magnitude in two types of isolated sample are different can be rejected by the probability 0.996. This means that these are the same distribution in highly probability. On the other hand, the hypothesis in the same distributions of $g - r$ color can be rejected by the probability 0.00268. Thus $g - r$ color distributions appear to show different between the isolated galaxies detected in HI and $^{12}\text{CO}(J = 1 - 0)$ and non-biased isolated galaxies. We must take into account that the isolated galaxies which we use comparison with cluster galaxies hereafter are a little bluer than general isolated galaxies.

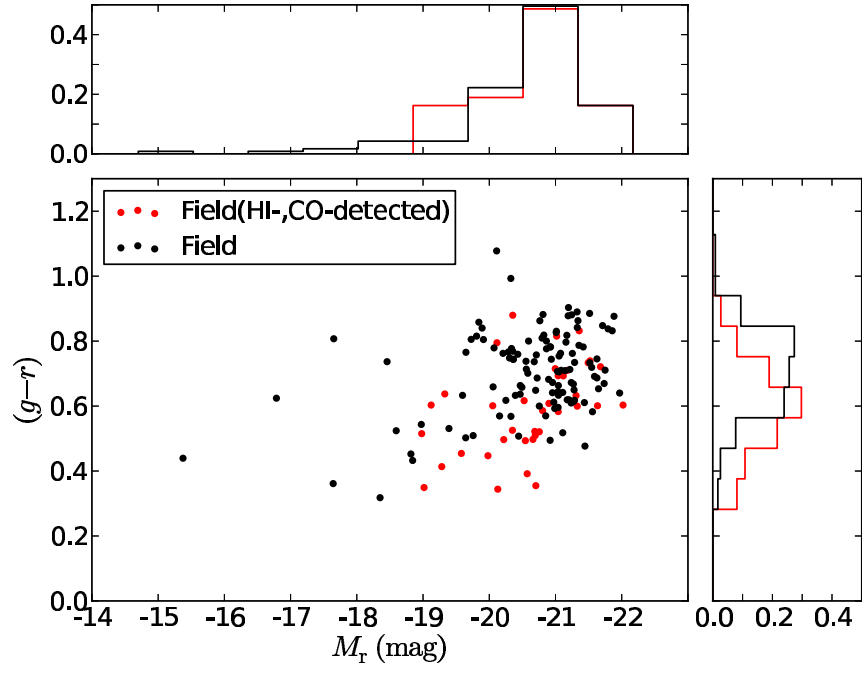


Figure 10 Color-magnitude diagram in isolated galaxies which are detected in both HI and $^{12}\text{CO}(J = 1 - 0)$ (red) and in non-biased isolated (black). Histograms of $g - r$ color and r -band magnitude are shown along each axes, which are normalized to the total number of each galaxies.

3.3.2 Selection Bias in a Sample of Cluster Galaxies

In order to clarify the difference in the content of atomic gas and molecular gas, and also properties of star formation between isolated galaxies and cluster galaxies, we compare them in following section. However, it is known that galaxies in cluster of galaxies are redder and lower luminous (section 1.1.2) and that a redder galaxy is expected to have lower gas mass. Although we select only spiral galaxies for a sample of isolated galaxies and cluster galaxies, the distribution of cluster galaxies and isolated galaxies are need to be similar in order to consider environmental effect separating evolution of star formation. Therefore we compare the distribution of galaxies in color–magnitude diagram between isolated galaxies and cluster galaxies. In these samples of galaxies, the data necessary for deriving HI deficiency, H₂ deficiency, SFR, and stellar mass can be assembled.

As shown in figure 11, there is no significant difference between isolated galaxies and cluster galaxies. According to K–S test, the hypothesis that the distributions of r –band magnitude in the cluster and the field are different can be rejected by the probability 0.527. In the distribution of color, the significance probability is 0.993. Thus, it is a possible that the color distribution is similar between cluster galaxies and isolated galaxies, while the distribution of r –band magnitude is slightly different between them. In fact, the histogram of r –band magnitude in a sample of cluster seems to be biased toward luminous.

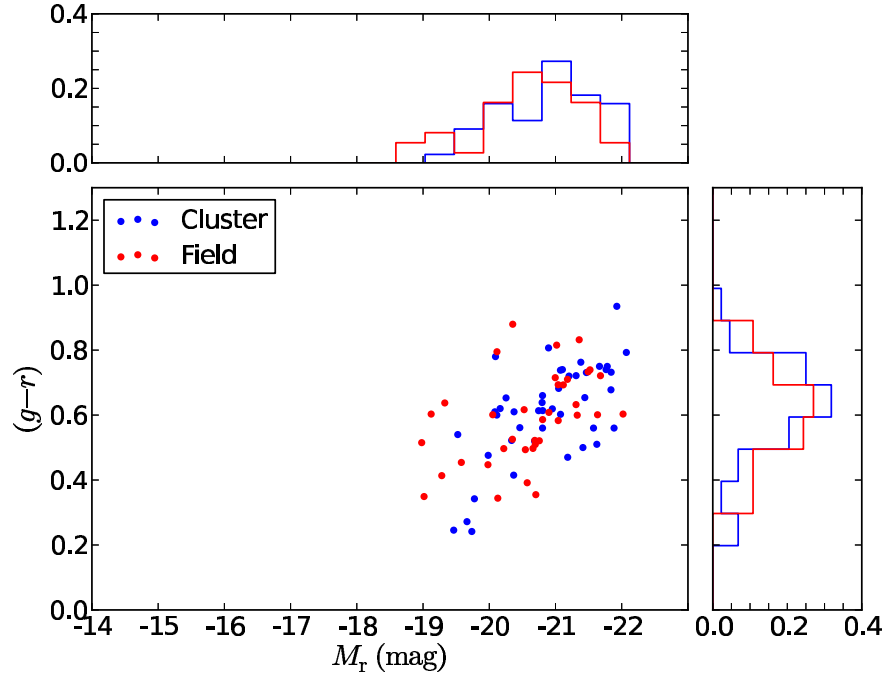


Figure 11 Color-magnitude diagram in cluster galaxies (blue) and in isolated galaxies (red). Histograms of $g-r$ color and r -band magnitude are shown along each axes, which are normalized to the total number of each galaxies.

4 Results

4.1 Observational Result

4.1.1 Spectra of $^{12}\text{CO}(J = 1 - 0)$ line in spirals in the Hercules cluster

Spectra of $^{12}\text{CO}(J = 1 - 0)$ emission of three galaxies in the Hercules cluster obtained with the Nobeyama 45-m telescope are shown in figure 12. We could detect the emission in CGCG 108-121 with signal-to-noise ratio of > 5 , and marginally detect emission in IC 1173 and CGCG 108-146 with signal-to-noise ratio of < 5 . The sensitivity of each observation at a velocity resolution of 50 km s^{-1} in T_{mb} scale is 3.5–4.1 mK (table 5). As shown in figure 12, baseline ripple is quite large. Thereby the uncertainty of the integrated intensity becomes large.

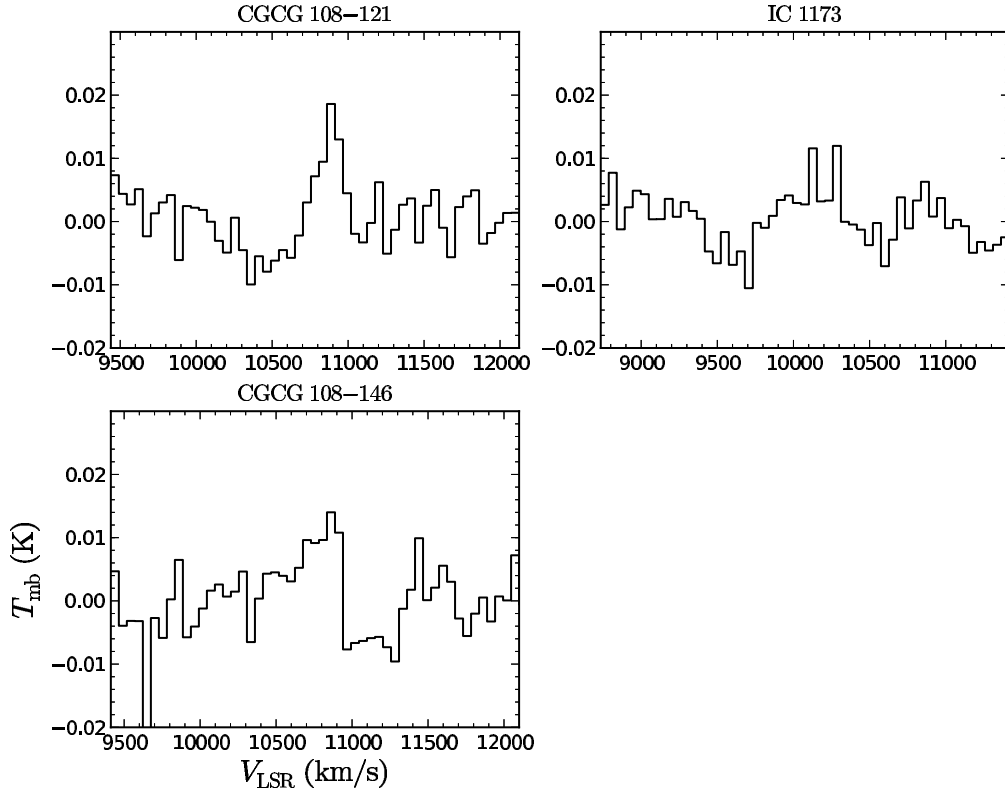


Figure 12 Observed $^{12}\text{CO}(J = 1 - 0)$ spectra. The horizontal axis is velocity on local standard of the rest, and vertical axis is the temperature in T_{mb} scale.

Table 5 Sensitivity of spectra of observed galaxies.

Galaxy	T_{rms} (mK)
CGCG 108–121	3.5
IC 1173	3.2
CGCG 108–146	4.1

4.1.2 Estimation of molecular gas mass

We estimated errors of velocity integrated intensity, ΔI_{CO} including the error of baseline (Sage 1993).

$$\Delta I_{\text{CO}} = \sqrt{\Delta V^2 \left(\frac{\Delta v}{\Delta V} \right) T_{\text{rms}}^2 + \Delta V^2 \left(\frac{\Delta v}{\Delta V_{\text{baseline}}} \right) T_{\text{rms}}^2} \quad (18)$$

where ΔV is the velocity width over which the spectrum is integrated as signal, Δv is the velocity resolution after smoothed, 50 km s^{-1} , and $\Delta V_{\text{baseline}}$ is the velocity width over which fitted to determine the baseline (figure 13). We estimated the molecular gas mass in the same way as in section 3.2.1 and obtained $1.5\text{--}2.3 \times 10^9 M_{\odot}$. The resultant molecular gas mass in each galaxy is shown in table 6 as well as ΔV and ΔI_{CO} .

