The Detection Rate of Molecular Gas in Elliptical Galaxies: Constraints on Galaxy Formation Theories

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Abstract

In order to constrain parameters in galaxy formation theories, especially those for a star formation process, we investigate cold gas in elliptical galaxies. We calculate the detection rate of cold gas in them using a semi-analytic model of galaxy formation and compare it with observations. We show that the model with a long star formation time-scale (∼ 20 Gyr) is inconsistent with observations. Thus, some mechanisms of reducing the mass of interstellar medium, such as the consumption of molecular gas by star formation and/or reheating from supernovae, are certainly effective in galaxies. Our model predicts that star formation induced when galaxies in a halo collide each other reduces the cold gas left until the present. However, we find that the reduction through random collisions of satellite (non-central) galaxies in mean free time-scale in a halo is not required to explain the observations. This may imply that the collisions and mergers between satellite galaxies do not occur so often in clusters or that they do not stimulate the star formation activity as much as the simple collision model we adopted. For cD galaxies, the predicted detection rate of cold gas is consistent with observations as long as the transformation of hot gas into cold gas is prevented in halos whose circular velocities are larger than 500 km s⁻¹. Moreover, we find that the cold gas brought into cDs through captures of gas-rich galaxies is little. Our fiducial models and the models with large reheating efficiency can reproduce observations well, although the comparison with a larger and complete sample of elliptical galaxies will constrain physical parameters in galaxy formation theories more strictly.

Key words: Galaxies: clusters: general — Galaxies: ISM — Galaxies: cooling flows — Galaxies: elliptical and lenticular, cD

1. Introduction

Theoretical models based on hierarchical clustering scenario are used to show the merging history and evolution of galaxies with various masses and of species simultaneously. N-body simulations with hydrodynamics have been often used to predict them. Although these simulations reproduce an outline of the formation and evolution of galaxies, it is not suitable for detailed study of baryonic component of galaxies at present. This is because many processes such as gas cooling, star formation, and supernova feedback are responsible for the evolution of the baryonic component and a large dynamic range in simulation is needed to treat those processes.

Semi-analytic models of galaxy formation are embedded within the framework of the hierarchical clustering scenario. In these models, gas cooling, star formation, and supernova feedback are approximated by simple rules. Contrary to N-body simulations, they can simultaneously treat physical processes in various scales such as formation of large scale structure in the universe and star formation in a galaxy. However, although the semi-analytic models have achieved notable successes in modeling many properties of galaxies, such as a luminosity function of galaxies (Kauffmann et al. 1993; Cole et al. 1994; Kauffmann, Charlot 1998; Baugh et al. 1998; Somerville, Primack 1999; Nagashima et al. 1999), the models still have many unknown parameters. In particular, the parameters regarding a star formation process such as the efficiency of supernova feedback and the

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time-scale of star formation have not been determined, although they are key parameters of galaxy formation. Since it is difficult to derive them only from theoretical studies at present, we need independent observational constraints to determine them. Observations of luminosities and colors of galaxies, or information on stars, have mainly been used as the constraints, but they appear to be insufficient. Thus we need other constraints.

In this paper, we investigate the evolution of cold gas in elliptical galaxies using a semi-analytic model, and compare the results with observations. Although the cold gas in general galaxies has been investigated (e.g. Somerville, Primack 1999), this is the first time to constrain the parameters regarding a star formation process by focusing on cold gas in elliptical galaxies. In the following, we classify elliptical galaxies into cD galaxies (cDs), cluster elliptical galaxies (clEs), and field elliptical galaxies (fiEs).

