Are Pressure-Confined Clouds in Galactic Halo Possible for a Model of Lyα Clouds?

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Abstract

Our understanding of the Lyman α forest has considerably changed between before and after the Hubble Space Telescope and Keck Telescope in operation, because the Lyα clouds at low redshifts (z<1.7) observed by HST showed us two unexpected features: Lanzetta et al (1995) found that most luminous galaxies at such redshifts produce Lyα absorptions at the mean impact parameter ∼160h⁻¹kpc and established the association between Lyα clouds and galaxies. Ulmer (1996) pointed out the strong clustering of Lyα clouds in this redshift range. Motivated by these observations together with another observation which reports the detection of metal in the Lyα clouds at high redshift universe, we propose the two-component protogalaxy model as a model.

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for the Lyα cloud based upon the previous work (Miyahata, Ikeuchi 1995). In our model, the Lyα clouds are supposed to be stable cold clouds confined by the pressure of ambient hot gas in galactic halo. We determine the properties of these cold clouds and hot gas on the basis of theoretical and observational constraints. Especially, we take into account the stability of a cold cloud in the galactic halo in addition to the general stability conditions in a two-component medium which was discussed in Ikeuchi, Ostriker (1986), and compare the derived quantities of Lyα clouds both cases in galactic halo and in intergalactic medium between high and low redshifts. We conclude that the condition that a cloud is stable against both evaporation and tidal destruction by a hot galactic halo is very restrictive. As a result, in the most noteworthy case, at $z \sim 0.5$, it is concluded that a pressure-confined, stable spherical Lyα cloud with typical neutral hydrogen column density $N_{HI} = 10^{14} \text{cm}^{-2}$ cannot survive in the galactic halo, although much higher column density clouds of $N_{HI} = 10^{17} \text{cm}^{-2}$ can do there. We discuss how our result constrains an alternative model for Lyα clouds which associate with galaxy observed by Lanzetta et al.

**Key words**: Galaxies: evolution—halo—ISM—Quasars: absorption lines

1. Introduction

The *Hubble Space Telescope* and Keck Telescope have revealed the history of the universe
from high redshifts to the present epoch, and our knowledge of galaxy formation and evolution has made a remarkable progress (Fukugita, et.al.1996). In this context, our understanding of the Ly$\alpha$ cloud has considerably changed before and after the HST and Keck Telescope in operation (Ikeuchi 1995; Shull 1997). Before these telescopes, we thought that the Ly$\alpha$ clouds are the intergalactic primordial gas clouds which are confined by the thermal pressure of intergalactic medium (Ostriker, Ikeuchi 1983; Ikeuchi, Ostriker 1986) and/or by the gravity of the cold dark matter (Ikeuchi 1986, Rees 1986). Therefore, it was supposed that they distribute randomly and have no or little correlations with galaxies. But a lot of new observational results have brought to us, which are not explained by the above standard picture of the Ly$\alpha$ clouds. Some of them suggest that remarkable fraction of the Ly$\alpha$ clouds have their origin in strong connection with galaxy.

First, for nearby ($z < 1.7$) Ly$\alpha$ clouds, it enables us for the first time to study whether they associate with galaxies or not by using HST. (Lanzetta et.al. 1995; Bowen et.al. 1996; Brun et.al. 1996). For example, Lanzetta et.al. reported that (1) at redshift $< 1$ most galaxies are surrounded by extended gaseous envelopes of its extent $\sim 160h^{-1}$kpc with the covering factor roughly unity, and (2) many or most Ly$\alpha$ absorption systems arise in extended gaseous envelopes of galaxies. Most recent data strengthen this previous result (Chen et.al. 1997; Lanzetta et.al. 1997a, 1997b),
although the conclusion is now controversial (Bowen et.al. 1996; Brun et.al. 1996; Morris 1996). Second, the strong clustering of Lyα clouds was discovered in this redshift (Ulmer 1996). Third, recent observations by Keck telescope indicate that CIV lines are generally associated with the Lyα clouds down to moderately low column densities ($N_{HI} \sim 10^{14.5} cm^{-2}$) even in high redshift (Tytler 1995; Cowie, Songaila 1995).

Theoretically, there are few models in which clouds in the galactic halo are the possible origin of Lyα absorption since Bahcall and Spitzer (1969), who proposed that extended gaseous galactic halo causes absorption lines in QSO spectra. On the other hand, Weymann (1995) emphasised that at least two populations of Lyα clouds are needed to explain many important characteristics about them reported until now. One is relatively unclustered, rapidly evolving population which dominates at high redshifts, and the other is more stable, possibly associated with galaxies which dominate at low redshifts.

As a probable model for the latter population of Lyα clouds, we proposed two-component protogalaxy model (Miyahata, Ikeuchi 1995). This model was originally proposed in the context of the globular cluster formation (Fall, Rees 1985, Murray, Lin 1993, and references therein), and have been investigated in many context of galaxy formation and evolution (Ferrara, Field 1994; Ikeuchi, Norman 1991; Norman 1994; Spaans, Norman 1997; Field et.al. 1997 and references
therein). When a protogalaxy collapses and virializes to its radius $\sim 100\text{kpc}$ (Rees, Ostriker 1977), small density fluctuations grow up in its halo due to the thermal instability (Field 1965). As a result, cold ($\sim 10^4\text{K}$) and small ($\sim 10^6 M_\odot$) clouds are formed in protogalactic halo (Fall, Rees 1985). Here, we analyze these cold clouds as the candidate of Ly$\alpha$ clouds. It is noted that in our model, the theoretically predicted scale of protogalactic halo is around $\sim 100\text{kpc}$ which is just the same order of impact parameter indicated by Lanzetta et al. (1995, 1997). By now, direct confirmation of the existence of hot halo extended to $>100\text{kpc}$ has not been reported although the hot extended X-ray emitting gas is generally observed in the elliptical galaxies out to $\sim 50\text{kpc}$ (Sarazin 1996), the highly ionized gas is observed far away from the disk of spiral galaxies in our Galaxy (Spitzer 1990), and the probability of metal-line absorption of QSO suggests such an extended gaseous galactic halo (Spitzer, Ostriker 1997).