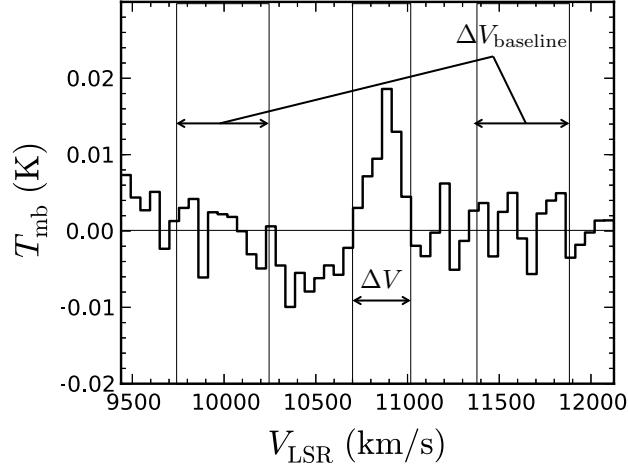


Figure 13 Observed $^{12}\text{CO}(J = 1 - 0)$ spectra of CGCG 108–121. The velocity widths over which the spectrum is integrated (ΔV) and fitted to determine the baseline ($\Delta V_{\text{baseline}}$) are shown.

Table 6 The molecular gas mass, velocity width, and integrated intensity in each galaxy.

Galaxy	ΔV (km s ⁻¹)	I_{CO} (K km s ⁻¹)	$\log M_{\text{H}_2}$ ($M_{\odot}$)
CGCG 108–121	300	2.8	9.3
IC 1173	500	2.3	9.2
CGCG 108–146	550	3.5	9.4

4.1.3 Comparison of general star formation law

The obtained molecular gas masses in the Hercules cluster galaxies are compared with those in nearby galaxies. Figure 14 shows a correlation between disk-averaged SFR and disk-averaged gas surface density of 61 normal spiral galaxies in Kennicutt (1998b) and three Hercules cluster galaxies. For fairly comparison, the molecular gas mass in normal nearby spiral galaxy is re-calculated using the conversion we adopt factor. In addition, the surface densities are estimated from the size of optical disk based on not RC2 but RC3. SFRs in Kennicutt (1998b) are estimated from H α emission luminosity, while SFRs in Hercules galaxies are from MPA–JHU catalog based on SDSS spectroscopic data (Brinchmann et al. 2004). The difference from the derivation of these SFRs can be negligible as mentioned in 3.2.3. Thus we can consider that both SFR and gas surface density does not depend on their deriving methods. Although the error of SFR surface densities in the Hercules cluster galaxies are larger, the SFR surface densities in the Hercules cluster galaxies have possibility to be lower than the normal star formation law.

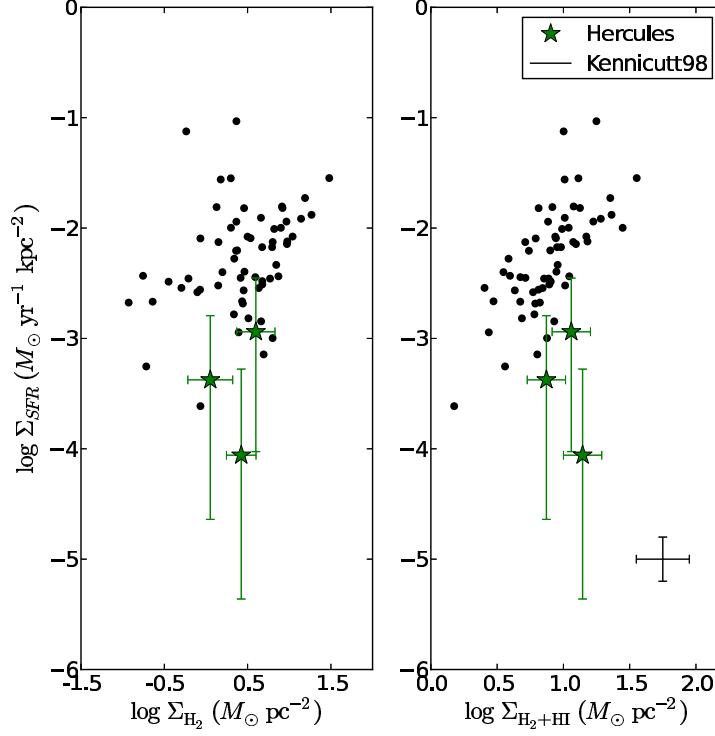


Figure 14 Relation between disk-averaged surface density of SFR and molecular gas mass (left), and total gas mass (right). Green stars are from our observations in the Hercules cluster. Black circles indicates nearby galaxies from Kennicutt et al. (1998b). Typical uncertainties of SFR surface density and total gas surface density in normal galaxies in the Kennicutt et al. (1998b) are shown in the lower right corner of the right panel. The authors have not describe that the uncertainties of molecular gas mass are approximately comparable to those of total gas mass.

4.2 Scaling Relations and Definition of Gas Deficiency

In order to define HI deficiency and H₂ deficiency, we determine the scaling relation between the atomic gas mass and the typical size of optical disk, D_{25} , and between the molecular gas mass and H -band luminosity, respectively.

4.2.1 HI gas scaling relation

For 66 spiral galaxies which prepared to derive this relation as described in section 3.1.1, the relation between atomic gas and D_{25} is shown in figure 15. There is a clear correlation similar to that have been seen in previous studies (e.g. Kudrya, Karachentseva, & Karachentsev 2011). The best fitting line is provided by a part of the IDL Astronomy User's Library (Landsman 1993), FITEXY. This routine is based on Press et al. (1992) and takes into account an error in both x - and y - axis. The resultant expression is as follow,

$$\log M_{\text{HI}} = (2.6 \pm 0.22) \log D_{25} + (5.9 \pm 0.32). \quad (19)$$

On the other hand, the least squares method without considering the error gives following formula,

$$\log M_{\text{HI}} = 1.51 \log D_{25} + 7.52. \quad (20)$$

This is consistent with that in Solanes, Giovanelli, & Haynes (1996) which is frequently used to define the HI deficiency,

$$\log M_{\text{HI}} = (1.46^{+0.02}_{-0.03}) \log D_{25} + (7.51 \pm 0.02). \quad (21)$$

While this is derived using 532 galaxies with Hubble type of Sa–Sc, this is also generally consistent with that from Hubble type of later than Scd in Boselli & Gavazzi (2009). Therefore we decide to use the formula in Solanes, Giovanelli, & Haynes (1996) to derive the HI deficiency.

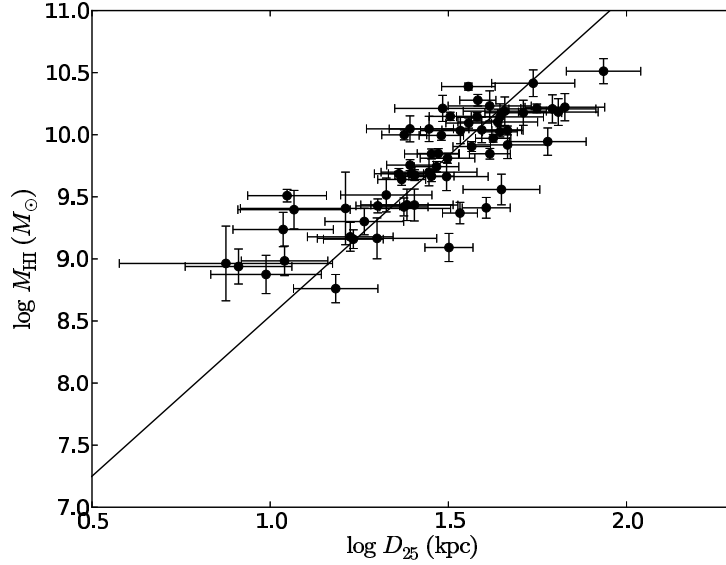


Figure 15 Correlation between D_{25} and atomic gas mass.

4.2.2 H_2 gas scaling relation

Using 103 spiral galaxies prepared in section 3.1.1, the scaling relation between molecular gas mass and H -band luminosity is obtained and shown in figure 16. The molecular gas mass is derived from COLD GASS for 20 galaxies, AMIGA for 78 galaxies, HRS for 3 galaxies, and NRO atlas for 2 galaxies. The H -band luminosity is estimated from total magnitude in 2MASS extended source catalog (Jarrett et al. 2000) using the formula of $\log L_H(L_{\text{sun}}) = 10.769 - 0.4H_T(\text{mag}) + 2\log D(\text{Mpc})$, where H_T is the total magnitude and D is the distance to a galaxy. In order to cover the same range of H -band luminosity as the cluster galaxies in our study, we select galaxies with $\log L_H > 9.0$. There is clear correlation but with large errors due to estimation of molecular gas mass. A linear approximation is obtained by FITEXY in the same manner as HI and can be shown in the following relation:

$$\log M_{H_2} = (1.1 \pm 0.079) \log L_H + (-1.7 \pm 0.79). \quad (22)$$

We decide to use this relation to define H_2 deficiency although an uncertainty of H_2 deficiency is expected to be large.

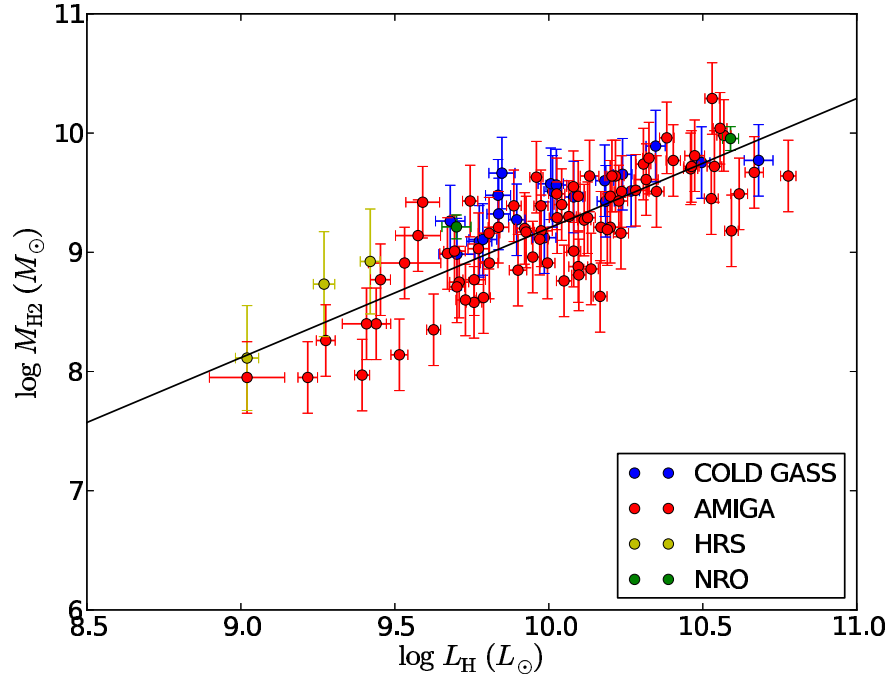


Figure 16 Correlation between H -band luminosity and molecular gas mass. Blue, red, yellow, and green circles indicate the data from the COLD GASS, AMIGA, HRS, and NRO survey, respectively.