cD galaxies are the ones which dominate centers of galaxy clusters. So far cold gas in cD galaxies has been investigated from the viewpoint of cooling flows. In the absence of heating, the intrachannel gas around cD galaxies is inferred to be cooling at a rate of \( M_{\text{CP}} \sim 100 M_\odot \text{yr}^{-1} \) (Fabian 1994). Thus, the total mass accumulated around the cD galaxies would result in \( \sim 10^{12} M_\odot \) if the cooling occurred steadily at the rate over the Hubble time. However, such a large amount of cold gas has not been detected in cD galaxies (e.g. Burns et al. 1981; Valentijn, Giovanelli 1982; McNamara et al. 1990; McNamara, Jaffe 1994; O'Dea et al. 1994; Fujita et al. 2000) except for NGC1275 in the Perseus cluster (e.g. Lazareff et al. 1989; Mirabel et al. 1989; Inoue et al. 1996). On the other hand, the semi-analytic models predict that cD galaxies have experienced mergers. Thus, the capture of gas-rich galaxies is another possible supply route of cold gas into cD galaxies. Fujita et al. (2000) show that the cold gas brought into cD galaxies should not be evaporated by the ambient hot intrachannel medium (ICM) gas if heat conduction rate is small as suggested by X-ray observations. Thus, the observations of cold gas in cD galaxies give the upper limit of the gas supplied through galaxy capture.

Contrary to cD galaxies, cold gas has been detected in many clEs and fiEs, although the mass is small (\( \sim 10^8 M_\odot \)). Wiklind et al. (1995) and Knapp and Rupen (1996) show that more than 40% of clEs and fiEs they investigated have CO emission or absorption. Thus, it is interesting to investigate if the difference of the detection rates of cold gas between cDs and non-c-Ds can be explained by the difference of their evolution histories. Previous studies suggest that some of clEs and fiEs are expected to have weak cooling flows of \( M_{\text{CP}} \sim 1 M_\odot \text{yr}^{-1} \) (e.g., Thomas et al. 1986). However, Wiklind et al. (1995) indicates that the the cold gas detected has an external origin.

The plan of our paper is as follows. The following section 2 describes the our model based on hierarchical clustering scenario. In §3, we predict the cold gas in elliptical galaxies and compare it with observations. We present our conclusions in §4.

2. Models

We use the semi-analytic model of Nagashima, Gouda 1999 (hereafter NG). The model includes some physical processes connected with galaxy formation, such as merging histories of dark halos, gas cooling, star formation, supernova feedback, mergers of galaxies, and so on. In order to realize the various merging paths of galaxies, the model is based on the Monte Carlo method. The outline of the procedure is as follows. First, the merging paths of dark halos are realized by the extension of the Press-Schechter formalism (Press, Schechter 1974). These paths are determined by properties of the initial density fluctuations. In this paper, we assume the cold dark matter model. Next, in each step of a merging path, that is, in each dark halo, evolutions of the baryonic component, namely, gas cooling, star formation, and supernova feedback, are calculated. We estimate the mass of cold gas considering cooling processes. The stars are formed from the cold gas with a time-scale proportional to a dynamical time-scale. In the Einstein-de Sitter universe, it is \( \tau_0 (1+z)^{-3/2} \), where \( z \) is the redshift and \( \tau_0 \) is the parameter specified below. In other universes, the redshift dependence (-3/2) changes a little. The cold gas is reheated by supernovae. The amount of the reheated gas is given by \( \beta (V_c) \Delta M_\bullet \), where \( V_c \) is the circular velocity, \( \Delta M_\bullet \) is the mass of the newly formed stars, and \( \beta (V_c) \) is the feedback strength, \( \beta = (V_c/V_{\text{hot}})^{-\alpha_{\text{hot}}} \).

The two parameters \( V_{\text{hot}} \) and \( \alpha_{\text{hot}} \) are specified below. We recognize a system consisting of the stars and cold gas as a galaxy. As Blumenthal et al. (1984) indicated, the baryonic gas can cool and galaxies form in dark halos with mass of \( \lesssim 10^{12} M_\odot \) because the cooling time is smaller than the dynamical time of the halos. Thus, in these halos at least one galaxy exists. Since our calculations show that dark halos with mass of \( \gtrsim 10^{12} M_\odot \) form through mergers of dark halos with mass of \( \lesssim 10^{12} M_\odot \), every dark halo has at least one galaxy.