From the viewpoint of above-mentioned two-population model for the Ly$\alpha$ clouds, Chiba, Nath (1997) discussed the origin of metallicity in high redshift Ly$\alpha$ clouds. They showed that the fraction of Ly$\alpha$ lines with associated metal lines can be understood in terms of the Ly$\alpha$ absorbers associated with galactic halo, assuming that pressure confined Ly$\alpha$-absorbing clouds are embedded in galactic halo. Recently, several large numerical simulations of the large scale structure formation in the universe were done to examine the origin and evolution of the Ly$\alpha$ clouds (Miralda-Escude,
et.al. 1996; Cen, Simcoe 1997; Zhang et.al. 1997; Weinberg et.al. 1997 and references therein).

The purpose of these simulations seems to explain the characteristics of the former population of the Lyα cloud which Weymann noted (1995), but even by such high resolution simulations it is impossible to resolve the galactic scale. So it would be emphasized here that it is important to analyze whether or not the Lyα clouds can exist near or inside the galactic halo by using a simple analytical model.

In this paper, we determine the physical quantities of cold clouds which are confined by the pressure of ambient hot galactic halo gas on the basis of theoretical and observational constraints in detail. In section 2, we discuss the stability conditions for both of a cold cloud and general hot ambient medium and compare the results with the observations between z=2.5 and z=0.5. These cold clouds can be applied to the intergalactic Lyα cloud. In section 3, in addition to the above discussion, we examine the stability of a small cloud in galactic halo and compare them with those of an intergalactic cloud. From the stability analyses of the calculated cloud model, we conclude that a pressure-confined, stable spherical Lyα cloud with typical neutral hydrogen column density $N_{HI} = 10^{14} cm^{-2}$ cannot survive in galactic halo for both cases of z=2.5 and z=0.5, although higher column density systems such as $N_{HI} = 10^{17} cm^{-2}$ can do there. In Section 4, we discuss several points which might affect our conclusion, and speculate an alternative model for such Lyα clouds.
2. Pressure Confined Clouds in Two-Component Intergalactic Medium

2.1. Basic Equations and Assumptions

Following the discussion by Ostriker, Ikeuchi(1983) and Ikeuchi, Ostriker(1986), we assume that the cold cloud is spherical and homogeneous for simplicity. Suppose that the cold cloud is embedded in a hot ambient gas. In our simple treatment, no dark matter is considered.

First, we assume pressure equilibrium between the cold cloud and the hot ambient medium as,

\[ \tilde{P} = n_c T_c = n_h T_h. \]  

The notations used above and hereafter are summerized in Table 1. Irradiated by the UV background radiation, the cold cloud is thought to be ionized, in thermal and ionization equilibria. From the latter assumption, the following relation holds;

\[ \Gamma_H n_{HI} = \alpha_H n_{HII} n_e, \]  

where we adopt the recombination coefficient \( \alpha_H = 4.36 \times 10^{-16} T^{-3/4} \) at \( T > 5000K \) and \( \Gamma_H \) is the ionization rate of neutral hydrogen and is written as (Black 1981)

\[ \Gamma_H = J(\nu_T) G_H. \]
Here, $\Gamma_H$ is the ionization rate of neutral hydrogen and $G_H = \int_{\nu_T}^{\nu_{max}} (\nu/\nu_T)^{-1} \sigma(\nu) d\nu$ where $\nu_T$ and $\sigma(\nu)$ are the frequency at Lyman Limit of hydrogen and the cross section for photoionization, respectively.

Coupling eq.(2) with an assumption of thermal equilibrium for a cloud, Ikeuchi, Ostriker (1986) showed that the equilibrium temperature $T_c$ is always $3\times10^4 K$ whenever the pressure-confined cloud is embedded in an expanding IGM and the cloud is almost fully ionized. So,

$$n_{\text{HII}} \sim n_e \sim n_c.$$  \hspace{1cm} (4)

The order of $T_c$ is determined by the fact that the cooling function has a sharp cut-off at this temperature because of recombination to hydrogen atoms (Binney,Tremaine 1987). Recent observations indicate that CIV lines are generally associated with the Ly$\alpha$ clouds in high redshifts (Tytler 1995, Cowie et.al. 1995). These are very important in relation to their origin, but such a low metalicity as $Z \sim 1/100 Z_\odot$ does not affect our results at all.