4.3 Comparison Between the Clusters

4.3.1 A relation between HI deficiency and H₂ deficiency

A gas deficiency is defined as the difference between the logarithm of expected gas mass and of observed one according to equation (1) and (2) in section 1. The expected gas mass can be estimated using the scaling relation derived in the previous subsection, 4.2. Therefore we can obtain the expected atomic gas through substituting D_{25} into equation (21). Similarly, H₂ deficiency is also derived from H -band luminosity and equation (22). We select isolated galaxies from 103 isolated galaxies prepared for H₂ scaling relation, which have available data to derive gas deficiencies, SFR, and stellar mass. Finally, HI deficiencies and H₂ deficiencies are derived in 37 isolated galaxies and 44 cluster galaxies. The typical errors are ~ 0.23 in HI deficiencies and ~ 1.2 in H₂ deficiencies. These somewhat large errors are caused by the fitting error in determining the scaling relation.

We summarize the gas deficiencies in table 7 and table ?? and show a correlation between HI deficiency and H₂ deficiency of cluster galaxies in figure 17. It is found that the H₂ deficiencies of three galaxies in the Hercules cluster are positive and larger than the other cluster galaxies nevertheless these are lower limits of H₂ deficiency. Therefore the Hercules galaxies are thought to have less molecular gas compared to the other cluster galaxies.

We show histograms of HI deficiency and H₂ deficiency along these axes in figure 17, which are normalized to the total number of cluster galaxies. The histogram of H₂ deficiency show a uniform distribution around the H₂ deficiency of ~ 0 in almost all the galaxies. Averages of H₂ deficiency in each bin of HI deficiency (x-marks in figure 17) indicate that H₂ deficiency tends to be larger with increasing HI deficiency. This trend is consistent with Boselli et al. (2014). Fumagalli et al. (2009) have also found that the H₂ deficient-galaxy (H₂ deficiency ≥ 0.2) is HI-deficient (HI deficiency ≥ 0.3) in nearby galaxies.

Table 7 Gas deficiency in isolated galaxies.

Galaxy	$\log D_{25}$ (kpc)	$\log L_{\mathrm{H}}$ ($L_{\odot}$)	HI deficiency	H ₂ deficiency
UGC 03944	1.45	9.74	-0.074	-0.46
UGC 04107	1.30	9.92	0.17	-0.042
IC 0509	1.61	9.97	-0.073	0.0344
UGC 04733	1.58	9.77	-0.083	-0.090
UGC 05055	1.67	10.4	-0.32	-0.10
NGC 3049	1.20	9.51	-0.017	0.59
IC 0619	10.2	1.41	-0.63	0.0089
NGC 3359	1.53	9.76	-0.26	0.40
UGC 06879	1.34	9.73	-0.17	0.35
NGC 4348	1.48	10.2	0.19	0.25
NGC4713	1.09	9.27	-0.41	-0.27
NGC 5584	1.41	9.63	-0.13	0.50
NGC 5913	1.15	10.0	0.15	0.33
UGC 11816	1.40	9.76	-0.32	0.21
CGCG 127-018	1.25	10.0	-0.29	-0.20
CGCG 127-038	1.72	10.4	-0.49	-0.25
CGCG 157-035	1.69	10.7	0.11	-0.27
CGCG 098-116	1.46	9.89	-0.22	-0.17
CGCG 158-054	1.38	9.93	-0.30	-0.036
CGCG 128-073	1.59	10.3	0.13	0.057
CGCG 128-080	1.09	10.1	-0.64	-0.22
CGCG 158-105	1.46	10.2	-0.29	0.26
CGCG 128-089	1.48	10.5	0.52	0.57
CGCG 159-008	1.68	10.4	0.33	0.018
CGCG 159-059	1.29	9.97	-0.53	-0.45
CGCG 160-182	1.54	10.4	0.30	0.024
CGCG 160-192	1.76	10.8	0.23	0.30
CGCG 101-054	1.52	10.5	-0.088	0.51
CGCG 159-033	1.66	10.5	0.92	0.67
CGCG 159-061	1.38	10.3	-0.031	0.57
CGCG 100-005	1.38	10.5	0.11	0.47
CGCG 129-021	0.93	10.0	-1.5	-0.018
CGCG 159-095	1.24	10.2	-0.51	0.67
CGCG 159-096	1.65	9.65	0.23	-0.065
CGCG 130-006	1.18	9.90	-0.36	-0.11
CGCG 130-008	1.08	10.0	-1.0	-0.39
CGCG 101-043	1.43	10.4	1.4	0.73

Table 8: Gas deficiency in cluster galaxies.

Galaxy	$\log D_{25}$ (kpc)	$\log L_H$ ($L_\odot$)	HI deficiency	H ₂ deficiency
CGCG 108–121	1.47	10.2	-0.23	0.16
IC 1173	1.61	10.5	-0.057	0.55
CGCG 108–146	1.43	-0.034	0.00066	0.088
NGC 4189	1.05	9.53	0.17	-0.038
NGC 4192	1.66	10.5	0.28	0.62
NGC 4208	1.17	9.82	0.29	-0.077
NGC 4254	1.40	10.3	-0.12	-0.47
NGC 4298	1.18	9.79	0.53	-0.031
NGC 4303	1.48	10.4	-0.043	-0.30
NGC 4321	1.54	10.5	0.28	-0.16
NGC 4419	1.19	10.1	1.3	0.20
NGC 4501	1.51	10.7	0.47	0.024
NGC 4535	1.52	10.2	0.088	-0.12
NGC 4536	1.55	10.1	0.093	-0.11
NGC 4548	1.40	10.3	0.76	0.62
NGC 4567	1.14	9.83	0.013	-0.55
NGC 4569	1.65	10.6	1.1	0.13
NGC 4579	1.44	10.6	0.84	0.45
NGC 4647	1.13	9.92	0.48	-0.072
NGC 4654	1.36	10.1	0.0058	-0.30
NGC 4689	1.30	10.0	0.70	-0.082
CGCG 159–102	1.43	10.6	-0.32	-0.18
CGCG 160–025	1.52	10.6	1.4	0.91
CGCG 160–026	1.28	9.67	0.10	-0.20
CGCG 160–032	1.21	10.1	0.94	0.25
CGCG 160–058	1.45	9.90	0.19	-0.42
CGCG 160–067	1.05	9.57	-0.26	-0.56
CGCG 160–073	1.16	9.72	0.67	-0.29
CGCG 160–081	1.56	10.5	1.4	0.82
CGCG 160–086	1.15	9.25	0.50	0.13
CGCG 160–088	1.50	10.4	0.36	0.069
CGCG 160–257	1.49	10.5	1.1	0.45
CGCG 160–260	1.59	10.6	0.72	0.0081
CGCG 160–098	1.23	9.82	0.27	-0.32
CGCG 160–095	1.82	10.9	0.83	0.45
CGCG 160–102	1.60	10.5	-0.041	0.49
CGCG 160–106	1.23	9.93	0.29	-0.30
CGCG 160–128	1.30	9.54	-0.29	-0.32
CGCG 160–127	1.40	9.29	-0.11	-0.37
CGCG 097–068	1.45	10.2	-0.29	-0.24
CGCG 097–072	1.34	10.3	0.39	0.019
CGCG 097–091	1.43	10.2	-0.096	0.19

Table 8: Gas deficiency in cluster galaxies (continued).

Galaxy	$\log D_{25}$ (kpc)	$\log L_{\mathrm{H}}$ ($L_{\odot}$)	HI deficiency	H ₂ deficiency
CGCG 097–129W	1.76	10.7	0.016	0.41
CGCG 127–052	1.72	10.8	0.31	0.66

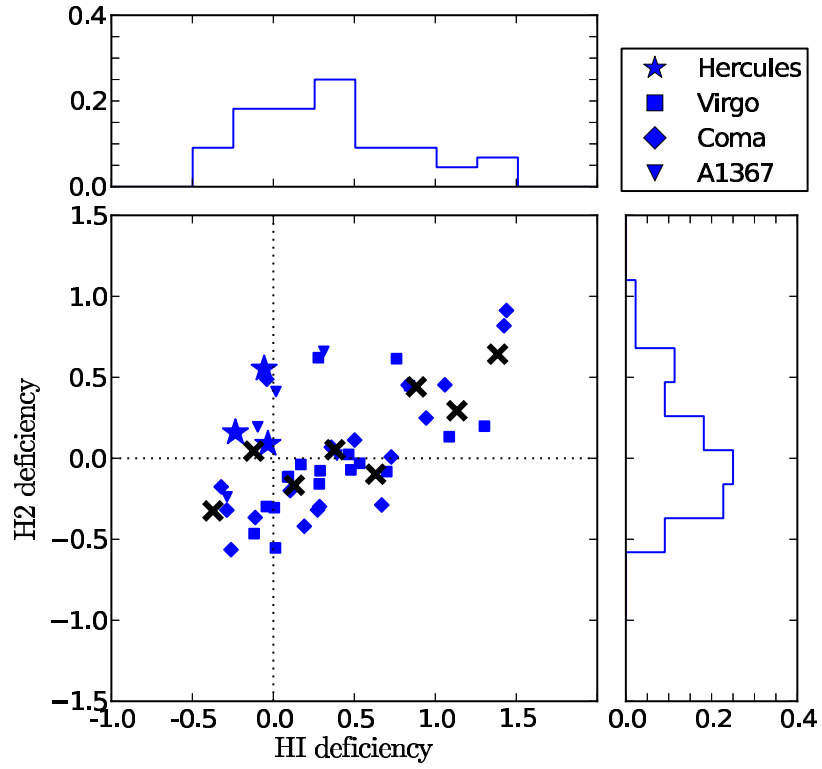


Figure 17 The correlation between HI deficiency and H_2 deficiency for cluster galaxies. Blue stars, squares, diamonds, and inverted triangles indicate galaxies in the Hercules, Virgo, Coma, and Abell 1367 clusters, respectively. Histograms of HI deficiency and H_2 deficiency are shown along each axes, which are normalized to the total number of cluster galaxies. Average of H_2 deficiencies within each range of HI deficiency in totally 35 cluster galaxies is shown in black x-mark.