When two or more dark halos merge together, there is a possibility that galaxies contained in progenitor halos merge together. We consider mergers between central and satellite galaxies for all models. We define the central galaxy in the most massive progenitor halo as the central galaxy in the new halo (see NG; Somerville, Primack 1999); generally, a central galaxy is the most massive galaxy in the halo. The rests are defined as satellite galaxies. We assume that radiatively cooled gas in a dark halo accretes only to the central galaxy. All the satellites lose their kinetic energy owing to dynamical fric-
tion against the dark matter background, fall in towards the central galaxy, and finally merge with the central galaxy in a certain time-scale. The judgment whether the galaxies merge together or not is determined by the dynamical friction time-scale (equation [7-26] in Binney, Tremaine 1987). If the dynamical friction time-scale is shorter than the lifetime of the merged new halo, which is defined as the elapsed time from the time when the halo forms through the merger of two or more dark halos with comparable masses to the time when the halo experiences another merger with halos with comparable masses, the galaxies merge. (‘Comparable’ means that the mass ratio of the largest halo to others is smaller than five.) If not, the galaxies do not merge and the common dark halo has two or more galaxies. This system is recognized as a group or cluster of galaxies. We assume that when galaxies with comparable masses merge, where ‘comparable’ means that their mass ratio is smaller than five, their cold gas turns into stars simultaneously (starburst). Finally, we calculate the color and luminosity of each galaxy from its star formation history by using a population synthesis model. In this paper, we use the population synthesis code given by Kodama and Arimoto (1997). Through the above procedure, the properties of each model galaxy can be calculated. More details on our model are found in NG.

Most of the parameters we use here are fixed at those in NG; cosmological parameters are $\Lambda = 0$ and $\Omega_{0} = 0.06$. We consider the Einstein-de Sitter universe ($\Omega_{0} = 1$, $h = 0.5$, $\sigma_{8} = 0.67$) and an open universe ($\Omega_{0} = 0.3$, $h = 0.7$, $\sigma_{8} = 1$), where $H_{0} = 100$ $h$ km s$^{-1}$ Mpc$^{-1}$. The feedback parameter in NG is fixed at $\alpha_{\text{hot}} = 2$, which means that the mass fraction reheated by supernovae is proportional to the inverse of the depth of the potential well of the halos. In addition to $\Omega_{0}$, we vary two parameters, the circular velocity of a galaxy under which reheating from supernovae becomes effective ($V_{\text{hot}}$) and the time-scale of star formation ($\tau_{\star}^{0}$). We ignore the evaporation of interstellar medium (ISM) by hot ICM because observations show that the heat conduction rate of ICM is small enough (Fujita et al. 2000). We also ignore ram-pressure stripping of ISM by ICM for simplicity. However, it is to be noted that the feedback parameter $V_{\text{hot}}$ can implicitly include the effects of evaporate and stripping for galaxies in clusters even if they are effective. If they are effective, star formation in galaxies is prevented, which is the same as the case of strong feedback.

We list the parameters in table 1. Models A and A’ are fiducial models and the predictions of the models are consistent with observations such as a luminosity function of galaxies. Models B and B’ are the extreme cases where cold gas in galaxies easily accumulates. That is, the star formation time-scale is very long and the cold gas is not much consumed. Models C and C’ are the opposites of models B and B’; the reheating is effective and cold gas hardly accumulates except for extremely massive galaxies. Models D and D’ are the same as models A and A’, respectively, except for including the effect of star formation when satellite galaxies in a dark halo collide and merge with each other; in other models we do not consider the collisions between satellites. We emphasize that the collisions between satellites are random events, which are distinct from collisions between central galaxies and satellite galaxies induced by dynamical friction. We adopt the collision and merger model of Somerville and Primack (1999; see also NG) that is based on the collision time-scale derived by Makino and Hut (1997) using numerical simulations. Following the model of Somerville and Primack (1999), we do not allow random collisions between central galaxies and satellite galaxies. As is the case of the collision between central galaxies and satellite galaxies, a starburst occurs when satellites with comparable masses merge together.