Under the above assumptions, we can derive the radius and mass of the cold cloud as follows:

$$R_c = 1.85 \times 10^3 J_{-21} T_4^{11/4} N_{14} \tilde{P}^{-2} \text{ pc},$$  \hspace{1cm} (5)

$$M_c = 6.63 \times 10^4 J_{-21} T_4^{29/4} N_{14}^3 \tilde{P}^{-5} \text{ } M_\odot,$$  \hspace{1cm} (6)

where $J_{-21} = J/(10^{-21} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1})$, $T_4 = T_c/10^4 \text{ K}$ and $N_{14} = N_{\text{HI}}/10^{14} \text{ cm}^{-2}$, $N_{\text{HI}}$
being the HI column density. It is defined as

\[ N_{HI} = n_{HI} R_c, \]  

where we neglect the geometrical factor. Using eq. (3), we can rewrite eq. (7) as follows,

\[ N_{HI} = 4.1 \times 10^{13} \left( \frac{R_c}{10 \text{ kpc}} \right) \tilde{P}^2 T_4^{-11/4} J_{-21}^{-1} \text{ cm}^{-2}, \]  

\[ = 1.45 \times 10^{12} \left( \frac{M_c}{10^8 M_\odot} \right)^{1/3} \tilde{P}^{5/3} T_4^{-29/12} J_{-21}^{-1} \text{ cm}^{-2}. \]

Note that the neutral hydrogen column density which is observed directly is sensitive to \( \tilde{P}(= n_c T_c) \) but not sensitive to \( M_c \).

2.2. Stability Conditions in Two-component System

In this subsection we examine the stability conditions in a two-phase medium, and give a constraint to the physical quantities of the cold cloud which we derive in the previous subsection. (i) The ambient medium must keep hot, otherwise the two-component system does not maintain any longer. Thus, we get the constraint,

\[ \tau_{cool} > \tau_H, \]  

where \( \tau_{cool} \) is the cooling time for hot ambient gas and \( \tau_H \) is the age of universe as

\[ \tau_{cool} = 1.5 \frac{kT_h}{n_h \Lambda(T_h)}, \quad \tau_H = \frac{4.1 \times 10^{17}}{(1 + z)^{1.5}} \text{ sec}, \]
where Λ is the cooling function of primordial gas in an absence of external UV radiation (Binney, Tremaine 1987). In fact, the effective cooling rate changes in the presence of UV background radiation (Thoul, Weinberg 1996). But as we show later, \( T_h \) is typically higher than \( \sim 10^5 \)K and our treatment is valid in this temperature range. Here, we assume \( \Omega = 1 \) and \( H_0 = 50 \text{km}s^{-1}Mpc^{-1} \) for simplicity. For these parameters, eq.(10) is rewritten as follows;

\[
T_h > 10^{33.3} n_h \Lambda(T_h)(1 + z)^{-1.5} \ K. \tag{12}
\]

This condition becomes more severe in the situation with larger \( n_h \).

(ii) The clouds must be gravitationally stable, otherwise we can no longer observe such clouds as Ly \( \alpha \) absorbers due to rapid collapse. This implies

\[
M_c < M_{\text{Jeans,p}}, \tag{13}
\]

where the Jeans mass of a pressure confined cloud \( M_{\text{Jeans,p}} \) is given by (Spitzer 1978)

\[
M_{\text{Jeans,p}} = 1.18 \left( \frac{kT_c/m_p}{G} \right)^{1.5} \left( \frac{P}{k} \right)^{-0.5}. \tag{14}
\]

Using eq.(10), it is shown that this condition gives a lower bound on \( \tilde{P} \), i.e.,

\[
\tilde{P} > 10^{-0.996} (N_{14} J_{-21})^{2/3} T_4^{7/6} \ cm^{-3} K. \tag{15}
\]

(iii) The cold clouds must not be evaporated by the heat conduction from ambient hot medium.
This implies

\[ \tau_{\text{evap}} > \tau_H, \quad (16) \]

where \( \tau_{\text{evap}} \) is the evaporation timescale. When we estimate this timescale, we must examine the saturation parameter \( \delta = 1.2 \times 10^4 T_h^2 n_h^{-1} R_{\text{c}}^{-1} \) (Balbus, McKee 1982) which is essentially the ratio of the mean free path of an electron to the scale of cooled region. For \( \delta \leq 1 \), in so called classical case, the evaporation time is expressed by

\[ \tau_{\text{evap}} = 1.1 \times 10^{-9} (R_c n_c)^2 T_c T_h^{-3.5} n_h^{-1} \text{ sec.} \quad (17) \]

Using eqs. \( (11) \) and \( (13) \), this condition \( (16) \) is rewritten as follows,

\[ T_h < 10^{2.35} n_h^{-0.545} (N_{14} J_{-21})^{0.364} T_4^{0.818} (1 + z)^{0.237} \text{ K.} \quad (18) \]

As we show in the next section, this simple estimate can be applied to a considerable range of physical quantities of two-component protogalaxy.

For \( 1 \leq \delta \leq 10^2 \), when the evaporation is saturated, \( \tau_{\text{evap}} \) is expressed as

\[ \tau_{\text{evap}} = 3.2 \times 10^{-6} N_c^{7/6} T_c^{1/6} (n_h T_h)^{-1} \text{ sec,} \quad (19) \]

and in this case, an upper bound on \( \tilde{P} \) is given by,

\[ \tilde{P} < 10^{-0.794} (N_{14} J_{-21})^{0.538} T_4^{1.02} (1 + z)^{0.692} \text{ cm}^{-3} \text{ K.} \quad (20) \]
For $\delta \geq 10^2$, the suprathermal evaporation must be examined and in this case $\tau_{\text{evp}}$ is as follows;

$$\tau_{\text{evp}} = 1.1 \times 10^{-5} R_c^{4/3} n_h^{1/3} T_h^{-1/6} T_c^{-1} \text{ sec.} \quad (21)$$

In this case, eq.(18) is rewritten as follows;

$$T_h < 10^{0.549} n_h^{-0.824} (N_{14} J_{-21})^{0.471} T_4^{0.941} (1 + z)^{0.529} \text{ K.} \quad (22)$$

In any case, if the density or temperature of the ambient hot gas is high enough, or the cold cloud is small, the cloud will be evaporated quickly.