4.3.2 Relation to properties of clusters

In order to reveal the relation between gas deficiency and some properties of belonging cluster, correlation between H_2 deficiency and physical quantities that characterize each cluster are investigated. We adopt the velocity dispersion of spiral and elliptical galaxies in each cluster (Binggeli, Popescu, & Tammann (1993) for Virgo cluster and Struble & Rood (1991) for other clusters) and X-ray temperature derived from *X-Rays Galaxy Clusters Database*, BAX ^{*3}. In figure 18, we show the relation between the HI deficiency in galaxies in the clusters and velocity dispersion (left) and the X-ray temperature (right) of their belonging cluster. Since there is a large variation of HI deficiencies within the each cluster, it is difficult to find a tendency between them. However, it is possible that there is a weak positive trend between the velocity dispersion and HI deficiency when we average them within each cluster. The X-ray temperature seems not to be related to HI deficiency. Contrary to HI deficiency, there might be a negative weak correlation between H_2 deficiency and the velocity dispersion (figure 19). It is possible that there is no H_2 -rich galaxy in the cluster whose velocity dispersion is small. As to X-ray temperature there is no relation of H_2 to deficiency.

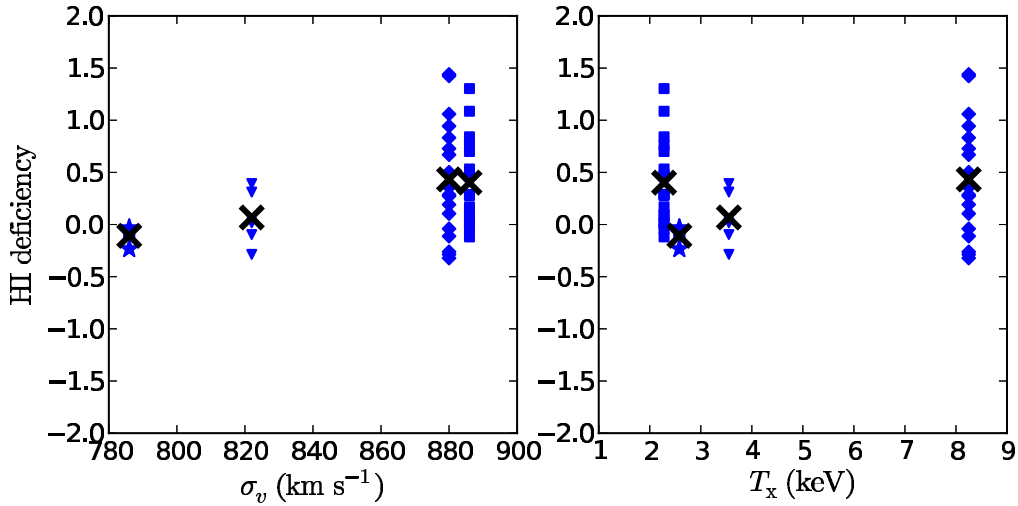


Figure 18 Relation between HI deficiency in galaxies in the clusters and velocity dispersion (left) and X-ray temperature (right) of their belonging cluster. Black x-mark shows the average of HI deficiency in each cluster. Blue symbols are the same as figure 17.

^{*3} <http://bax.ast.obs-mip.fr/>

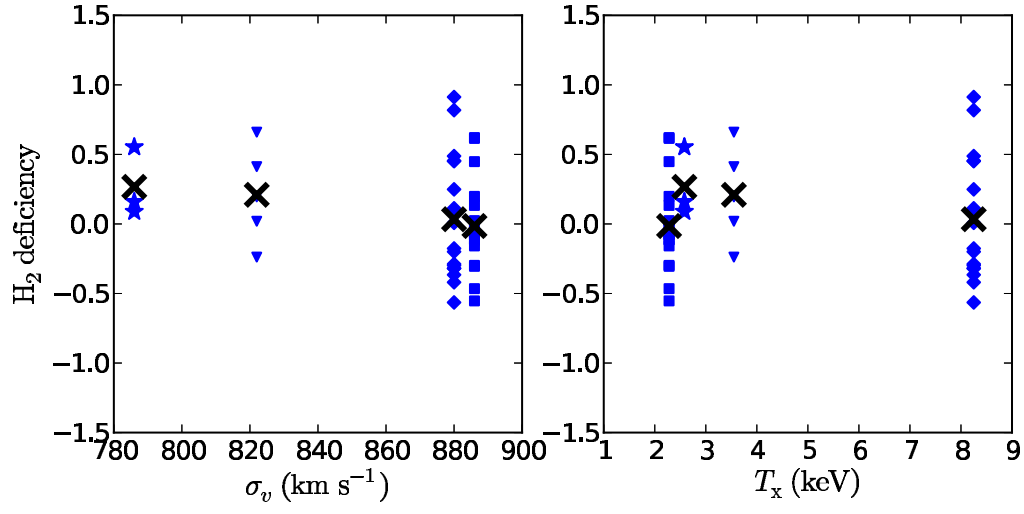


Figure 19 Relation between H₂ deficiency in galaxies in the clusters and velocity dispersion (left) and X-ray temperature (right) of their belonging cluster. Symbols are the same in figure 18.

5 Discussion

In the previous section, there are some cluster galaxies whose molecular gas mass is smaller than isolated galaxies with similar H -band luminosity. We expect that the H_2 deficiency would be correlated with the properties of the belonging cluster if molecular gas is deficient due to environmental effects. However, it is found that the H_2 deficiency does not increase with the velocity dispersion and X-ray temperature of their belonging cluster (figure 19). This implies that the properties of belonging cluster seem not to relate with the depletion of molecular gas. Since the velocity dispersion and X-ray temperature may be invalid as the parameters that represent the global property of their cluster, here we explore three possibilities to cause the depletion of gas by considering an alternative global property of the cluster.

5.1 Ram Pressure

Ram pressure is thought to be a dominant process in environmental effects (section 1.2). Hence we investigate a relation between the gas deficiency and global property representing ram pressure as an alternative to the velocity dispersion and X-ray temperature. The ram pressure is represented as $\rho_{\text{IGM}} V_{\text{gal}}^2$ from equation (1). We estimate this assuming that the IGM density is an average density within the cluster, $\bar{\rho} = M_{\text{vir}}((4/3)\pi R_{\text{vir}}^3)^{-1}$, where M_{vir} and R_{vir} are virial mass and virial radius, respectively. The velocity of galaxy can represent the relative velocity to the cluster core (V_{cluster}), $dV = |V_{\text{gal}} - V_{\text{cluster}}|$. The relations to the gas deficiencies are shown in figure 20. If the ram pressure induces the depletion of gas, gas deficiencies are expected to be large with increasing the ram pressure. However, such trend cannot be seen. Therefore it is difficult to consider the ram pressure as the only cause of gas deficiencies.

On the other hand, it has been found that the HI deficiency tends to become large with the ram pressure (Boselli & Gavazzi 2006). Since their sample of cluster galaxies is from the main subcluster in the Virgo cluster, cluster A, there is a possibility to need to consider the internal distribution of galaxy in each cluster.

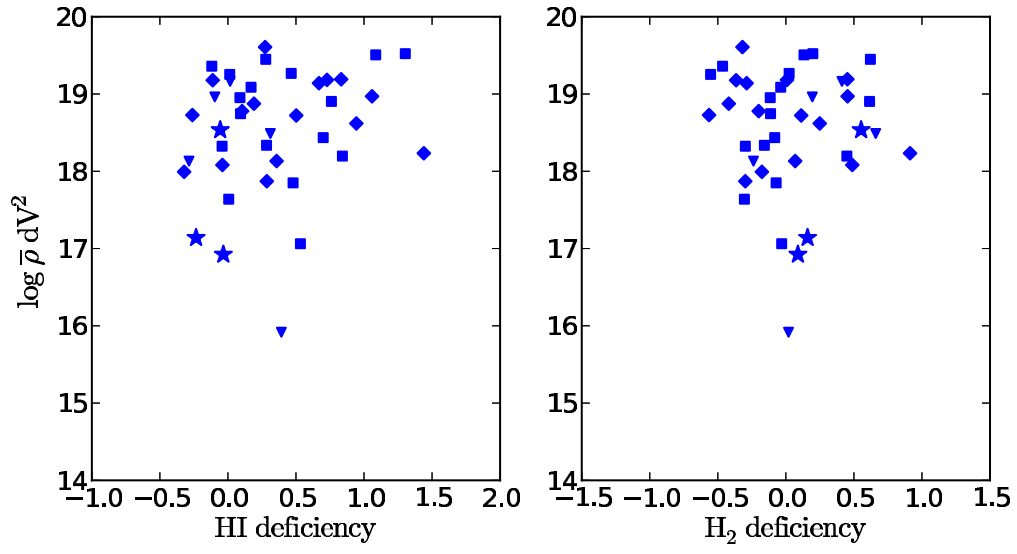


Figure 20 Correlations between the average density within the cluster times the square of the relative velocity to the cluster core, which represents ram pressure, and HI deficiency (left) or H₂ deficiency (right). Blue symbols are the same as figure 17.

5.2 Galaxy–Galaxy Interaction

While global structure of a cluster of galaxies might not affect gas fraction, interaction among galaxies has possibility to affect it. We estimate local density in two ways; the distance to the tenth nearest galaxies (d_{10} (Mpc)) and the distance to the cluster core (θ (Mpc)). In both ways, galaxies which located within projected radius of 1 Mpc and velocity within $\pm 1000 \text{ km s}^{-1}$ are searched from the catalog which is based on SDSS photometric catalog for Hercules, Coma, and Abell 1367 cluster galaxies and the Extended Virgo Cluster Catalog (Kim et al. 2014) for Virgo cluster. In order to count galaxies with the same sensitivity independent of the distance, we select galaxies with an absolute magnitude of $M_r < -18.25$, which corresponds to an apparent magnitude limit of $r = 17.77$ in the distance of 160 Mpc.

Correlation between gas deficiency and the distance to the tenth nearest galaxies d_{10} is shown in figure 21. There is no significant trend between them. Since number density of galaxies is in general higher in the core of the cluster, the number density of galaxies is thought to depend on the distance to the center of cluster. Thus we also quantified local density by the distance to the cluster core, θ . Normalized distance by virial radius R_{vir} is used in order to compensate for the difference of size of each cluster. In figure 22, correlation between gas deficiency and the normalized distance to the cluster core, θ/R_{vir} is shown. While there is no clear correlation between them, it is found that there is no galaxy with large deficiency in distant region from the cluster core. It is shown that an average HI deficiency in some width of the distance to the core decreases with the distance in the Coma cluster (Gavazzi et al. 2006). Since our sample of cluster galaxies is limited by observed in $^{12}\text{CO}(J = 1 - 0)$, the number of galaxies is not sufficient to represent these statistical feature.