We define an elliptical galaxy as the one whose B-band bulge to total luminosity ratio is larger than 0.6. Among the elliptical galaxies, cDs and cIEs reside in dark halos with circular velocities of $V_{c} = 1000$ and 600 km s$^{-1}$; the halos with $V_{c} = 1000$ and 600 km s$^{-1}$ correspond to a cluster of galaxies and a group of galaxies, respectively. cDs are the most massive galaxies in the dark halos and cIEs are the rests. The results in the following show that these ‘cDs’ are at least a few times as massive as other galaxies in the halos. In most cases, cDs are central galaxies. Field ellipticals (fIEs) are the elliptical galaxies that reside in the dark halos of $V_{c} = 220$ km s$^{-1}$.

### Table 1. Model parameters.

| Model | $V_{\text{hot}}$ (km s$^{-1}$) | $\tau_{\star}^{0}$ (Gyr) | $\Omega_{0}$ | collision |
|-------|-----------------|-----------------|-----------|-----------|
| A     | 140             | 5               | 1         | no        |
| B     | 140             | 20              | 1         | no        |
| C     | 280             | 5               | 1         | no        |
| D     | 140             | 5               | 1         | yes       |
| A’    | 140             | 5               | 0.3       | no        |
| B’    | 140             | 20              | 0.3       | no        |
| C’    | 280             | 5               | 0.3       | no        |
| D’    | 140             | 5               | 0.3       | yes       |

### 3. Results and Discussion

The results of Monte Carlo realizations of merging history are shown in table 2. For each kind of galaxies at $z = 0$, we present the predicted detection rates of elliptical galaxies with cold gas more abundant than the typical observational limit $M_{\text{cold}}$. We take $M_{\text{cold}} = 10^9 M_{\odot}$ for cDs and $M_{\text{cold}} = 10^8 M_{\odot}$ for cIEs and fIEs, because the mean redshift of cDs for which the CO observations have been made is larger than that of cIEs and fIEs. Ta-
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The Detection Rate of Molecular Gas

Table 2. Molecular gas detection rate.

| Model | cD \( (V_c = 1000) \) | clE \( (V_c = 1000) \) | cD \( (V_c = 600) \) | clE \( (V_c = 600) \) | fiE |
|-------|------------------|------------------|------------------|------------------|-----|
| A     | 0.02(1/47)       | 0.65(1098/1684)  | 0.18(33/181)     | 0.69(737/1067)   | 0.66(754/1146) |
| B     | 0.06(3/47)       | 0.72(893/1238)   | 0.31(57/185)     | 0.77(622/812)    | 0.85(1457/1714) |
| C     | 0.00(0/47)       | 0.42(442/1062)   | 0.14(24/173)     | 0.46(292/641)    | 0.59(343/581)   |
| D     | 0.02(1/45)       | 0.09(526/6132)   | 0.11(19/180)     | 0.09(455/4964)   | 0.32(851/2642)  |
| A'    | 0.10(5/48)       | 0.28(1288/4614)  | 0.22(42/193)     | 0.24(848/3498)   | 0.53(850/1599)  |
| B'    | 0.10(5/48)       | 0.78(3319/4247)  | 0.36(70/197)     | 0.82(2692/3293)  | 0.90(1977/2191) |
| C'    | 0.08(4/48)       | 0.26(527/2062)   | 0.21(41/192)     | 0.17(239/1047)   | 0.58(539/934)   |
| D'    | 0.02(1/50)       | 0.05(508/10756)  | 0.11(21/191)     | 0.05(425/8878)   | 0.13(1123/8385) |

Numbers of galaxies are presented in parentheses; the numerators are the numbers of galaxies with observable cold gas and the denominators are the total numbers of galaxies. The units of \( V_c \) are km s\(^{-1}\).