Using these three stability conditions, we can give a constraint to the cloud quantities such as $R_c$(eq.(5)), $M_c$(eq.(6)) and $N_{HI}$(eq.(7)) through constraints given to $(n_h, T_h)$ or $(n_c, T_c)$.

2.3. Results

In Figure 1a, we show three stability conditions plotted in the density and temperature of hot phase gas for $z=2.5$ and in this redshift $J_{-21}$ is estimated nearly unity (Savaglio, Webb 1995). For other parameters, we summerize them in Table 3 (Model 1). This figure reproduces the essence of stability conditions for the high redshift, intergalactic pressure-confined Ly$\alpha$ clouds (Ostriker, Ikeuchi 1983). As is seen, the right below, left below and right upper region in this figure are forbidden due to the cooling condition, gravitationally unstable condition, and evaporation condition, respectively. For comparison, a constant cloud radius $R_c$(see eq.(5)) (short-dashed line) and a constant cloud mass $M_c$(see eq.(6))(dot-dashed line) are shown. As a result, the
allowed region for the pressure-confined clouds to survive in two-phase media is in the density region between $10^{-7}$ and $10^{-5} \text{cm}^{-3}$ and temperature region between $10^{5.5}$ and $10^{6.7} \text{K}$. For the median value of $n_h \sim 10^{-6} \text{cm}^{-3}$, the typical cloud radius is $\sim 50 \text{kpc}$ and mass $\sim 10^7 \text{M}_\odot$, which is comparable to the lower bound of the observed size of high redshift Ly$\alpha$ absorbers (Bechtold, et al. 1994; Dinshaw et al. 1994). These results and those in hereafter are summarized in Table 4.

In Figure 1b, we show the allowed range of the cloud mass with respect to the ambient pressure. The upper and lower mass bounds of the cloud are constrained by the stability condition against the Jeans instability and evaporation, respectively. The allowed region is limited to the trapezoid region left below for three cases of the density of the hot halo (solid and short-dashed line). For comparison, a constant cloud radius $R_c$ (short-dashed line) and a constant neutral hydrogen column density of the cloud $N_{HI}$ (dotted line) are also shown. From this figure, we can see that the wide range of the observed column density of Ly$\alpha$ cloud is reproduced in our model.

Figure 2a is the same as in Figure 1a, but for $z=0.5$ (Model 2). Since the UV background radiation dramatically drops off from high redshift to the present (Savaglio, Webb 1994), we assume the parameter as $J_{-21}=0.01$. Figure 2b is equivalent to Figure 1b but for $z=0.5$.

The cooling and evaporation condition are more stringent at $z=0.5$ compared to those at $z=2.5$. On the other hand, because the UV background radiation dramatically decreases from $z \sim 2.5$ to
z=0.5, the cloud radius and mass become smaller for the same value of $\tilde{P}$ and $N_{HI}$. As a result, the allowed region for ambient hot gas exists in the density range from $n_h \sim 10^{-8}$ to $n_h \sim 10^{-6} \text{cm}^{-3}$. The typical cloud radius is $\sim 100\text{kpc}$ and the mass is $\sim 10^8 M_\odot$ for the median value $n_h \sim 10^{-7} \text{cm}^{-3}$.

3. The Ly$\alpha$ Clouds in Hot Galactic Halo

3.1. Stability Conditions for the Clouds in Galactic Halo

In addition to the general stability conditions of cold clouds in two-phase medium, we must examine additional conditions when the Ly$\alpha$ clouds are in a hot galactic halo (Mo 1994; Mo, Miralda-Escude 1996; Miyahata, Ikeuchi 1995). Before we discuss these conditions, we determine $T_c$ for a cloud embedded in galactic halo. Thoul, Weinberg (1996) showed that the equilibrium temperature of the cloud irradiated by the UV background radiation varies according to the change of both cloud density and the shape and amplitude of the spectrum of radiation. Their results for $J_{-21} = 1$, $n_c = 10^{-2} \text{cm}^{-3}$ and $n_c = 10^{-4} \text{cm}^{-3}$ are shown in Table 2. We calculate $T_c$ for $J_{-21} = 0.01$ in the similar manner as them and our results are also shown. We justify later that this range of $n_c$ covers the situation where we are interested in, and show that our final conclusion does not change at all for the different cases of $n_c$, although the cloud properties themselves are sensitive
to $T_c$ (see, eqs (3) and (4)). For this reason, we mainly calculate for the fiducial parameters shown in Table 3. We now take account of six conditions for a stable cloud in galactic halo.

(iv) When we discuss the Ly$\alpha$ cloud in galactic halo, the timescale which characterizes this system would be the dynamical time of galaxy, $\tau_{\text{halo}}$. So in this case, the stability conditions against the cooling (eq.(12)) and evaporation (eq.(18)) are replaced as follows;

$$\tau_{\text{cool}} > \tau_{\text{halo}} \quad \tau_{\text{evap}} > \tau_{\text{halo}}.$$  \hspace{1cm} (23)

Here we take $\tau_{\text{halo}}$ as the crossing time of the halo in our Galaxy that $\tau_{\text{halo}} \sim R_h/v_{\text{rot}} \sim 10^9 \text{yr}$, with $R_h \sim 100 \text{kpc}$ and $v_{\text{rot}} \sim 220 \text{km sec}^{-1}$.