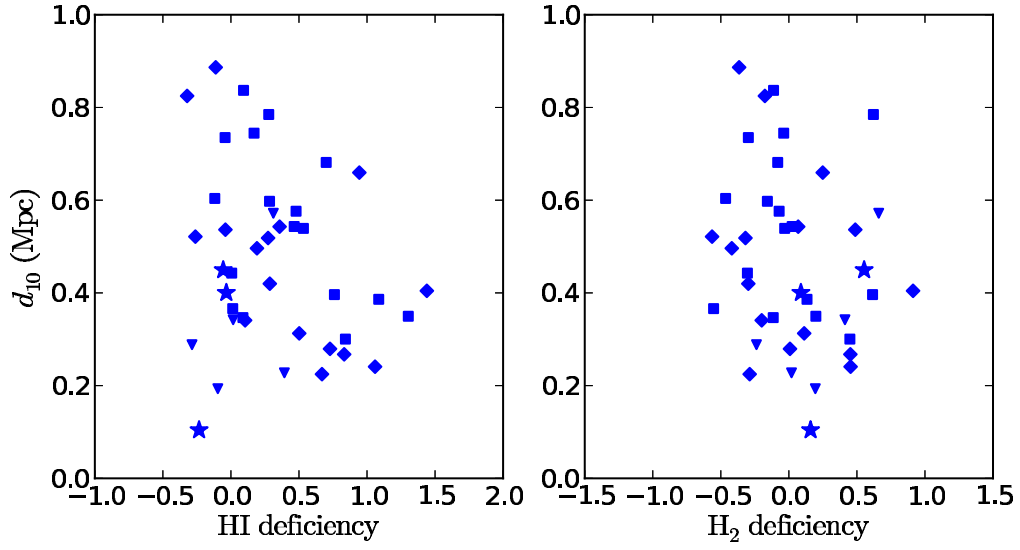


Figure 21 Correlations between the distance to the tenth nearest galaxies and HI deficiency (left) and H₂ deficiency (right) . Blue symbols are the same as figure 17.

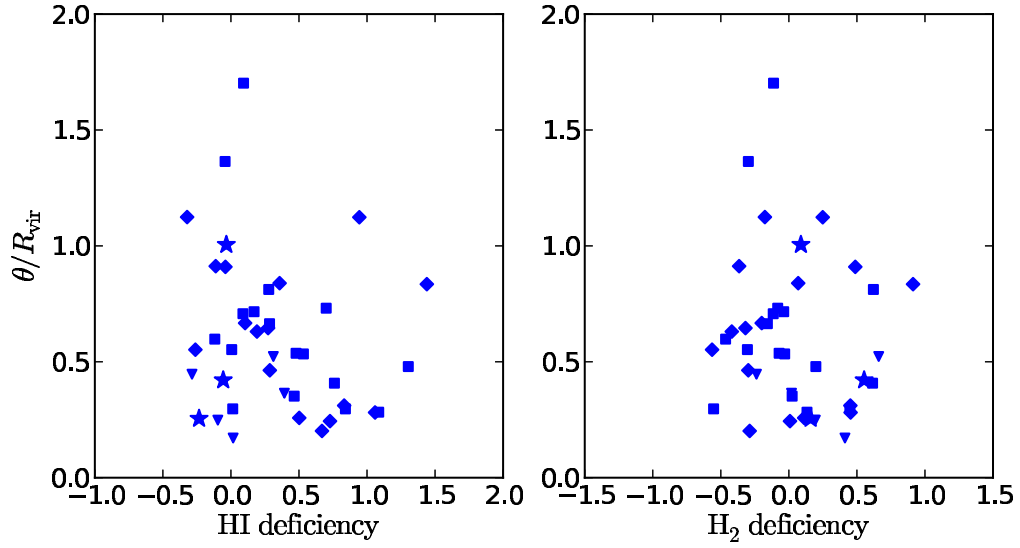


Figure 22 Correlations between the normalized distance to the cluster core and HI deficiency (left) and H₂ deficiency (right). Blue symbols are the same as figure 17.

5.3 Internal Effects

It is important to take into account the internal process that occurs in the each galaxy since several physical process which contributes to the quenching of star formation has been proposed in section 1.1.2. Thus we discuss relations between gas deficiencies and internal effects in not only cluster galaxies but also isolated galaxies.

In the first, we compare a comparison of a correlation of gas deficiencies between cluster galaxies and isolated galaxies in figure 23. Here we select 37 isolated galaxies that have all data required to derive gas deficiencies, SFR, and stellar mass. It is found that most isolated galaxies are located around HI deficiency ~ 0 and H₂ deficiency ~ 0 . The histograms of HI deficiency and H₂ deficiency in each sample show that the distribution of HI deficiency in cluster galaxies is slightly biased toward larger than that in isolated galaxies although there is no difference in the histograms of H₂ deficiency.

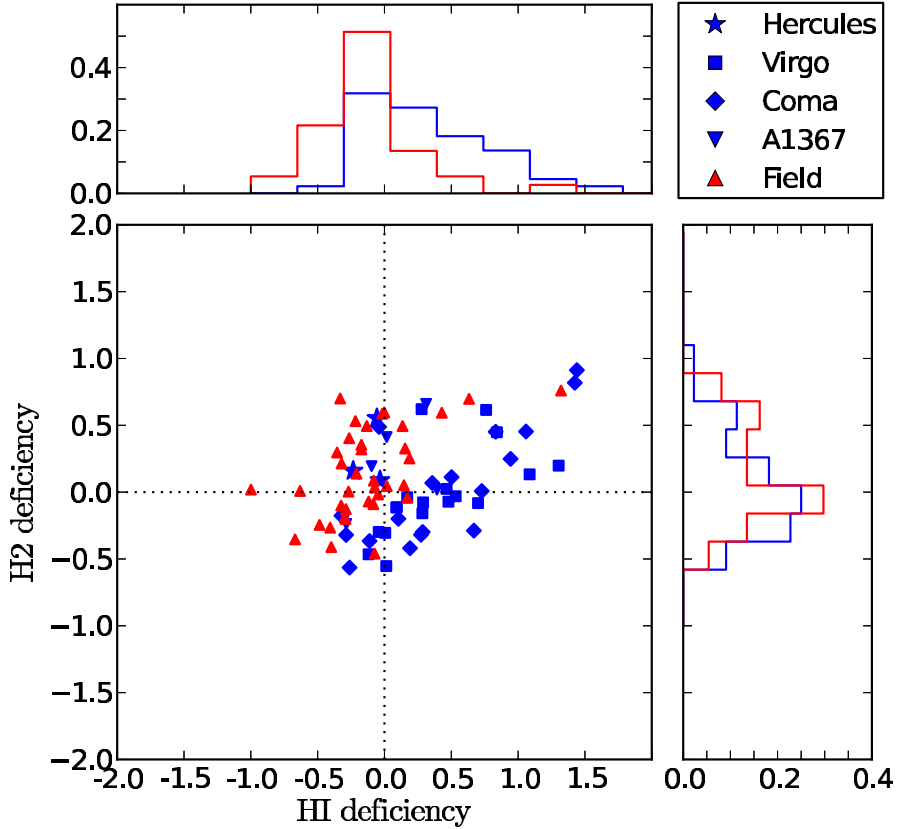


Figure 23 Correlation between HI deficiency and H₂ deficiency for cluster galaxies and isolated galaxies. Symbols are the same as figure 17. Red triangle shows isolated galaxy. Histograms are also shown as the same way in figure 17 and isolated galaxies colored red are added.

5.3.1 Star Formation

We discuss possibilities to consumption of gas caused by formation of stars. First, we plot the relation between HI deficiency and the properties of star formation such as SFR, stellar mass, and sSFR using the sample of isolated and cluster galaxies (figure 24). Correlation coefficients in cluster galaxies are -0.31, 0.35, and -0.40 for SFR, stellar mass, and sSFR, respectively. In isolated galaxies, correlation coefficients are -0.43, 0.26, and -0.50, respectively. There might be trends that the HI deficiency increases with decreasing SFR and sSFR, and with increasing stellar mass of both isolated and cluster galaxies.

Next, we investigate the relation between H₂ deficiency and SFR, stellar mass, and sSFR (figure 25). It is clear that the H₂ deficiency increases with decreasing SFR and sSFR, and with increasing stellar mass of both isolated and cluster galaxies. Correlation coefficients in cluster galaxies are -0.58, 0.62, and 0.74 for SFR, stellar mass, and sSFR, respectively, and in isolated galaxies, -0.56, 0.28, and -0.61, respectively. Since the depletion of molecular gas clearly have correlation with star formation, there are two possibilities that molecular gas is used up by star formation and that the depletion of molecular gas that caused by some processes suppresses formation of stars. On the other hand, Boselli et al. (2014) have shown there is clear correlation between the H₂ deficiency of nearby spiral galaxy and NUV-*i* color index that is regarded as a proxy for sSFR, which is consistent with the lower left panel in figure 25. They have concluded that the depletion of molecular gas suppresses star formation.

There are some isolated galaxies with higher H₂ deficiency (H₂ deficiency $\gtrsim 0.0$) and lower stellar mass ($\log M_{\text{star}} \lesssim 10.5$). The five corresponding galaxies are NGC 3049, NGC 3359, NGC 5584, UGC 06879, and UGC 11816. Since star formation in these galaxies are not so active ($-0.47 \lesssim \log SFR (M_{\odot} \text{ yr}^{-1}) \lesssim -0.13$), the slightly large value of H₂ deficiency does not seem to be the result of starburst. In addition, these galaxies are HI-normal galaxies. Since UGC 06879 is an edge-on galaxy and others are barred galaxies whose radial gas distributions are different from those in normal spiral galaxies, the aperture correction in the estimation of molecular gas mass might not work well.