Table 2 shows that the differences between the predictions of the models of \( \Omega_0 = 1 \) and \( \Omega_0 = 0.3 \) are small for cDs and fiEs. In an open universe, the formation epoch of galaxies and clusters is earlier in comparison with the Einstein-de Sitter universe. Thus, more ISM is consumed by star formation. On the contrary, since the time-scale of dynamical friction in a given halo does not depend on cosmological parameters, the cDs in an open universe have more chances to capture gas-rich satellite galaxies and accumulate more cold gas. This is also the case for most fiEs because \( \geq 70\% \) of fiEs are the central galaxies in the halos \( (V_c = 220 \text{ km s}^{-1}) \). Since these two effects are canceled, the results for \( \Omega_0 = 1 \) and \( \Omega_0 = 0.3 \) are not so much different. On the other hand, clEs do not capture other gas-rich galaxies except for models D and D'. Thus, the gas detection rates in an open universe are lower than those in the Einstein-de Sitter universe. The low gas detection rates in models D and D' are due to star formation and gas consumption when satellites collide each other. Moreover, these reduce the gas supply to central galaxies through the capture of the satellites.

So far 26 cDs have been searched in CO (those in table 4 in O’Dea et al. 1994, NGC 1275 and NGC 1129) and it resulted in one detection. On the contrary, CO emission has been observed in many elliptical galaxies other than cDs. For example, Wiklind et al. (1995) detected CO in 16 elliptical galaxies out of 29. Knapp and Rupen (1996) searched for CO emission from 42 early-type galaxies with 100 \( \mu \)m flux densities greater than 1 Jy. They detected emission from 11 of the galaxies. On the contrary, although Braine et al. (1997) observed 6 X-ray bright elliptical galaxies, none of the galaxies were detected in CO.

However, the samples of elliptical galaxies are not complete. Since the data sets of Wiklind et al. (1995) and Knapp and Rupen (1996) are biased toward ellipticals known to contain a FIR component, the galaxies do not represent all elliptical galaxies. Thus, the quantitative comparison between the observations and our calculations may be difficult at present, although the samples would increase in the future. Bearing that in mind, we will discuss the detection rate of CO.

Table 2 shows that the detection rates of CO for clEs and fiEs predicted by models B and B’ are high. Wiklind et al. (1995) detected CO emission from 67\% of fiEs and from 41\% of clEs. Knapp and Rupen (1996) found that the detection rate of CO for non-cD ellipticals is 45\% for their sample and those in literatures, although they do not discriminate between cEs and fiEs. Quantitatively, the high detection rates in models B and B’ appear to be inconsistent with the observations. Although we do not present the result, the model with \( V_c < 140 \text{ km s}^{-1} \) and \( \tau_s^c = 5 \text{ Gyr} \), that is, reheating from supernova is ineffective, gives a similar result. These mean that the consumption of molecular gas by star formation and/or reheating cannot be ignored in galaxy formation theories. Since ram-pressure stripping and evaporation by hot ICM do not significantly affect fiEs, they will not solve the inconsistency for fiEs. For clEs, however, ram-pressure stripping and evaporation may be effective and may make the detection rates of cold gas smaller.

Low detection rates of CO predicted by models D and D’ are also inconsistent with the observations of non-cD galaxies. This indicates that our collision-induced starburst model overestimates the gas consumption when satellites collide each other. This may mean that the collisions and mergers between satellites seldom occur in a cluster halo or that they do not stimulate the star formation activity, in comparison with the prediction of the simple model.