(v) The cloud must be gravitationally stable, so eq.(13) holds also in this case.

(vi) The clouds should not be tidally disrupted, so that

$$R_c < R_{c, \text{tidal}} \sim R_h \left( \frac{M_c}{M_{\text{gal}}} \right)^{1/3} \sim 1 \left( \frac{R_h}{100 \text{kpc}} \right)^{1/3} \left( \frac{10^{12} M_\odot}{M_{\text{gal}}} \right)^{1/3} \left( \frac{M_c}{10^6 M_\odot} \right)^{1/3} \text{kpc},$$ \hspace{1cm} (24)

where $R_h$ and $M_{\text{gal}}$ are the typical scale of galactic halo and the mass of a galaxy, respectively. Together with eqs.(3) and eqs.(4), this criterion is rewritten as follows;

$$\tilde{P} > 95.6 \times T_4 \left( \frac{100 \text{kpc}}{R_h} \right)^3 \left( \frac{M_{\text{gal}}}{10^{12} M_\odot} \right) \text{cm}^{-3} \text{K}.$$ \hspace{1cm} (25)

We take $R_h \sim 160 h^{-1} \text{kpc} \sim 320 \text{kpc}$ which is the value reported by Lanzetta et.al.(1995), and $M_{\text{gal}} \sim 4 \times 10^{11} M_\odot$ from the minimal halo model of Fish, Tremaine (1991) for the total mass, respectively. Using these values, eq.(25) reduces to a simple criterion, $\log T_h > -\log n_h + 0.54$. It is
possible that in the extended halo, $M_{gal}$ is larger than the value we adopted here (Zaritsky, White 1994), but we adopt the above value as conservative one.

(vii) The clouds must be stable against the hydrodynamic instability. We assume that the hydrodynamical instability occurs when the momentum from a cold cloud to the hot gas is transferred (Miyahata, Ikeuchi 1995). So that, we get

\[ 2n_c R_c > n_h R_h. \]  

(26)

Using eq.(1), we rewrite this as

\[ R_c > R_{c, crit} = 5 \times 10^2 \left( \frac{T_c}{10^4 K} \right) \left( \frac{10^6 K}{T_h} \right) \left( \frac{R_h}{100 kpc} \right) \text{ pc}. \]  

(27)

Our criterion might be a little different from the one for the Kelvin-Helmholtz instability, which is one of the most important destruction processes when two media having different densities are in relative motion (Chandrasekhar 1961; Murray et.al. 1993). But the criterion we examined here would be more generous and realistic.

(viii) The temperature of hot halo of which thermal pressure confines a Ly$\alpha$ cloud must be roughly equal to the virial temperature of a galaxy. Since virial equilibrium for the galaxy says

\[ 0.6 \frac{GM_{gal}}{R_h} = 3 \frac{kT_h}{m_p}. \]  

(28)
the virial temperature of halo is written as,

\[ T_h = 1.70 \times 10^7 \left( \frac{M_{\text{gal}}}{10^{12} M_\odot} \right) \left( \frac{100 \text{kpc}}{R_h} \right) \text{K.} \]  

(29)

By substituting the above value, this relation reduces to \( T_h \sim 2 \times 10^6 \text{K.} \) In addition to this condition, the luminosity of hot extended halo inferred from X-ray observation (Sarazin 1996) might also constrain our model when we consider more realistic density profile of galactic halo. We discuss this point later.

In this paper, we assume that the Ly\( \alpha \) cloud is irradiated only by the diffuse UV background radiation. But in more realistic situations when such a small cloud is in galactic halo, additional sources of UV radiation such as young stars or AGN (Kang, et.al. 1990) may be taken account of. Recently, Norman, Spaans(1997) and Spaans, Norman (1997) studied a multi-component protogalaxy model in the presence of UV radiation both from background source and young stars in galaxy, as a model for protogalactic disk and dwarf galaxy, respectively. Here we neglect such sources because we do not have any definite data about the amount of the radiation from such sources, although it is noted that from eq.(\ref{eq:5}) we expect that the evaporation condition is effectively relaxed under additional UV sources.

3.2. Results

In Figure 3a (Model 3) and Figure 4 (Model 4), we show the stability condition for a cloud
in galactic halo except for those against hydrodynamic instability, which is less important in our case. These figures show that in both cases of $z=2.5$ and $z=0.5$, the condition that a cold cloud is stable against evaporation as well as tidal disruption is very narrowly limited.

As a result, there remains a little allowed region for $n_h = 10^{-4.8} \text{cm}^{-3}$ and $T_h = 10^{5.5} \text{K}$ at $z=2.5$. But such a low temperature gas is hardly expected in typical galactic halo. So, it might be concluded that the pressure-confined Ly$\alpha$ cloud can not survive in galactic halo at $z=2.5$. In the most noteworthy case, $z=0.5$, there is no allowed region for a cloud, too. So we conclude that pressure-confined, spherical Ly$\alpha$ clouds with typical column density $N_{HI} = 10^{14} \text{cm}^{-2}$ cannot survive in galactic halo, in general. In Figure 3b, we show the results for a cloud which has two orders of magnitude lower density and a little higher temperature (Table 2). Comparing Figure 3a and Figure 3b, we can recognize that variation of cloud temperature and density does not change our conclusion concerning the stability of cloud.