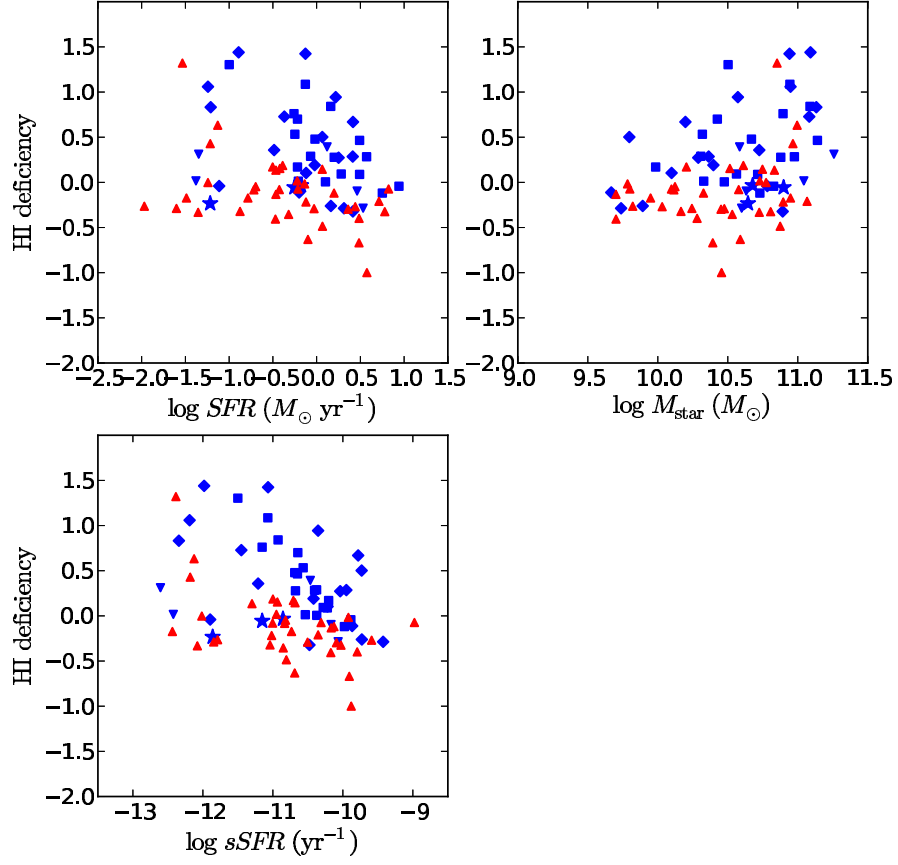


Figure 24 Correlations between HI deficiency and SFR (top left), stellar mass (top right), and sSFR (bottom left). Blue symbols are the same as figure 17. Red triangle indicates isolated galaxies.

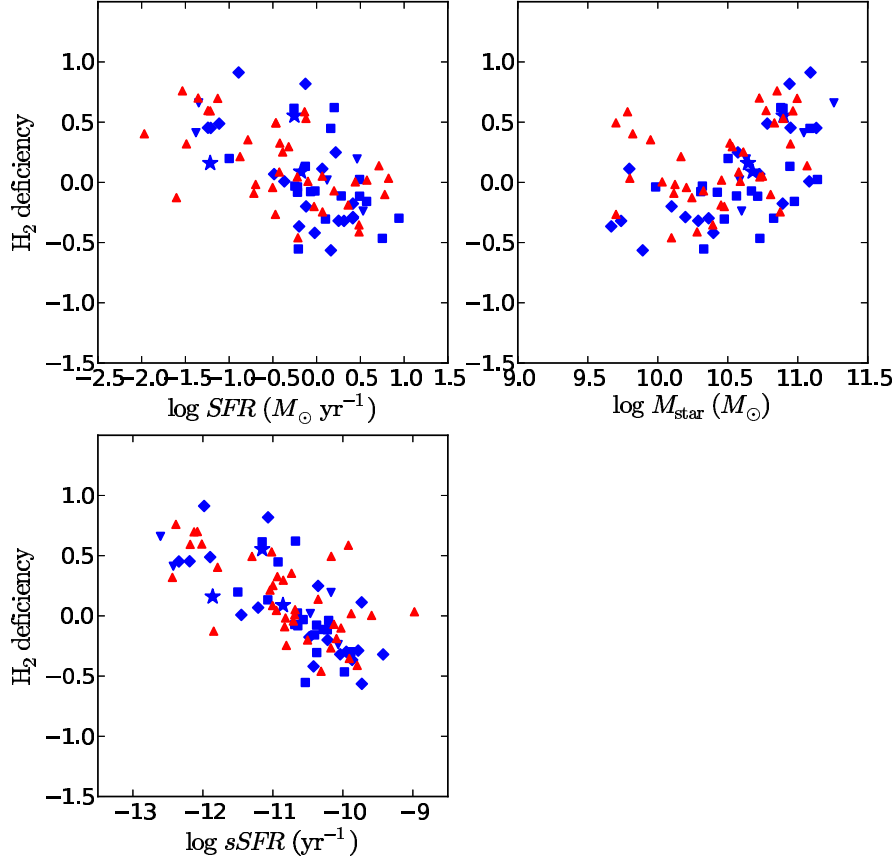


Figure 25 Correlations between H₂ deficiency and SFR (top left), stellar mass (top right), and sSFR (bottom left). Blue and red symbols are the same as figure 24.

5.3.2 AGN Feedback

We examine a possibility that the depletion of gas is induced by AGN feedback. As the parameter that represents AGN activity, flux ratio of [NII] to H α emission line is from MPA–JHU catalog. We selected galaxies whose BPT class is AGN, low-ionization nuclear emission-line region (LINER), or composite type between AGN and star-forming nuclei. Figure 26 shows weak positive trend between [NII]/H α and HI deficiency (left) and H₂ deficiency (right). Therefore this tendency might be attributed to the AGN feedback that heats or expels the surrounding gas, which is consistent with Saintonge et al. (2012). In addition, it is certain that most AGN-host galaxies are in the region of the green valley that is a transition region from the blue to red sequence. This implies that AGN feedback has a role of quenching of star formation (Martin et al. 2007; Schawinski et al. 2007). However AGN is necessary to

be obscured or radiatively inefficient during in blue cloud (Schawinski et al. 2009; Schawinski et al. 2014). In fact, in also our sample of galaxies, nuclear activity becomes large in passive spiral galaxies (figure 27).

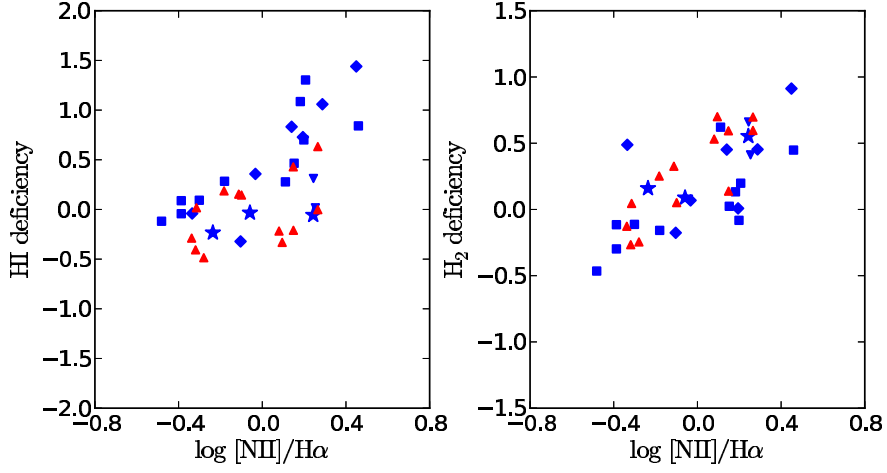


Figure 26 Correlation between HI deficiency (left) and H₂ deficiency (right) and AGN activity, flux ratio of [NII] to H α . Colors and symbols are the same as figure 23.

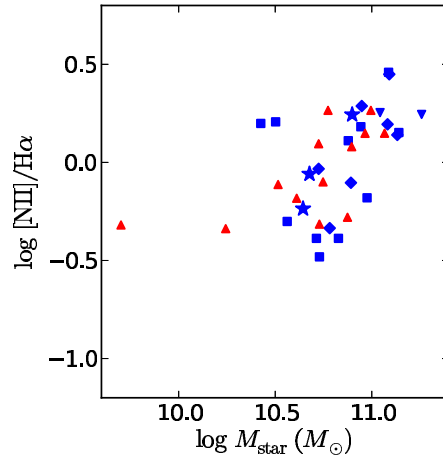


Figure 27 Correlation between stellar mass and AGN activity. Colors and symbols are the same as figure 23.

5.4 Distribution on HI deficiency–H₂ deficiency plot

Here we look at the distribution in the correlation plot between HI deficiency and H₂ deficiency again. It is found that H₂ deficiency increases with HI deficiency in both isolated galaxies and cluster galaxies (figure 23). In order to reveal what determines this distribution, we investigate the relations among these deficiencies and nine quantities that we have explored in 5.1, 5.2, and 5.3; SFR, stellar mass, sSFR, flux ratio of [NII] to H α , X-ray temperature of belonging cluster, velocity dispersion of belonging cluster, distance to the 10th nearest galaxy, normalized projected distance to the cluster core, and parameter of ram pressure. In order to represent the relation on the HI deficiency–H₂ deficiency plot by these physical quantities, multi regression analysis is performed. In this analysis, physical quantities that are independent each other have to be selected. Hence, first of all, we perform a principal component analysis, which produces some composed variables which are independent from each other.

Three new composed variables are derived through the principal component analysis. The values in table 9 correspond to coefficients of each physical quantity for each composed variable. Relations between coefficients for the first components and those for the second components (left) and those for the third components (right) are shown in figure 28. The coefficient is corresponding to the correlation coefficients between the composed variable and each physical quantity. Therefore it is found that the first component is related to star formation and nuclear activity (stellar mass, SFR, sSFR, and [NII]/H α). The second one is related to local environment which is represented by d_{10} and θ/R_{vir} . The third one is related to global environment which is represented by the velocity dispersion and X-ray temperature of belonging cluster.

Table 9 Coefficients of each physical quantity for each composed variable.

Component	SFR	M_{star}	sSFR	[NII]/H α	T_X	σ_{cluster}	d_{10}	θ/R_{vir}	$\bar{\rho}dV^2$
First	0.76	-0.68	0.91	-0.72	0.11	0.44	0.57	0.53	-0.014
Second	-0.0071	0.49	0.23	-0.44	0.28	-0.29	-0.71	-0.67	0.013
Third	-0.19	-0.11	-0.089	0.15	0.44	0.67	0.047	-0.19	0.74

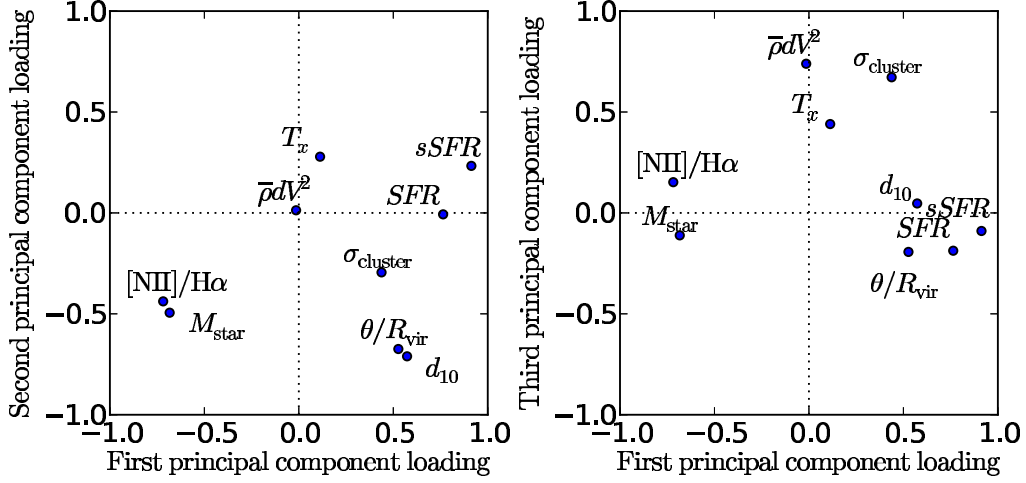


Figure 28 Correlation plot of coefficients of each physical quantity in each physical quantity for the first composed variable to the those for the second composed variable (left) and to the those for the third composed variable (right).