In the following, we discuss the remaining models A, A’, C, and C’. Considering the fact that most of the cD galaxies searched for CO are in clusters with \( V_c > 700 \text{ km s}^{-1} \), the detection rates predicted by these
models (especially, models A and C) in table 2 seem to be consistent with the observations (1/26). There are two reasons for the lack of cold gas in cDs. One is the assumption that the transformation of hot gas into cold gas is suppressed after the circular velocities of the halos grow up to $V_c = 500 \text{ km s}^{-1}$. Since the transformation stopped more recently for halos with $V_c = 600 \text{ km s}^{-1}$ than for those with $V_c = 1000 \text{ km s}^{-1}$, the detection rates of cold gas in cDs in the formers are higher. The assumption is often adopted in the field of the semi-analytic approach to suppress the formation of monster galaxies. The calculations without the assumption result in large number density of the monsters, which is inconsistent with the observations (e.g. Kauffmann et al. 1993). Although the assumption is ad hoc, it may be justified as follows. In a halo with $V_c \geq 500 \text{ km s}^{-1}$, the cooling time of gas is larger than the dynamical time of the halo but still smaller than the lifetime of the halo, that is, a cooling flow is expected to occur (Fabian 1994). As many authors indicate, cooled gas expected by the cooling flow model becomes neither normal stars nor cold gas (e.g. Fabian 1994; McNamara, Jaffe 1994; Fujita et al. 2000). Thus, it may become ‘baryonic dark matter’ such as dust (Fabian et al. 1994; Voit, Donahue 1995; Edge et al. 1999; Allen 2000) or low mass stars (Sarazin, O’Connell 1983; Mathews, Brighenti 1999). Recently, Wu et al. (1999) consider cooling flows in a semi-analytic model and indicate that cooled gas should turn to be ‘baryonic dark matter’ in halos with $\gtrsim 10^{12} M_{\odot}$; it may not be detected as cold gas or normal stars. The other reason for the lack of cold gas in cDs is that the amount of the cold gas brought through galaxy captures is small. Although the cDs capture four galaxies in average for $z < 1$, the cold gas brought by the galaxies is consumed by star formation activity and is not left.

Table 2 also shows that the fraction of galaxies with cold gas is small for clEs in comparison with that for fiEs. This is because clEs are satellites which do not capture other galaxies (except for models D and D’) while most fiEs are central galaxies which capture gas-rich galaxies. Moreover, cooled gas in a dark halo accretes only to the central galaxy. The tendency is consistent with the observation of Wiklind et al. (1995) (41% for cEs and 67% for fiEs). Quantitatively, models A and C seem to be preferable to models A’ and C’. If ram-pressure stripping and evaporation of cold gas are effective for cEs, the remaining cold gas should decrease and inconsistency between the observations and the predictions of models A’ and C’ should be more prominent. However, we think that we need more observations and more improved models to obtain a definite conclusion about models A, A’, C, and C’.

4. Conclusions

In order to constrain the parameters regarding star formation process in galaxy formation theory, we have investigated the detection rate of cold gas in elliptical galaxies. Using a semi-analytic model of galaxy formation, we have predicted the amount of cold gas in elliptical galaxies and compare it with observations. The models with a large time-scale of star formation predict high detection rates of cold gas. They are inconsistent with the observations of non-cD elliptical galaxies and are quantitatively rejected. This means that the mechanisms of reducing the mass of the ISM, such as the consumption of molecular gas by star formation and/or reheating from supernovae, cannot be ignored in galaxy formation theories. We found that the collisions and mergers between satellite galaxies in a cluster halo reduce cold gas in them. However, observations show that the simple collision model we adopted overestimates the effect, and that the models without the collisions are preferable. This may imply that the satellites collide each other less frequently or that the collisions cause star formation less effectively than the model predicts. For cD galaxies, the predicted detection rate of cold gas is consistent with the observations as long as the transformation of hot gas into cold gas is prevented in halos with $V_c \gtrsim 500 \text{ km s}^{-1}$. Moreover, we have shown that the amount of cold gas brought into cDs through captures of gas-rich galaxies is small. For elliptical galaxies other than cDs, our models predict that the fraction of galaxies with observable cold gas is small for cluster ellipticals in comparison with that for field ellipticals. In this study, we found that our fiducial models and the models with large reheating efficiency are consistent with the observations of cold gas in elliptical galaxies of different types. With larger samples of elliptical galaxies, the parameters in theories of galaxy formation will more strictly be constrained.

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