The same analyses have been done for the same redshift but with different column density of a cloud, and results are shown in Figure 5a and Figure 5b. For a smaller cloud of $N_{HI} = 10^{12} \text{cm}^{-2}$, the evaporation condition becomes severer and a cloud quickly disappears, as is expected. In contrast to this, for a cloud of higher column density $N_{HI} = 10^{17} \text{cm}^{-2}$, which is hard against evaporation, there remains allowed region where typical quantites of a cloud are $R_c \sim 10 \text{kpc}$ and
$M_c \sim 10^{6.5} M_\odot$ and those of galactic halo are $n_h \sim 10^{-6} \text{cm}^{-3}$ and $T_h = 10^{6.3} \text{K}$. Such a cloud is not destroyed by hydrodynamical instability and $T_h$ is comparable to the virial temperature of galactic halo. For a case of $N_{HI} = 10^{16} \text{cm}^{-2}$, the cloud survival is marginal and we suppose that this column density is the critical one for the cloud to survive in galactic halo. Although, pressure confined clouds in galactic halo fail to reproduce the observed quantities of Ly$\alpha$ clouds, it is noted that this model may be still valid for a model of metallic absorption line systems which associate with galaxy (Steidel 1995).

4. Summary and Discussion

Motivated by the recent observations (Lanzetta et al. 1995, 1997a) which report that most of the nearby ($z < 1$) Ly$\alpha$ clouds are associated with extended gaseous envelopes of galaxies with impact parameter $\sim 160 h^{-1} \text{kpc}$, we examined the conditions for stable Ly$\alpha$ clouds within the context of two-component gaseous medium. In the case for protogalaxy model, it is expected that the association of the Ly$\alpha$ clouds with galaxies is naturally expected. We determined the physical quantities of both the cold cloud and the hot ambient gas on the basis of various stability conditions. For simplicity, we assumed that the cold cloud confined by the pressure of the hot ambient medium is spherical, homogeneous, and in thermal and ionization equilibria irradiated by the diffuse UV background radiation.
We calculated physical quantities of the pressure-confined Ly\(\alpha\) cloud in high redshift\((z=2.5)\) and low redshift\((z=0.5)\). One is in intergalactic medium and the other is in galactic halo. In the former case, the upper mass bound of the cloud is given by the stability condition against Jeans instability, while the lower mass bound of it is constrained by the evaporation condition, respectively. In the latter case, in addition to the above-mentioned constraints the stability conditions for the cloud with respect to the tidal disruption gives a severe upper bound of the cloud radius, while the hydrodynamical stability condition gives the lower bound of it.

As for a pressure-confined spherical cloud in intergalactic medium, our model is consistent to some of the observed properties of Ly\(\alpha\) clouds. So such a model is still valid for Ly\(\alpha\) clouds detected in intergalactic medium (Shull et.al. 1995) together with an alternative model for a Ly\(\alpha\) cloud which has little or no correlation with each other and with galaxies (Ikeuchi 1986, Rees 1986, Miralda-Escude et.al. 1996; Cen, Simcoe 1997; Zhang et.al. 1997; Weinberg et.al. 1997 and references therein).

For a cloud in galactic halo, a smaller cloud is quickly evaporated due to heat conduction from ambient hot medium and a larger cloud is tidally disrupted by galactic halo potential. As a result, it is concluded that for both cases of \(z=2.5\) and \(z=0.5\) pressure-confined Ly\(\alpha\) cloud with typical column density \(N_{HI} = 10^{14} cm^{-2}\) cannot survive in galactic halo, although a cloud having higher
column density $N_{HI} = 10^{17} \text{cm}^{-2}$ can do there in stable.

In our simple treatment, several factors are neglected. Do they change our conclusion?

First, the thermal conductivity may be fairly reduced if the magnetic field exists (Pistinner et al. 1996 and references therein), and a severe lower bound for the mass of a Lyα cloud may be relaxed as well as the suppression of hydrodynamical instability. If so, the pressure-confined Lyα cloud of $N_{HI} = 10^{14} \text{cm}^{-2}$ may exist in galactic halo, but we have few knowledge concerning the magnetic field to an extent of $\sim 100\text{kpc}$ of galaxy so that we cannot analyze quantitatively this effect on cloud properties.

Second, we do not take into account of the UV radiation from young stars in galaxy (Norman, Spaans 1997; Spaans, Norman 1997). As we mentioned in the previous section, this UV component effectively relaxes the evaporation condition. But at the same time, evaporation time scale we estimate becomes shorter due to electrons in heavy elements synthesized in newly formed stars. Both of these effects are difficult to include quantitatively in this stage.

Third, we do not take into account the hierarchical clustering picture of galaxy formation (Cole et al. 1994, Kauffmann et al. 1993). If galaxies are formed in this way, we have to replace $\tau_{halo}$ in eqs. (23) by a typical merging timescale of halos, $\Delta t_{merge}$, and to consider various stability conditions for a cloud at each time when galaxies merged and resultant halo heated up. It is too
complicated for us to follow this history at present, but we can simply indicate that our conclusion does not change at all as far as $\Delta t_{\text{merge}}$ is in order of $10^8$ year.

Finally, we speculate how the alternative model for the Ly$\alpha$ cloud may be, from the viewpoint of our conclusion that pressure-confined, spherical Ly$\alpha$ cloud with $N_{HI} = 10^{14} \text{cm}^{-2}$ cannot survive in galactic halo. The other spherical cloud models may be classified to two categories. One is the cloud confined by the gravity of CDM and the other is a ram pressure-confined cloud which will finally collapse in a longer timescale than a free-fall time of a cloud.