Finally, we perform multiple regression analysis. Since the first, second, and third components derived from the principal component analysis are independent from each other, these three composed variables for the sample galaxies are calculated and used for the regression analysis. The results of the regression analysis are shown by

$$\text{HI deficiency} = -6.5 \times 10^{-17} - 0.38X_{\text{first}} - 0.13X_{\text{second}} + 0.50X_{\text{third}}, \quad (23)$$

$$\text{H}_2 \text{ deficiency} = -4.4 \times 10^{-17} - 0.74X_{\text{first}} - 0.31X_{\text{second}} - 0.0042X_{\text{third}}, \quad (24)$$

where X_{first} , X_{second} , and X_{third} are the composed variables. Since these expressions are achieved from standardized composed variables, their coefficients are corresponding to the correlation coefficients to HI deficiency or H_2 deficiency. Hence HI deficiency is closely related to the third component, which represents global environment, and H_2 deficiency is closely related to the first component, which represents internal effect such as star formation activity and nuclear activity.

The first component varies along the dashed line in figure 29 when both the second and third components in the above formulae are 0, in other words, when both the second and third components are average values of these sample of galaxies. The direction that internal effects are effective is indicated by an arrow in this figure. Similarly, directions that indicate positive effect of the second component and the third component are also shown through substituting the above formulae into $X_{\text{first}} = X_{\text{third}} = 0$ and $X_{\text{first}} = X_{\text{second}} = 0$, respectively. Length of each arrow shows relative effect.

It is found that only the first variable has a positive component of H_2 deficiency. This implies that the internal effects have closely relation to the depletion of molecular gas. Since there is

no composed variable to relate H_2 deficiency but the internal effects, the scenario that star formation becomes passive due to depletion of gas is rejected and alternatively, we can interpret the depletion of molecular gas is the result of internal effect. On the other hand, the direction of the third component (blue arrow in figure 29) corresponds to the direction that HI deficiency becomes large. Therefore the global environment dose not seem to relate to the depletion of molecular gas. In addition, a dependence of gas deficiency on the second component, or local environment is thought to be small. The direction that the second variable becomes effective and also the direction that the third variable becomes effective (green and blue arrow, respectively in figure 29) are slightly dependent on the physical quantity prepared for the principal component analysis. However, the result that performed the principal component analysis by different selection of physical quantities from the above is not against conclusions.

In this way, it is revealed that galaxies deplete their molecular gas mass mainly due to internal mechanisms such as star formation or AGN feedback, and moreover the global environments make only atomic gas decrease and hardly contribute to the depletion of molecular gas.

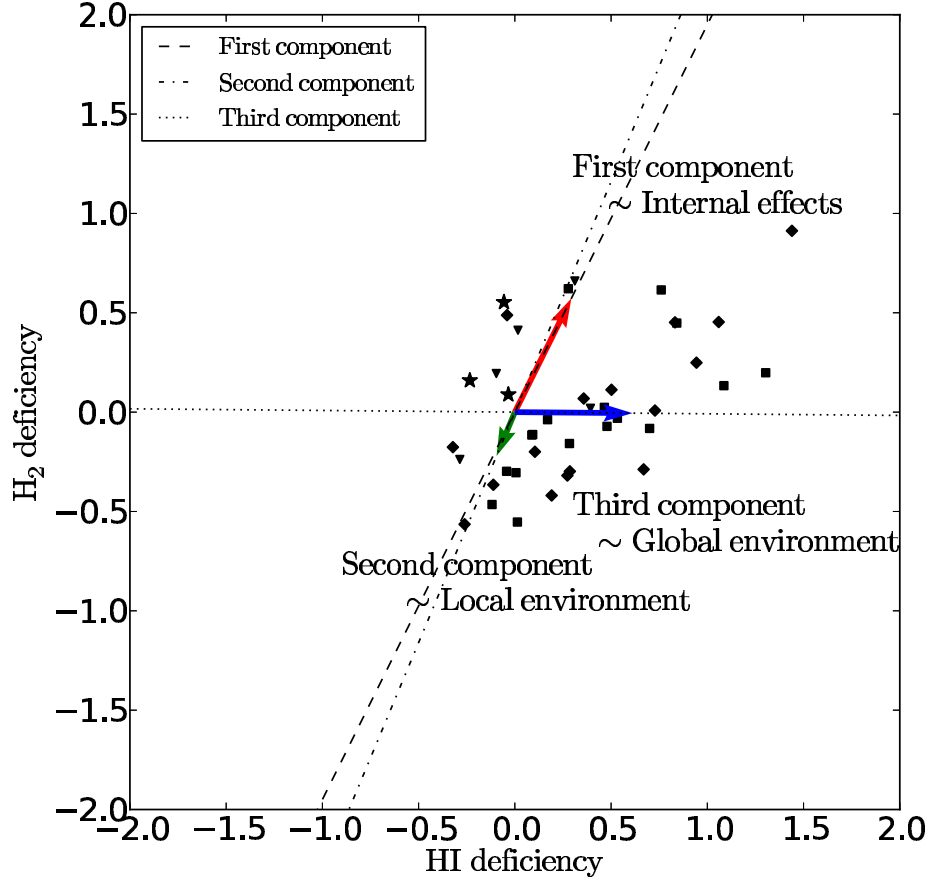


Figure 29 Correlation between HI deficiency and H₂ deficiency and the results of regression analysis are shown. Arrows show the direction that each composed variable becomes large. However red arrow is the direction that the first component becomes small since the first component has anti-correlation to passive star formation. Length of each arrow corresponds to relative effect.

6 Conclusions

In order to reveal the mechanism that causes H_2 deficiency clear, we derived molecular gas mass of galaxies in the Hercules cluster that is in different evolutionary stage with previously observed clusters of galaxies. We observed $^{12}\text{CO}(J = 1-0)$ line in three spiral galaxies (CGCG 108-121, IC 1173, CGCG 108-146) in the Hercules cluster using the 45-m radio telescope in the Nobeyama Radio Observatory. We could detect the emission in all three galaxies. The molecular gas masses are estimated as $\log M_{\text{H}_2} (M_{\odot}) = 9.2-9.4$. We compare these value with that in isolated galaxies and derive HI deficiency and H_2 . It is found that these galaxies have possibility to be H_2 -deficient despite of having normal contents of atomic gas.

As well as the Hercules cluster galaxies, we derive HI deficiency and H_2 deficiency of cluster galaxies in the Virgo, the Coma, and Abell 1367 clusters using archival data. Correlations between average gas deficiencies within each cluster and velocity dispersion and X-ray temperature of belonging cluster have a possibility that global environment removes atomic gas, while it has little effect on molecular gas.

Moreover, we investigate two alternative possibilities that cause the depletion of gas; galaxy-galaxy interaction and internal effect such as star formation and AGN feedback. It is found that local density which represents galaxy-galaxy interaction has no clear correlation with gas deficiencies. On the other hand, relations of H_2 deficiency to star formation rate (SFR), stellar mass, and specific star formation rate (sSFR) for both isolated and cluster galaxies show that gas deficiency tends to be larger with star formation becoming passive independent of their environment. In addition, we have examined the correlation between emission line ratio $[\text{NII}]/\text{H}\alpha$ and H_2 deficiency. The result shows that H_2 deficiency becomes larger with increasing nuclear activity. Therefore we might interpret that molecular gas is deficient due to star formation and/or AGN feedback.

Finally, in order to interpret the weak positive correlation between HI and H_2 deficiencies, we perform regression analysis and represent HI and H_2 deficiencies using three composed variables which are obtained from principal component analysis; the first variable represents internal effect, the second one represents local environment, and the third one represents global environment.

It is found that the only variables which represent internal effect has a positive component of H_2 deficiency. This implies that molecular gas becomes deficient due to internal effect. On the other hand, the direction that global environment becomes effective does not have a component of H_2 deficiency, and corresponds to the direction that HI deficiency becomes large. Therefore, the global environment seems to have no relation to the depletion of molecular gas and remove only atomic gas. In this way, it is revealed that cluster galaxies deplete their gas

mainly due to internal mechanism such as star formation and/or AGN feedback, and the global environment removes only atomic gas and hardly contribute to the depletion of molecular gas.