When the cold cloud is gravitationally confined by the CDM potential, the stability condition against the tidal disruption may be relaxed, hydrodynamical instability is greatly suppressed, and the properties of hot halo are not constrained through cooling and evaporation condition. Therefore, it is highly probable that the non-evolving component of Ly$\alpha$ forest in associated with galaxies may be the clouds confined by the CDM, and the evolving one in intergalactic medium may be the pressure confined clouds.

Ram pressure-confined, cloud model would be emphasized as follows. In this paper we assume that the extended gaseous halo is isothermal ($n_h \sim r^{-2}$) which is expected in our Galaxy. Using this relation and eq. (8), we can predict a remarkable feature for the Ly$\alpha$ clouds. In the single halo, higher $N_{HI}$ systems exist near the center of the halo and lower $N_{HI}$ systems exist in the outer
region of it. The correlation between the equivalent widths of Lyα absorption lines and the impact parameters from nearby galaxies indicated by Lanzetta et al. (1995, 1997) may reflect this distribution law. So in our next step to examine the physical properties of pressure-confined Lyα clouds associated with galaxy, it may be natural to analyze the properties of a cloud for various positions of a single halo and for various halos. For example, at a different distance from galactic center, the stable conditions against evaporation and tidal disruption for a cloud as well as the typical column density $N_{HI}$ of a cloud are also different. After such an estimate has been done, we will compare the results with recent data for Lyα clouds which associate with galaxies,—strong correlation of Lyα absorption equivalent width, galaxy impact parameter, and galaxy B-band luminosity (Chen et al. 1997; Lanzetta et al. 1997b). From those analyses, we will also be able to predict physical quantities of hot halo which posesses Lyα clouds in relation to X-ray observation (Sarazin 1996) or extreme-UV observation of galactic halo.

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Figure Captions

Fig. 1a
The three conditions presented in §2.2. are shown in the plane of density and temperature of the hot ambient gas of two-component system at z=2.5 (Model 1). This situation essentially corresponds to Lyα cloud in hot intergalactic medium. The hatched sides are forbidden. As we noted in the text, the right below, left below and right upper region in this figure are not allowed due to the cooling, gravitationally unstable, and evaporation conditions, respectively. For comparison, a constant cloud radius and a constant cloud mass which discussed in §2.1 are shown for the cases of $R_c=100, 10$ and 1kpc (short-dashed line) and of $M_c=10^8, 10^6$ and $10^4M_\odot$ (dot-dashed line) from left to right, respectively.

Fig. 1b
The allowed mass ranges of cold clouds is shown with respect to the pressure of the hot phase for the case of $T_1=J_{-21}=1$. The evaporation conditions are shown for three cases of $n_h=10^{-5}, 10^{-6}$ and $10^{-7}cm^{-3}$. Note that roughly speaking, the upper and lower mass bound of the cloud is constrained by the stability condition against the Jeans instability and evaporation, respectively. The allowed region is indicated in the trapezoid region left below for the three cases of the density of the hot halo (solid line). For comparison, a constant cloud radius is shown for the case of $R_c=100, 10$ and 1kpc from top to bottom (short-dashed line), and a constant neutral hydrogen column density is also plotted (dash-dotted line).

Fig. 2a
The same as in Figure1(a) but for the case of a cloud in two-component system at z=0.5 (Model 2). A constant cloud radius and a constant cloud mass are shown for the cases of $R_c=100kpc$ (short-dashed line) and of $M_c=10^8M_\odot$ (dot-dashed line).

Fig. 2b
The same as in Figure1(b), but for the case of cloud at z=0.5. The evaporation conditions are shown for three cases of $n_h=10^{-6}, 10^{-7}$, and $10^{-8}cm^{-3}$. Lines of constant $R_c$ and $N_{HI}$ are shown for the same parameters as in Figure1(b).

Fig. 3a
The conditions presented in §3.1 are shown in the plane of density and temperature of the hot halo of two-component protogalaxy at z=2.5 (Model 3). For such a cloud, the stability against the tidal disruption gives a lower bound on a pressure $\tilde{P}$, which is shown by a dotted line. Horizontal dotted line shows the virial temperature of typical galaxy. Lines of constant $R_c$ and $M_c$ are shown
for 1kpc and $10^4 M_\odot$.

**Fig. 3b**
The same as in Figure 3a but for a cloud of $T_4=6.3$. Lines of constant $R_c$ and $M_c$ are shown for 1kpc and $10^6 M_\odot$.

**Fig. 4**
The same as in Figure 3(a) but for a cloud in a hot galactic halo at $z=0.5$ (Model 4). This figure apparently shows that there is no allowed region.

**Fig. 5a**
The same as in Figure 4 but for the case of $N_{HI} = 10^{12} cm^{-2}$ (Model 5).

**Fig. 5b**
The same as in Figure 4 but for the case of $N_{HI} = 10^{17} cm^{-2}$ (Model 6). Lines of constant $R_c$ and $M_c$ are shown for 10, 1kpc and $10^6, 10^4 M_\odot$ from left to right, respectively.