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References

- Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, *PASP*, 93, 5
- Beijersbergen, M. 2003, Ph.D. Thesis, Groningen University
- Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, *ApJS*, 149, 289
- Bell, E. F. et al. 2004, *ApJ*, 608, 752
- Bell, E. F., Zheng, X. Z., Papovich, C., Borch, A., Wolf, C., & Meiseneimer, K. 2007, *ApJ*, 663, 834
- Binggeli, B., Sandage, A., & Tammann, G. A. 1985, *AJ*, 90, 1681
- Binggeli, B., Popescu, C. C., & Tammann, G. A. 1993, *A&AS*, 98, 275
- Birnboim, Y. & Dekel, A. 2003, *MNRAS*, 345, 349
- Boselli, A., Gavazzi, G., Combes, F., Lequeux, J., & Casoli, F. 1994, *A&A*, 285, 69
- Boselli, A., Casoli, F., & Lequeux, J. 1995, *A&AS*, 110, 521
- Boselli, A., Gavazzi, G., Lequeux, J., Buat, V., Casoli, F., Dickey, J., & Donas, J. 1997, *A&A*, 327, 522
- Boselli, A. & Gavazzi, G. 2009, *A&A*, 508, 201
- Boselli, A., et al. 2010, *PASP*, 122, 261
- Boselli, A., Cortese, L., & Boquien, M. 2014, *A&A*, 564, 65
- Brinchmann, J., Charlot, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., & Brinkmann, J. 2004, *MNRAS*, 351, 1151
- Bravo-Alfaro, H., Cayatte, V., van Gorkon, J. H., & Balkowski, C. 2000, *AJ*, 119, 580
- Brown, M. J. I., Dey, A., Jannuzi, B. T., Brand, K., Benson, J., Brodwin, M., Croton, D. J., & Eisenhardt, P. R. 2007, *ApJ*, 654, 858
- Butcher, H. & Oemler, Jr., A. 1984, *ApJ*, 285, 426
- Byrd, G. & Valtonen, M. 1990, *ApJ*, 350, 89
- Catinella, B., et al. 2010, *MNRAS*, 403, 683
- Casoli, F., Boissé, P., Combes, F., & Dupraz, C. 1991, *A&A*, 249, 359
- Casoli, F., Dickey, J., Kazes, I., Boselli, A., Gavazzi, G., & Jore, K. 1996, *A&AS*, 116, 193
- Cayatte, V., Kotanyi, C., Balkowski, C., & van Gorkom, J. H. 1994, *AJ*, 107, 1003
- Charlot, S., Kauffmann, G., Longhetti, M., Tresse, L., White, S. D. M., Maddox, S. J., & Fall, S. M. 2002, *MNRAS*, 330, 876
- Chincarini, C. L., Giovanelli, R., & Haynes, M. P. 1983, *ApJ*, 269, 13
- Chung, E. J., Rhee, M.-H., Kim, H., Yun, Min S., Heyer, M., & Young, J. S. 2009a, *ApJS*, 184, 199
- Chung, A., van Gorkom, J. H., Kenney, J. D. P., Cowl, H., & Vollmer, B. 2009b, *ApJ*, 138, 1741

- Cowie, L. L. & Songaila, A. 1977, *Nature*, 266, 501
- Croton, D. J., et al. 2006, *MNRAS*, 365, 11
- Dickey, J. M., & Kazes, I. 1992, *ApJ*, 393, 530
- Dickman, R. L., Snell, R. L., & Schloerb, F. P. 1986, *ApJ*, 309, 326
- Dressler, A. 1980, *ApJ*, 236, 351
- Dressler, A., Oemler, A., Jr., Couch, W. J., Smail, I., Ellis, R. S., Barger, A., Butcher, H., Poggianti, B. M., & Sharples, R. M. 1997, *ApJ*, 490, 577
- Eder, J., Giovanelli, R., & Haynes, M. P. 1991, *AJ*, 102, 572
- Faber, S. M., et al. 2007, *ApJ*, 665, 265
- Fabian, A. C. 1999, *MNRAS*, 308, L39
- Fontanelli, P. 1984, *A&A*, 138, 85
- Fujita, Y. 1998, *ApJ*, 509, 587
- Fujita, Y. 2004, *PASJ*, 56, 29
- Fumagalli, M., Krumholz, M. R., Prochaska, J. X., Gavazzi, G., & Boselli, A. *ApJ*, 2009, 697, 1811
- Gavazzi, G. 1987, *ApJ*, 320, 96
- Gavazzi, G. 1989, *ApJ*, 346, 59
- Gavazzi, G. & Boselli, A. 1996, *ApL&C*, 35, 1
- Gavazzi, G., Boselli, A., van Driel, W., & O’Neil, K. 2005, *A&A*, 429, 439
- Gavazzi, G., O’Neil, K., Boselli, A., & van Driel, W. 2006, *A&A*, 449, 929
- Giovanelli, R. & Haynes, M. 1985, *ApJ*, 292, 404
- Giovanelli, R., et al. 2005, *AJ*, 130, 2598
- Goto, T. et al. 2003, *PASJ*, 55, 739
- Granato, G. L., De Zotti, G. , Silva, L., Bressan, A., & Danese, L. 2004, *ApJ*, 600, 580
- Gunn, J. E. & Gott, J. R. 1972, *ApJ*, 176, 1
- Haynes, M. P. & Giovanelli, R. 1984, 89, 758
- Haynes, M. P., Giovanelli, R., & Chincarini, G. L. 1984, *ARA&A*, 22, 445
- Haynes, M. P., Giovanelli, R., Herter, T., Vogt, N. P., Fpeudling, W., Maia, M. A. G., Salzer, J. J., & Wegner, G. 1997, *AJ*, 113, 1197
- Haynes, M. P., Giovanelli, R., & Kent, B. R. 2007, *ApJ*, 665, 19
- Haynes, M. P., et al. 2011, *AJ*, 142, 170
- Holmberg, E. 1958, *MeLu2*, 136, 1
- Hopkins, P. F., Hernquist, L., Cox, T. J., di Matteo, T., Robertson, B., & Springel, V. 2006, *ApJS*, 163, 1
- Jarrett, T. H., Chester, T., Cutri, R., Chneider, S., Skrutskie, M., & Huchra, J. P. 2000, *AJ*, 119, 2498
- Karachentseva, V. E. 1973, *Soobshcheniya Spetsial’noj Astrofizicheskoy Observatorii*, 8, 3

- Karachentseva, V. E., Mitronova, S. N., Melnyk, O. V., & Karachentsev, I. D., 2010, *AstBu*, 65, 1
- Kennicutt, R. C. 1998a, *ARA&A*, 36, 189
- Kennicutt, R. C. 1998b, *ApJ*, 498, 541
- Kennicutt, R. C., Hao, C. –N., Calzetti, D., Moustakas, J., Dale, D. A., Bendo, G., Engelbracht, C. W., Johnson, B. D., & Lee, J. C. 2009, *ApJ*, 703, 1672
- Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, 363, 2
- Kim, S., et al. 2014, *ApJS*, 215, 22
- Koopmann, R. A., Kenney, J. D. P., & Young, J. 2001, *ApJS*, 135, 125
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2009, *ApJ*, 693, 216
- Kudrya, Y. N., Karachentseva, V. E., & Karachentsev, I. D. 2011, *Ap*, 54, 445
- Kuno, N., et al. 2007, *PASJ*, 59, 117
- Landsman, W. B. 1993, *ASPC*, 52, 246
- Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, *ApJ*, 237, 692
- Lavezzi, T. E., Dickey, J. M., Casoli, F., & Kazes, I. 1999, *AJ*, 117, 1995
- Lisenfeld, U., et al., 2011, *A&A*, 534, 102
- Mamon, G. A. 1987, *ApJ*, 321, 622
- Martin, D. C. et al. 2007, *ApJS*, 173, 342
- Merritt, D. 1984, *ApJ*, 276, 26
- Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A., Jr. 1996, *Nature*, 379, 613
- Moore, B., Lake, G., & Katz, N. 1998, *ApJ*, 495, 139
- Moore, B., Lake, G., Quinn, T., & Stadel, J. 1999, *MNRAS*, 304, 465
- Nilson, P. 1973, *Uppsala General Catalogue of Galaxies*, Uppsala Astronomical Observatory Ann,m Vol. 6
- Nulsen, P. E. J. 1982, *MNRAS*, 198, 1007
- Pappalardo, S. et al. 2012, *A&A*, 545, 75
- Peng, Y.-J., et al., 2010, *ApJ*, 721, 193
- Postman, M. & Geller, M. J. 1984, *ApJ*, 281, 95
- Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, *Numerical Recipes* (2nd ed.; Cambridge: Cambridge Univ. Press)
- Rakos, K. D. & Schombert, J. M 1995, *ApJ*, 439, 47
- Rees, M. J. & Ostriker, J. P. 1977, *MNRAS*, 179, 541
- Sage, L. J. 1993, *A&A*, 272, 123
- Saintonge, A., et al. 2011, *MNRAS*, 415, 32
- Saintonge, A., et al. 2012, *ApJ*, 758, 73
- Salpeter, E. E. 1955, *ApJ*, 121, 161

- Scodeggio, M., & Gavazzi, G. 1993, *ApJ*, 409, 110
- Scott, T. C., Usero, A., Brinks, E., Boselli, A., Cortese, L., & Bravo-Alfaro, H. 2013, *MNRAS*, 429, 221
- Schawinski, K., Thomas, D., Sarzi, M., Maraston, C., Kaviraj, S., Joo, S., Yi, S. K., & Silk, J. 2007, *MNRAS*, 382, 1415
- Schawinski, K. et al. 2014, *MNRAS*, 440, 889
- Schawinski, K., Virani, S., Simmons B., Urry, C. M., Treister, E., Kaviraj, S., & Kushakuley, B. 2009, *ApJ*, 692, L19
- Schlaflly, E. F. & Finkbeiner, D. P. 2011, *ApJ*, 737, 103
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Schommer, R., A., Sullivan, III, W. T., & Bothun, G. D. 1981, *AJ*, 86, 943
- Shostak, G. S. 1978, *A&A*, 68, 321
- Solanes, J. M., Giovanelli, R., & Haynes, M. P. 1996, *ApJ*, 461, 609
- Solanes, J. M., Manrique, A., Garcia-Gomez, C., Gonzalez-Casado, G., Giovanelli, R., & Haynes, M. P. 2001, *ApJ*, 548, 97
- Springob, C. M., Haynes, M.P., Giovanelli, R., Kent, B. R. 2005, *ApJS*, 160, 149
- Stark, D. V., Kannappanm S. J., Wei, L. H., Baker, A. J., Leroy, A. K., Eckert, K. D., & Vogel, S. N., 2013, *ApJ*, 769, 82
- Strateva, I., et al. 2001, *AJ*, 122, 1861
- Strauss, M. A., et al., 2002, *AJ*, 124, 1810
- Struble, M. F. & Rood, H. J. 1991, *ApJS*, 77, 363
- Sullivan, W. T., III, Bates, B., Bothun, G. D., Schommer, R. A. 1981, *AJ*, 86, 919
- Sullivan, M., Treyer, M. A., Ellis, R. S., Bridges, T. J., Milliard, B., & Donas, J. 2000, *MNRAS*, 312, 442
- Treu, T., Ellis, R. S., Kneib, J.-P. Dressler, A., Smail, I., Czoske, O., Oemler, A., & Natarajan, P. 2003, *ApJ*, 591, 53
- Valluri, M. & Jog, C. J. 1990, *ApJ*, 357, 367
- Verdes-Montenegro, L., Sulentic, J., Lisenfeld, U., Leon, S., Espada, D., Garcia, E., Sabater, J., & Verley, S. 2005, *A&A*, 436, 443
- Vollmer, B., Cayatte, V., Balkowski, C., & Duschl, W. J. 2001, *ApJ*, 561, 708
- Vollmer, B., Balkowski, C., Cayatte, V., van Driel, W., & Huchtmeier, W. 2004, *A&A*, 419, 35
- Whitmore, B. C. & Gilmore, D. M. 1991, *ApJ*, 367, 64
- Whitmore, B. C., Gilmore, D. M., & Jones, C. 1993, *ApJ*, 407, 489