### Table 1. Symbols and their meanings

| symbol | unit | meaning |
|--------|------|---------|
| $z$ |  | redshift |
| $\Omega$ |  | density parameter |
| $H_0$ | $Mpc km^{-1} sec^{-1}$ | Hubble constant |
| $n_h$ | $cm^{-3}$ | hot phase density |
| $T_h$ | K | hot phase temperature |
| $n_c$ | $cm^{-3}$ | cloud density |
| $T_c$ | K | cloud temperature |
| $T_4$ | $10^4 K$ | normalized cloud temperature |
| $R_c$ | pc | cloud radius |
| $M_c$ | $M_\odot$ | cloud mass |
| $R_h$ | pc | typical scale of galaxy |
| $M_{gal}$ | $M_\odot$ | total mass of galaxy |
| $N_{HI}$ | $cm^{-2}$ | HI column density of cloud |
| $N_{14}$ | $10^{14} cm^{-2}$ | normalized HI column density |
| $J_{-21}$ | $10^{-21} erg cm^{-2} s^{-1} Hz^{-1} str^{-1}$ | mean UV intensity |
| $\tau_H$ | sec | Hubble time |
| $\tau_{cool}$ | sec | cooling time |
| $\tau_{eep}$ | sec | evaporation time |
| $\tau_{halo}$ | sec | crossing time of halo |
Table 2. Physical Processes and adopted values of Parameters

| parameters | adopted value | references |
|------------|---------------|------------|
| z          | 0.5, 2.5      | —         |
| Ω          | 1             | —         |
| H₀         | 50            | —         |
| J_{-21}    | 10^{-2}(z=0.5), 1(z=2.5) | Savaglio & Webb |
| N_{14}     | 1, 10^{-2}, 10^3 | —         |
| T₄ (cloud in IGM) | 3.0 | Ikeuchi & Ostriker |
| T₄ (cloud in halo) | 2.5(J_{-21} = 1, n_c = 10^{-2}) | Thoul & Weinberg |
|            | 6.3(J_{-21} = 1, n_c = 10^{-4}) |           |
|            | 1.2(J_{-21} = 10^{-2}, n_c = 10^{-2}) | this work |
|            | 2.3(J_{-21} = 10^{-2}, n_c = 10^{-4}) |           |

Table 3. Model parameters in our calculation

| model number | cloud situation | z (J_{-21}) | N_{14} | T₄ |
|--------------|-----------------|-------------|--------|----|
| Model 1      | IGM             | 2.5 (1)     | 1      | 3  |
| Model 2      | IGM             | 0.5 (10^{-2}) | 1      | 3  |
| Model 3      | galactic halo   | 2.5 (1)     | 1      | 2.5|
| Model 4      | galactic halo   | 0.5 (10^{-2}) | 1      | 1.2|
| Model 5      | galactic halo   | 0.5 (10^{-2}) | 10^{-2} | 1.2|
| Model 6      | galactic halo   | 0.5 (10^{-2}) | 10^{3} | 2.3|

Table 4. Summary of Results; Allowed physical quantities for the Lyα cloud

| model number | log R_c (pc) | log M_c (M_☉) |
|--------------|--------------|---------------|
| Model 1      | 3.0~5.4      | 4.1~9.2       |
| Model 2      | 3.6~6.2      | 6.8~9.3       |
| (Model 3)    | (2.9~3.4)    | (4.0~4.7)     |
| Model 4      | ×            | ×             |
| Model 5      | ×            | ×             |
| Model 6      | 3.8~4.2      | 6.4~6.9       |
| (Model 6)    | (2.6~4.6)    | (3.9~7.9)     |

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(\sim): results for $T_h = 10^{5.5}$K not $T_h = 10^{6.3}$K
\times: no allowed region
Figure 1(a) $z=2.5, J_{-21}=1, T_4=3, N_{14}=1$

- Gravitationally unstable
- Evaporation
- Cooling

Figure 1(b) $z=2.5, J_{-21}=1, T_4=3$

- Gravitationally unstable
- Evaporation ($n_h=10^{-5} \text{cm}^{-3}$)
- Cold Cloud Mass ($\log M_c \text{ (M}_\odot)$)
- Hot Phase Temperature ($\log T_h \text{(K)}$)
- Hot Phase Density ($\log n_h \text{(cm}^{-3}\text{)}$)
- Cold Cloud (= Hot Phase) Pressure ($\log P \text{ (cm}^{-3}\text{K)}$)
Figure 2(a)  
$z=0.5, J_{-21}=0.01, T_4=3, N_{14}=1$

 gravitationally unstable  
 evaporation  
 cooling

Figure 2(b)  
$z=0.5, J_{-21}=0.01, T_4=3$

 gravitationally unstable  
 evaporation ($n_h=10^{-6}(\text{cm}^{-3})$)  
 $n_h(\text{cm}^{-3})$ $10^{-8}$ $10^{-7}$ $10^{-6}$  
 $10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$ $10^{17}$ $N_{\text{H}_1}(\text{cm}^{-2})$
Figure 3(a)

$z = 2.5, J_{-21} = 1, T_4 = 2.5, N_{14} = 1$

- Evaporation
- Gravitationally unstable
- Tidal disruption
- Cooling

Figure 3(b)

$z = 2.5, J_{-21} = 1, T_4 = 6.3, N_{14} = 1$

- Evaporation
- Gravitationally unstable
- Tidal disruption
- Cooling
Figure 4

$z=0.5, J_{-21}=0.01, T_4=1.2, N_{14}=1$

- Evaporation
- Tidal disruption
- Gravitationally unstable
- Cooling

Hot Halo Temperature ($\log T_h(K)$)

Hot Halo Density ($\log n_h(cm^{-3})$)
Figure 5(a) $z=0.5, J_{-21}=0.01, T_4=1.2, N_{14}=0.01$

- Gravitationally unstable
- Evaporation
- Tidal disruption
- Cooling
- $T_{\text{vir}}$

Figure 5(b) $z=0.5, J_{-21}=0.01, T_4=1.2, N_{14}=1000$

- Gravitationally unstable
- Evaporation
- Tidal disruption
- Cooling
- $T_{\text{vir}}$